

Modern C++ Refresher Course

Comprehensive Reference - C++11 through C++23

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1 Modern C++ Examples - Comprehensive Reference

A comprehensive collection of Modern C++ examples covering C++11 through C++23, design patterns, embedded systems, real-time programming, and safety-critical development.

1.1 Document Information

Version: 1.0.0

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Repository: <https://github.com/AungKyawSoe-Tech/ModernCppExamples>

1.2 About This Project

This repository contains over 70 comprehensive C++ examples demonstrating modern C++ features, design patterns, best practices, and real-world applications. Each example is self-contained, well-documented, and includes practical use cases.

1.2.1 Key Features:

- **Complete C++ Standards Coverage:** Examples from C++11 through C++23
 - **Safety-Critical Systems:** MISRA C++, AUTOSAR C++14, ISO 26262, DO-178C
 - **Real-Time Programming:** Deterministic timing, WCET analysis, bounded memory
 - **Design Patterns:** Gang of Four, CRTP, Pimpl, NVI, SOLID principles
 - **Embedded Systems:** ARM instruction sets, ROMability, resource constraints
 - **Modern Concurrency:** C++20 coroutines, thread pools, `async/await`
 - **Interoperability:** Python bindings (`pybind11`), C API wrapping, Protocol Buffers
 - **Performance:** Move semantics, perfect forwarding, template metaprogramming
-

1.3 Quick Start

1.3.1 Prerequisites

- C++20 or later compiler (GCC 10+, Clang 10+, MSVC 2019+)
- CMake 3.20 or later
- Optional: Python 3.8+ (for pybind11 examples)
- Optional: Protocol Buffers compiler (for protobuf examples)

1.3.2 Build Instructions

1.3.2.1 Linux/Mac:

```

1 # Clone the repository
2 git clone https://github.com/AungKyawSoe-Tech/ModernCppExamples.git
3 cd ModernCppExamples
4
5 # Build all examples
6 mkdir build && cd build
7 cmake ..
8 make -j$(nproc)
9
10 # Run a specific example
11 ./bin/Cpp20Examples

```

1.3.2.2 Windows (PowerShell):

```

1 # Clone the repository
2 git clone https://github.com/AungKyawSoe-Tech/ModernCppExamples.git
3 cd ModernCppExamples
4
5 # Build all examples
6 mkdir build
7 cd build
8 cmake ..
9 cmake --build . --config Release
10
11 # Run a specific example
12 .\bin\Release\Cpp20Examples.exe

```

1.4 Navigation & Documentation

1.4.1 Detailed Index

For comprehensive topic mapping, concept lookup, and cross-references, see: - [INDEX.md](#) - Complete index mapping concepts, keywords, features, and problems to specific examples

1.4.2 Supporting Documentation

Additional detailed guides are available in the `MarkDownDocuments/` folder: - [CPP11.md](#) - C++11 features guide - [CPP14.md](#) - C++14 enhancements - [CPP17.md](#) - C++17 major features - [CPP20.md](#) - C++20 revolutionary features - [CPP23.md](#) - C++23 latest additions - [EventDrivenProgramming.md](#) - Event-driven architecture - [MultiThreadedMicroservices.md](#) - Microservices patterns -

[Protobuf.md](#) - Protocol Buffers integration - [Pybind11.md](#) - Python bindings - [SECURITY.md](#) - Security best practices

1.4.3 Automatic Updates

When you add new source files, the documentation automatically updates: - [README.md](#) - Alphabetical listing auto-updates (see [AUTO_UPDATE_GUIDE.md](#)) - [INDEX.md](#) - Template generated for manual topic categorization - [PDF](#) - Automatically includes all new files

See: [AUTO_UPDATE_GUIDE.md](#) for complete details on adding new examples.

1.5 Complete Examples - Alphabetical Reference

Below is a complete alphabetical listing of all C++ example files in this repository. Each entry links to the source file with a brief description of its contents.

1.5.1 A

1. [AdvancedExceptionHandling.cpp](#)

- AdvancedExceptionHandling.cpp
- Namespaces: std
- Classes: DatabaseException, TracedException, StackTrace

2. [ARMIInstructionSets.cpp](#)

- compiled as Thumb
- Functions: explain_alignment_issues, explain_interworking, explain_instruction_sets

3. [AsioAndModernCppConcurrency.cpp](#)

- Note: This example demonstrates ASIO concepts using standard C++ features.
- Namespaces: std
- Classes: SimulatedAsioTimer, HybridServer, EventLoop

4. [AsioMultipleContexts.cpp](#)

- ...
- Namespaces: SimulatedAsio, std
- Classes: io_context, executor_work_guard, steady_timer

1.5.2 B

5. [BinarySearch.cpp](#)

- Modern C++ example demonstrating various features
- Classes: Solution
- Functions: main

1.5.3 C

6. [CameraModule.cppm](#)

- =====
- Classes: ImageProcessor, Image, Camera

7. [ConceptsExamples.cpp](#)

- =====

- Classes: Rectangle, Point2D, Circle
 - Functions: print_sum, example_basic_concept, example_standard_concepts
8. **ConfigLoaderAndChecker.cpp**
- ConfigLoaderAndChecker.cpp
 - Namespaces: std, fs
 - Classes: ConfigManager, ConfigMonitor
9. **Cpp11Examples.cpp**
- =====
 - Classes: Color, Traffic, MoveableResource
 - Functions: example_auto, foo
10. **Cpp14Examples.cpp**
- =====
 - Namespaces: std
 - Functions: example_generic_lambdas, example_lambda_capture_initializers, example_binary_literals
11. **Cpp17Concurrency.cpp**
- =====
 - Namespaces: std
 - Classes: AsyncFileProcessor, CancellableFuture, ThreadPool
12. **Cpp17Examples.cpp**
- =====
 - Namespaces: fs, A
 - Functions: example_template_argument_deduction, example_structured_bindings, sum_fold
13. **Cpp20Examples.cpp**
- =====
 - Classes: Color
 - Functions: example_concepts, example_designated_initializers, example_three_way_comparison
14. **Cpp23Examples.cpp**
- =====
 - Classes: GPIOPin, MemoryRegister, SensorError
 - Functions: demonstrate_expected, demonstrate_byteswap
15. **CppWrappingCLibrary.cpp**
- =====
 - Classes: Socket, TcpServer, SocketError
 - Functions: demonstrate_raii, demonstrate_nodiscard, demonstrate_noexcept
16. **CreatingCApiFromCpp.cpp**
- Create a new image
 - Namespaces: image_processing
 - Classes: Image
17. **CRTPvsVirtualFunctions.cpp**

- CRTP vs Virtual Functions: Static vs Dynamic Polymorphism
- Namespaces: static_functions, virtual_functions
- Classes: Dog, AnimalBase, Base

1.5.4 D

18. [DependencyInjection.cpp](#)

- =====
- Classes: ConsoleLogger, ILogger, FileLogger
- Functions: example_traditional_di, example_constructor_injection, example_interface_injection

19. [DiamondProblem.cpp](#)

- DiamondProblem.cpp
- Namespaces: virtual_inheritance_solution, diamond_problem
- Classes: InputDevice, OutputDevice, Device

1.5.5 E

20. [EigenSensorFusion.cpp](#)

- EXPECTED OUTPUT:
- Namespaces: Eigen
- Classes: ComplementaryFilter, ParticleFilter, KalmanFilter

21. [EmbeddedSystemsAvoid.cpp](#)

- =====
- Classes: BaseSensor, TempSensor, SensorBase
- Functions: demonstrate_vector_problems, demonstrate_string_problems, demonstrate_heap_fragmentation

22. [EmbeddedSystemsProgramming.cpp](#)

- =====
- Namespaces: BitOps
- Classes: MemoryPool, PinMode, CircularBuffer

23. [ErrorHandling.cpp](#)

- =====
- Classes: runtime_error, CameraException, CameraNotConnectedException
- Functions: demonstrate_custom_exceptions, demonstrate_basic_exception_handling, demonstrate_exception_hierarchy

24. [ErrorHandlingStroustrup.cpp](#)

- =====
- Classes: FileHandler_GOOD, FileHandler_BAD, ConfigParser
- Functions: demonstrate_return_values, demonstrate_exceptions, demonstrate_termination

25. [EventDrivenProgramming_Inheritance.cpp](#)

- =====

- Classes: IObserver, ConsoleObserver, CountingObserver
- Functions: example_inheritance_observer, example_listener_pattern, example_event_hierarchy

26. [EventDrivenProgramming_Lambdas.cpp](#)

- =====
- Classes: Subject, Signal, Button
- Functions: example_variant_dispatcher, example_signal_slot, example_lambda_observer

27. [ExceptionWithSourceLocation.cpp](#)

- =====
- Classes: DetailedException, SourceLocationException, BaseLocationException
- Functions: demonstrate_detailed_location, demonstrate_basic_location, some_function_that_fails

1.5.6 F

28. [FindCountOfCommonNodes.cpp](#)

- Modern C++ example demonstrating various features
- Namespaces: std
- Classes: Solution

29. [FindFirstCommonNode.cpp](#)

- Modern C++ example demonstrating various features
- Namespaces: std
- Classes: Solution

30. [FindMaxNoOfConsecutiveOnesFromIntArray.cpp](#)

- Instructions:
- Functions: main

31. [FindMToLastElement.cpp](#)

- Modern C++ example demonstrating various features
- Namespaces: std
- Classes: Solution

32. [FragileBaseClass.cpp](#)

- FragileBaseClass.cpp
- Namespaces: composition_solution, fragile_example
- Classes: Counter_V1, LoggingCounter_V1, Counter_V2

33. [FunctionalSafetyISO26262.cpp](#)

- FunctionalSafetyISO26262.cpp
- Classes: SafetyResult, SafetyState, ASILLevel
- Functions: demonstrate_safe_data_types, demonstrate_redundancy_voting, demonstrate_asil_levels

34. [FuturePromiseAsync.cpp](#)

- FuturePromiseAsync.cpp

- Namespaces: std, async_examples
- Classes: RequestProcessor, SimpleThreadPool

1.5.7 G

35. [GenericLambdas.cpp](#)

- =====
- Functions: example_basic_generic_lambda, example_generic_lambda_operations, example_generic_lambda_containers

1.5.8 I

36. [InheritanceTypes.cpp](#)

- =====
- Classes: Animal, Dog, Timer
- Functions: example_public_inheritance, example_private_inheritance, example_protected_inheritance

37. [InsertAndDeleteNodes.cpp](#)

- PrintListNode(pInHead);
- Namespaces: std
- Classes: Solution

1.5.9 L

38. [LambdaCaptures.cpp](#)

- =====
- Classes: ExampleClass, ExampleClass2, Button
- Functions: example_capture_all_by_reference, example_no_capture, example_capture_all_by_value

1.5.10 M

39. [MISRACppDemo.cpp](#)

- =====
- Namespaces: expressions_and_operators, types_and_declarations
- Classes: Resource, GoodBase, BadBase

40. [MoveSemantics.cpp](#)

- =====
- Classes: MoveOnlyType, LargeObject, Resource
- Functions: demonstrate_copy_vs_move, demonstrate_std_move, demonstrate_lvalue_rvalue

41. [MoveSemanticsPerfectForwarding.cpp](#)

- =====
- Namespaces: lvalues_rvalues, move_semantics
- Classes: Resource, Widget

42. [MultiThreadedMicroservices.cpp](#)

- MultiThreadedMicroservices.cpp
- Namespaces: std
- Classes: ThreadType, ThreadContext, Logger

1.5.11 N

42. [NlohmannJsonExample.cpp](#)

- =====
- Functions: example_basic_json, example_arrays, example_custom_types

42. [NoexceptBestPractices.cpp](#)

- =====
- Namespaces: always_use_noexcept, what_is_noexcept
- Classes: Resource, Swappable, MoveableResource

42. [NVIIIdiomTemplateMethod.cpp](#)

- NVIIIdiomTemplateMethod.cpp
- Namespaces: std, basic_nvi
- Classes: CSVProcessor, JSONProcessor, DataProcessor

1.5.12 O

42. [ObjectSlicingCpp20.cpp](#)

- =====
- Classes: Shape, Rectangle, Circle
- Functions: draw_shape, process_shape, example_concepts_prevent_slicing

42. [ObjectSlicingSmartPtr.cpp](#)

- =====
- Classes: Shape, Rectangle, Circle
- Functions: example_shared_ptr_slicing_wrong, example_container_slicing_wrong, example_classic_slicing

42. [OptionalExamples.cpp](#)

- =====
- Functions: example_basic_optional, example_optional_return, example_value_or

1.5.13 P

42. [PerfectForwardingAndRequires.cpp](#)

- tests
- Classes: ThreadSafeQueue, Serializable, Register
- Functions: demonstrate_perfect_forwarding, call_with_forward, call_by_value

42. [PimplIdiom.cpp](#)

- =====
- Namespaces: what_is_pimpl, modern_cpp_pimpl

- Classes: WidgetCpp98, WidgetNoPimpl, WidgetWithPimpl

42. [ProtobufExample.cpp](#)

- =====
- Functions: example_binary_deserialization, example_binary_serialization, example_create_sensor_reading

42. [Pybind11Example.cpp](#)

- PYTHON USAGE EXAMPLES:
- Namespaces: py
- Classes: Vector2D, Shape, Circle

1.5.14 R

42. [RangesExamples.cpp](#)

- =====
- Namespaces: views, ranges
- Functions: example_filter_view, example_basic_ranges, example_transform_view

42. [RealTimeProgramming.cpp](#)

- RealTimeProgramming.cpp
- Namespaces: big_o_notation, thread_architecture
- Classes: RealTimeFlagManager, SensorSystem, SensorStatus

42. [ResourceLeaks.cpp](#)

- EXPECTED OUTPUT HIGHLIGHTS:
- Namespaces: ModernCpp, OldCpp
- Classes: Node, ExpensiveResource, ResourceIntensive

42. [RestApiExample.cpp](#)

- =====
- Classes: CurlHandle, CurlHeaders, RestClient
- Functions: example_create_post, example_update_post, example_json_placeholder_api

42. [ROMability.cpp](#)

- ROMability.cpp
- Namespaces: const_vs_constexpr, rom_arrays
- Functions: demonstrate, get_runtime_value

42. [RuleOf3_5_0.cpp](#)

- no-op
- Classes: RuleOffFiveExample, RuleOfThreeExample, RuleOfZeroExample
- Functions: example_rule_of_zero, example_rule_of_five, example_rule_of_three

42. [RuntimePolymorphism.cpp](#)

- =====
- Classes: IShape, Rectangle, Circle

- Functions: example_virtual_destructor, example_virtual_with_default, example_pure_virtual

1.5.15 S

42. SafetyCriticalSTLContainers.cpp

- =====
- Namespaces: container_classification, containers_to_avoid
- Classes: SafetyPoolAllocator

42. SearchAnagramsDictionary.cpp

- Example program
- Functions: main

42. SinglyLinkedList.cpp

- pHHead
- Functions: print, main

42. SOLIDPrinciples.cpp

- =====
- Namespaces: open_closed, single_responsibility
- Classes: Employee, BadEmployee, TaxCalculator

42. STLContainersNoHeap.cpp

- =====
- Classes: PoolAllocator, FixedVector, StackAllocator
- Functions: example_std_array, example_std_span, process_data

42. StopTokenExample.cpp

- StopTokenExample.cpp
- Namespaces: std, old_vs_new
- Classes: RESTService, OldStyleThread, NewStyleThread

42. StructuredBindings.cpp

- =====
- Functions: example_array_bindings, example_tuple_bindings, example_basic_structured_bindings

42. SystemInteractionAndParsing.cpp

- =====
- Namespaces: fs
- Classes: BankAccount, ThreadSafeLogger, SharedCounter

1.5.16 T

42. TemplatizedCameraInterface.cpp

- =====
- Classes: Camera8bit, Image, Camera
- Functions: demonstrate_16bit_camera, demonstrate_float_camera, demonstrate_8bit_camera

42. **TemplatedCameraModules.cpp**

- =====
- Functions: demonstrate_camera_capture, demonstrate_concepts, display_camera_info

42. **ThreadPoolExamples.cpp**

- ThreadPoolExamples.cpp
- Namespaces: std
- Classes: BasicThreadPool, TaskPriority, ThreadPoolWithFutures

42. **TuplesAndStructuredBindings.cpp**

- =====
- Functions: demonstrate_structured_bindings, demonstrate_basic_tuples, demonstrate_tie

1.5.17 V

42. **VariadicTemplateRecursion.cpp**

- =====
- Classes: GPIO_Pin
- Functions: demonstrate_basic_recursion, print_recursive

42. **VirtualFunctionsInTemplates.cpp**

- VIRTUAL FUNCTIONS IN TEMPLATES: THE CODE BLOAT PROBLEM
- Namespaces: the_problem, bad_example_t80
- Classes: template, Vector, DemoInstantiation

1.5.18 Interview Preparation

75. **MockInterview.cpp**

- **Complete C++ Interview Questions & Answers** - Comprehensive mock interview preparation guide
- **Topics Covered:**
 - Section 1: C++ Fundamentals (pointers vs references, const correctness, RAII)
 - Section 2: Memory Management (smart pointers, memory alignment, custom allocators)
 - Section 3: OOP & Design Patterns (virtual dispatch, CRTP, PIMPL)
 - Section 4: Templates & Metaprogramming (SFINAE, variadic templates, compile-time computation)
 - Section 5: Concurrency & Multithreading (singleton, producer-consumer, atomic operations)
 - Section 6: Performance & Optimization (move semantics, RVO/NRVO, copy elision)
- **Key Demonstrations:** 25+ interview questions with detailed explanations and runnable code
- **Namespaces:** std
- **Classes:** FileHandler, Data, Widget, ThreadSafeSingleton, ProducerConsumer, LargeObject, Expensive
- **Functions:** pointers_vs_references, const_correctness, raii_demo, smart_pointers_advanced, memory_alignment, virtual_dispatch_details, crtp_mixins_demo, sfinae_demo, vari-

adic_demo, compile_time_demo, singleton_demo, producer_consumer_demo, atomic_operations_demo,
move_semantics_performance, copy_elision_demo

1.6 Project Structure

```

1 ModernCppExamples/
2   src/                      # All C++ source files (.cpp, .cppm)
3     Cpp11Examples.cpp      # C++11 features
4     Cpp20Examples.cpp      # C++20 features
5     RealTimeProgramming.cpp
6     SafetyCriticalSTLContainers.cpp
7     PimplIdiom.cpp
8     ... (70+ examples)
9
10  MarkDownDocuments/        # Detailed documentation
11    CPP20.md
12    EventDrivenProgramming.md
13    MultiThreadedMicroservices.md
14    Protobuf.md
15    Pybind11.md
16    SECURITY.md
17    ...
18
19  scripts/                  # Build and utility scripts
20    build.sh                # Main build script
21    build_modules.sh        # C++20 modules build
22    build_protobuf.sh      # Protocol Buffers build
23    build_pybind.sh        # Pybind11 build
24    run_all.sh              # Run all examples
25
26  proto/                   # Protocol Buffer definitions
27    sensor_data.proto
28
29  build/                   # Build output directory
30    bin/                    # Compiled executables
31
32  CMakeLists.txt           # CMake configuration
33  INDEX.md                 # Comprehensive topic index
34  README.md                # This file
35  config.json              # Configuration file

```

1.7 Finding Examples by Topic

For detailed topic mapping, see [INDEX.md](#). Quick topic guide:

1.7.1 By C++ Standard

- C++11: [Cpp11Examples.cpp](#), [LambdaCaptures.cpp](#), [MoveSemantics.cpp](#)
- C++14: [Cpp14Examples.cpp](#), [GenericLambdas.cpp](#)

- **C++17:** [Cpp17Examples.cpp](#), [StructuredBindings.cpp](#), [OptionalExamples.cpp](#)
- **C++20:** [Cpp20Examples.cpp](#), [ConceptsExamples.cpp](#), [RangesExamples.cpp](#), [CameraModule.cppm](#)
- **C++23:** [Cpp23Examples.cpp](#)

1.7.2 By Application Domain

- **Embedded Systems:** [EmbeddedSystemsProgramming.cpp](#), [ROMability.cpp](#), [ARMIInstructionSets.cpp](#)
- **Real-Time Systems:** [RealTimeProgramming.cpp](#), [STLContainersNoHeap.cpp](#)
- **Safety-Critical:** [SafetyCriticalSTLContainers.cpp](#), [FunctionalSafetyISO26262.cpp](#), [MIS-RACppDemo.cpp](#)
- **Concurrency:** [Cpp17Concurrency.cpp](#), [FuturePromiseAsync.cpp](#), [ThreadPoolExamples.cpp](#)

1.7.3 By Design Pattern

- **CRTP:** [CRTPvsVirtualFunctions.cpp](#)
- **Pimpl:** [PimplIdiom.cpp](#)
- **NVI:** [NVIIdiomTemplateMethod.cpp](#)
- **Dependency Injection:** [DependencyInjection.cpp](#)
- **SOLID:** [SOLIDPrinciples.cpp](#)

1.8 Testing & Running Examples

Each example is a standalone executable. After building:

```

1 cd build/bin
2
3 # Run a specific example
4 ./Cpp20Examples
5
6 # Run all examples (Linux/Mac)
7 cd ../..
8 ./scripts/run_all.sh
9
10 # Run all examples (Windows PowerShell)
11 Get-ChildItem .\bin\Release\*.exe | ForEach-Object { & $_.FullName }
```

1.9 Dependencies

Most examples have no external dependencies. Optional dependencies for specific examples:

- **Boost.Asio:** [AsioAndModernCppConcurrency.cpp](#), [AsioMultipleContexts.cpp](#)
- **Eigen:** [EigenSensorFusion.cpp](#)
- **nlohmann/json:** [NlohmannJsonExample.cpp](#)
- **Protocol Buffers:** [ProtobufExample.cpp](#)
- **pybind11:** [Pybind11Example.cpp](#)

Build scripts automatically check for these dependencies.

1.10 Contributing

Contributions are welcome! Please follow these guidelines:

1. **Code Style:** Follow the existing code style (Google C++ Style Guide)
 2. **Documentation:** Each example should have clear comments explaining the concepts
 3. **Compilation:** Ensure code compiles with C++20 standard
 4. **Testing:** Test on multiple compilers if possible
 5. **Commit Messages:** Use clear, descriptive commit messages
-

1.11 License

This project is licensed under the MIT License. See LICENSE file for details.

1.12 Contact & Support

For questions, suggestions, or issues: - **GitHub Issues:** <https://github.com/AungKyawSoe-Tech/ModernCppExamples/issues> - **Email:** aungksoe.mobile@gmail.com

1.13 Acknowledgments

Special thanks to: - The C++ Standards Committee for continuously evolving the language - Open source contributors: Boost, Eigen, nlohmann/json, pybind11 - The C++ community for valuable feedback and suggestions

1.14 Additional Resources

1.14.1 Official Documentation

- [C++ Reference](#)
- [ISO C++ Standard](#)
- [C++ Core Guidelines](#)

1.14.2 Safety Standards

- [MISRA C++:2008](#)
- [AUTOSAR C++14](#)
- [ISO 26262](#) - Automotive functional safety
- [DO-178C](#) - Airborne software safety

1.14.3 Books

- “Effective Modern C++” by Scott Meyers
- “C++ Concurrency in Action” by Anthony Williams
- “Real-Time C++” by Christopher Kormanyos
- “C++ Move Semantics” by Nicolai Josuttis

Last Updated: January 3, 2026

Version: 1.0.0

Repository: <https://github.com/AungKyawSoe-Tech/ModernCppExamples>

ewpage

2 Source Code: ARMInstructionSets.cpp

File: src/ARMInstructionSets.cpp

Repository: [View on GitHub](#)

```

1 #include <iostream>
2 #include <cstdint>
3 #include <cstring>
4 #include <array>
5
6 // =====
7 // ARM INSTRUCTION SETS: ARM, THUMB , THUMB-2
8 // =====
9 // This example discusses instruction set modes, alignment issues,
10 // and compiler switches for ARM Cortex-M processors.
11 //
12 // IMPORTANT: This is a DEMONSTRATION for understanding concepts.
13 // The actual crashes occur on ARM hardware, not x86/x64.
14 // Compiler flags discussed apply to ARM cross-compilers (arm-none-eabi-gcc).
15 // =====
16
17 // =====
18 // 1. ARM INSTRUCTION SET OVERVIEW
19 // =====
20
21 void explain_instruction_sets() {
22     std::cout << "\n== 1. ARM INSTRUCTION SET OVERVIEW ==" << std::endl;
23
24     std::cout << "\n THREE INSTRUCTION SET MODES:" << std::endl;
25
26     std::cout << "\n1. ARM (A32) - 32-bit instructions:" << std::endl;
27     std::cout << " • Original ARM instruction set" << std::endl;
28     std::cout << " • Fixed 32-bit instruction size" << std::endl;
29     std::cout << " • Most powerful, but code size larger" << std::endl;
30     std::cout << " • Used in: ARM7, ARM9, ARM11, Cortex-A" << std::endl;
31     std::cout << " • Example instruction: ADD r0, r1, r2 (32 bits)" << std
32         ::endl;
33
34     std::cout << "\n2. THUMB (T16) - 16-bit instructions:" << std::endl;

```

```

34     std::cout << " • Compact 16-bit instruction subset" << std::endl;
35     std::cout << " • ~30% smaller code size vs ARM" << std::endl;
36     std::cout << " • Limited register access (r0-r7)" << std::endl;
37     std::cout << " • Used in: ARM7TDMI, ARM9, early Cortex-M0" << std::endl;
38     std::cout << " • Example: ADD r0, r1 (16 bits, 2-operand only)" << std::endl;
39
40     std::cout << "\n3. THUMB-2 (T32) - Mixed 16/32-bit:" << std::endl;
41     std::cout << " • Mix of 16-bit and 32-bit instructions" << std::endl;
42     std::cout << " • Best of both worlds: compact + powerful" << std::endl;
43     std::cout << " • Full register access, conditional execution" << std::endl;
44     std::cout << " • Used in: Cortex-M3, M4, M7, M33 (modern MCUs)" << std::endl;
45     std::cout << " • Example: ADD r0, r1, r2 (16 or 32 bits as needed)" << std::endl;
46
47     std::cout << "\n MODERN CORTEX-M PROCESSORS:" << std::endl;
48     std::cout << " • Cortex-M0/M0+: Thumb + subset of Thumb-2" << std::endl;
49     std::cout << " • Cortex-M3/M4/M7: Thumb-2 only (no ARM mode)" << std::endl;
50     std::cout << " • Cortex-M33/M55: Thumb-2 + DSP + optional FPU" << std::endl;
51 }
52
53 // =====
54 // 2. ALIGNMENT ISSUES - THE MAIN CAUSE OF CRASHES
55 // =====
56
57 // Simulated aligned data structure
58 struct __attribute__((aligned(4))) AlignedData {
59     uint32_t value1;
60     uint32_t value2;
61     uint32_t value3;
62 };
63
64 // Potentially misaligned data
65 struct UnalignedData {
66     uint8_t byte;      // 1 byte
67     uint32_t value;    // Should be 4-byte aligned, but might not be!
68     uint16_t halfword; // 2 bytes
69 };
70
71 void explain_alignment_issues() {
72     std::cout << "\n== 2. ALIGNMENT ISSUES (MAIN CRASH CAUSE) ==" << std::endl;
73
74     std::cout << "\n ARM ALIGNMENT REQUIREMENTS:" << std::endl;
75     std::cout << " • uint8_t (byte): 1-byte aligned (any address)" << std::endl;
76     std::cout << " • uint16_t (halfword): 2-byte aligned (address % 2 == 0)" << std::endl;
77     std::cout << " • uint32_t (word): 4-byte aligned (address % 4 == 0)" << std::endl;

```

```

78     std::cout << " • uint64_t (doubleword): 8-byte aligned (address % 8 == 0)" << std::endl;
79
80     std::cout << "\n WHAT HAPPENS ON MISALIGNED ACCESS:" << std::endl;
81     std::cout << " • Cortex-M0/M0+: HARDFAULT (crash)" << std::endl;
82     std::cout << " • Cortex-M3/M4/M7: May work BUT slower (extra cycles)" << std::endl;
83     std::cout << " • Depends on UNALIGN_TRP bit in CCR register" << std::endl;
84
85 // Demonstrate alignment
86 std::cout << "\n ALIGNMENT EXAMPLES:" << std::endl;
87
88 AlignedData aligned;
89 std::cout << " AlignedData size: " << sizeof(AlignedData) << " bytes" << std::endl;
90 std::cout << " Address of value1: " << reinterpret_cast<uintptr_t>(&aligned.value1) << " (mod 4 = " << (reinterpret_cast<uintptr_t>(&aligned.value1) % 4) << ")" << std::endl;
91
92 UnalignedData unaligned;
93 std::cout << "\n UnalignedData size: " << sizeof(UnalignedData) << " bytes" << std::endl;
94 std::cout << " Address of byte: " << reinterpret_cast<uintptr_t>(&unaligned.byte) << std::endl;
95 std::cout << " Address of value: " << reinterpret_cast<uintptr_t>(&unaligned.value) << " (mod 4 = " << (reinterpret_cast<uintptr_t>(&unaligned.value) % 4) << ")" << std::endl;
96
97 std::cout << "\n PROBLEM: If unaligned.value is at address 0x20000001:" << std::endl;
98 std::cout << " • ARM instruction: LDR r0, [r1] (load word from unaligned address)" << std::endl;
99 std::cout << " • Result: HARDFAULT on Cortex-M0, silent corruption on some others" << std::endl;
100 }
101
102 // =====
103 // 3. INTERWORKING ISSUES - STATE SWITCHING
104 // =====
105
106 void explain_interworking() {
107     std::cout << "\n==== 3. INTERWORKING ISSUES (STATE SWITCHING) ===" << std::endl;
108
109     std::cout << " HOW PROCESSOR KNOWS WHICH MODE:" << std::endl;
110     std::cout << " • Function address LSB (Least Significant Bit):" << std::endl;
111     std::cout << " - LSB = 0: ARM mode (A32 instructions)" << std::endl;
112     std::cout << " - LSB = 1: Thumb/Thumb-2 mode (T16/T32 instructions)" << std::endl;
113     std::cout << " • BX/BLX instructions switch modes automatically" << std::endl;
114
115 }
```

```

    ::endl;

116    std::cout << "\n CRASH SCENARIOS:" << std::endl;
117    std::cout << "\n 1. WRONG FUNCTION ADDRESS:" << std::endl;
118    std::cout << "      // C code" << std::endl;
119    std::cout << "      void my_function() { /* compiled as Thumb */ }" << std
120        ::endl;
121    std::cout << "      " << std::endl;
122    std::cout << "      // Assembly calling without setting LSB" << std::endl;
123    std::cout << "      LDR r0, =my_function ; Address without LSB=1" << std::
124        endl;
125    std::cout << "      BLX r0           ; Tries to execute as ARM!" <<
126        std::endl;
127    std::cout << "      " << std::endl;
128    std::cout << "      CORRECT:" << std::endl;
129    std::cout << "      LDR r0, =my_function+1 ; Set LSB to indicate Thumb" <<
130        std::endl;
131    std::cout << "      BLX r0           ; Correctly switches to
132        Thumb" << std::endl;

133    std::cout << "\n 2. INTERRUPT SERVICE ROUTINES (ISR):" << std::endl;
134    std::cout << " • Some ARM7/ARM9 enter exceptions in ARM mode" << std::
135        endl;
136    std::cout << " • If ISR compiled as Thumb: CRASH!" << std::endl;
137    std::cout << " • Solution: Force ISR to ARM mode or ensure processor
138        supports Thumb ISRs" << std::endl;

139    std::cout << "\n 3. ASSEMBLY CODE MISMATCH:" << std::endl;
140    std::cout << "      // File: startup.s (ARM mode)" << std::endl;
141    std::cout << "      .arm" << std::endl;
142    std::cout << "      Reset_Handler:" << std::endl;
143    std::cout << "      LDR sp, =_estack" << std::endl;
144    std::cout << "      BL main           ; Calls main as ARM!" << std::
145        endl;
146    std::cout << "      " << std::endl;
147    std::cout << "      CORRECT:" << std::endl;
148    std::cout << "      .thumb           ; Switch to Thumb mode" << std::
149        endl;
150    std::cout << "      Reset_Handler:" << std::endl;
151    std::cout << "      LDR sp, =_estack" << std::endl;
152    std::cout << "      BLX main           ; Properly switches to main's
153        mode" << std::endl;
154 }

155 // =====
156 // 4. COMPILER SWITCHES AND FLAGS
157 // =====

158 void explain_compiler_switches() {
159     std::cout << "\n== 4. COMPILER SWITCHES FOR ARM ==" << std::endl;
160
161     std::cout << "\n ARM-NONE-EABI-GCC FLAGS:" << std::endl;
162
163     std::cout << "\n1. INSTRUCTION SET MODE:" << std::endl;

```

```

159 std::cout << "      -marm" << std::endl;
160 std::cout << " •      Generate ARM (A32) instructions" << std::endl;
161 std::cout << " •      Larger code size, faster execution" << std::endl;
162 std::cout << " •      Use for: ARM7, ARM9, Cortex-A" << std::endl;
163 std::cout << " •      Example: arm-none-eabi-gcc -marm -mcpu=arm7tdmi main.
164     c" << std::endl;
165
166 std::cout << "\n      -mthumb" << std::endl;
167 std::cout << " •      Generate Thumb/Thumb-2 instructions" << std::endl;
168 std::cout << " •      Smaller code size, good performance" << std::endl;
169 std::cout << " •      DEFAULT for Cortex-M (they only support Thumb-2)" <<
170     std::endl;
171 std::cout << " •      Example: arm-none-eabi-gcc -mthumb -mcpu=cortex-m4
172     main.c" << std::endl;
173
174 std::cout << "\n2. CPU/ARCHITECTURE:" << std::endl;
175 std::cout << "      -mcpu=cortex-m0      # Cortex-M0 (Thumb subset)" << std::
176     endl;
177 std::cout << "      -mcpu=cortex-m3      # Cortex-M3 (Thumb-2)" << std::endl;
178 std::cout << "      -mcpu=cortex-m4      # Cortex-M4 (Thumb-2 + DSP)" << std
179     ::endl;
180 std::cout << "      -mcpu=cortex-m7      # Cortex-M7 (Thumb-2 + DSP + FPU)" <<
181     std::endl;
182
183 std::cout << "\n3. ALIGNMENT OPTIONS:" << std::endl;
184 std::cout << "      -mno-unaligned-access" << std::endl;
185 std::cout << " •      Disable unaligned memory access" << std::endl;
186 std::cout << " •      Compiler generates multi-instruction sequences" <<
187     std::endl;
188 std::cout << " •      Slower but safer on Cortex-M0" << std::endl;
189 std::cout << " •      Example: arm-none-eabi-gcc -mthumb -mno-unaligned-
190     access" << std::endl;
191
192 std::cout << "\n4. INTERWORKING:" << std::endl;
193 std::cout << "      -mthumb-interwork" << std::endl;
194 std::cout << " •      Generate code that can call between ARM and Thumb" <<
195     std::endl;
196 std::cout << " •      Required for mixed ARM/Thumb projects" << std::endl;
197 std::cout << " •      Not needed for Cortex-M (Thumb-2 only)" << std::endl;
198 }
199
200 // =====
201 // 5. PRACTICAL EXAMPLE: ALIGNMENT CRASH SIMULATION
202 // =====
203
204 // This simulates what happens on ARM hardware
205 void demonstrate_alignment_crash() {
206     std::cout << "\n==== 5. ALIGNMENT CRASH SIMULATION ===" << std::endl;

```

```

203
204     std::cout << "\n NOTE: On x86/x64, unaligned access works (slower)" <<
205         std::endl;
206     std::cout << "    On ARM Cortex-M0: Would cause HARDFAULT" << std::endl;
207
208     // Create a buffer with known alignment
209     alignas(4) uint8_t buffer[16];
210
211     // Write data at aligned address (safe)
212     std::cout << "\n ALIGNED ACCESS (address % 4 == 0):" << std::endl;
213     uint32_t* aligned_ptr = reinterpret_cast<uint32_t*>(&buffer[0]);
214     *aligned_ptr = 0x12345678;
215     std::cout << "    Address: " << reinterpret_cast<uintptr_t>(aligned_ptr)
216         << " (aligned)" << std::endl;
217     std::cout << "    Value written: 0x" << std::hex << *aligned_ptr << std::
218         dec << std::endl;
219     std::cout << "    Result: SUCCESS (no crash on ARM)" << std::endl;
220
221     // Try unaligned access (dangerous on ARM!)
222     std::cout << "\n UNALIGNED ACCESS (address % 4 != 0):" << std::endl;
223     uint32_t* unaligned_ptr = reinterpret_cast<uint32_t*>(&buffer[1]);
224     std::cout << "    Address: " << reinterpret_cast<uintptr_t>(unaligned_ptr)
225         << " (unaligned, offset by 1)" << std::endl;
226
227     // On x86/x64 this works, on ARM Cortex-M0 it would HARDFAULT
228     std::cout << "    Attempting to write uint32_t at unaligned address..." <<
229         std::endl;
230     *unaligned_ptr = 0xAABBCCDD; // Works on x86, HARDFAULT on Cortex-M0!
231     std::cout << "    Result on x86: Works (slow)" << std::endl;
232     std::cout << "    Result on ARM Cortex-M0: HARDFAULT! (crash)" << std::
233         endl;
234     std::cout << "    Result on ARM Cortex-M4: Works but slow (multiple bus
235         cycles)" << std::endl;
236 }
237
238 // =====
239 // 6. SOLUTION: PORTABLE UNALIGNED ACCESS
240 // =====
241
242 // SAFE: Portable unaligned read (works on all platforms)
243 uint32_t read_uint32_unaligned(const uint8_t* ptr) {
244     uint32_t value;
245     std::memcpy(&value, ptr, sizeof(value)); // Compiler optimizes this
246     return value;
247 }
248
249 // SAFE: Portable unaligned write
250 void write_uint32_unaligned(uint8_t* ptr, uint32_t value) {
251     std::memcpy(ptr, &value, sizeof(value));
252 }
253
254 // UNSAFE: Direct cast (crashes on unaligned ARM)
255 uint32_t read_uint32_unsafe(const uint8_t* ptr) {
256     return *reinterpret_cast<const uint32_t*>(ptr); // HARDFAULT if unaligned

```

```

!
252 }
253
254 void demonstrate_portable_unaligned() {
255     std::cout << "\n== 6. PORTABLE UNALIGNED ACCESS ==" << std::endl;
256
257     alignas(4) uint8_t buffer[16] = {};
258
259     std::cout << "\n SAFE METHOD (using memcpy):" << std::endl;
260     std::cout << "    uint32_t read_uint32_unaligned(const uint8_t* ptr) {" <<
261         std::endl;
262     std::cout << "        uint32_t value;" << std::endl;
263     std::cout << "        std::memcpy(&value, ptr, sizeof(value));" << std::
264         endl;
265     std::cout << "        return value;" << std::endl;
266     std::cout << "    }" << std::endl;
267
268     write_uint32_unaligned(&buffer[1], 0x12345678);
269     uint32_t safe_value = read_uint32_unaligned(&buffer[1]);
270     std::cout << "\n    Written to unaligned address using memcpy" << std::endl
271         ;
272     std::cout << "    Value: 0x" << std::hex << safe_value << std::dec << std::
273         endl;
274     std::cout << "    Works on ALL platforms (x86, ARM, RISC-V)" << std::endl
275         ;
276     std::cout << "    Compiler optimizes memcpy to efficient code" << std::
277         endl;
278
279     std::cout << "\n UNSAFE METHOD (direct cast):" << std::endl;
280     std::cout << "    uint32_t value = *reinterpret_cast<uint32_t*>(ptr);" <<
281         std::endl;
282     std::cout << "    HARDFAULT on ARM Cortex-M0 if unaligned!" << std::endl;
283 }
284
285 // =====
286 // 7. ASSEMBLY DIRECTIVES FOR MIXED CODE
287 // =====
288
289 void explain_assembly_directives() {
290     std::cout << "\n== 7. ASSEMBLY DIRECTIVES ==" << std::endl;
291
292     std::cout << "\n ARM ASSEMBLY DIRECTIVES:" << std::endl;
293
294     std::cout << "\n1. SET INSTRUCTION MODE:" << std::endl;
295     std::cout << "    .arm           ; Switch to ARM (A32) mode" << std::
296         endl;
297     std::cout << "    .thumb          ; Switch to Thumb/Thumb-2 (T16/T32)
298         mode" << std::endl;
299
300     std::cout << "\n2. MARK THUMB FUNCTIONS:" << std::endl;
301     std::cout << "    .thumb_func      ; Next symbol is a Thumb function" <<
302         std::endl;
303     std::cout << "    " << std::endl;
304     std::cout << "    Example:" << std::endl;

```

```

295     std::cout << ".thumb" << std::endl;
296     std::cout << ".thumb_func" << std::endl;
297     std::cout << "my_function:" << std::endl;
298     std::cout << "    PUSH {lr}" << std::endl;
299     std::cout << "    ; ... function code ..." << std::endl;
300     std::cout << "    POP {pc}" << std::endl;
301
302     std::cout << "\n3. ALIGNMENT DIRECTIVES:" << std::endl;
303     std::cout << ".align 2" ; Align to 2^2 = 4 bytes (word) << std
304         ::endl;
304     std::cout << ".align 3" ; Align to 2^3 = 8 bytes (doubleword)
305         << std::endl;
305     std::cout << "" << std::endl;
306     std::cout << "Example:" << std::endl;
307     std::cout << ".align 2" ; Force 4-byte alignment << std::endl;
308     std::cout << "my_data:" << std::endl;
309     std::cout << "    .word 0x12345678" << std::endl;
310 }
311
312 // =====
313 // 8. REAL-WORLD EXAMPLE: PROTOCOL PARSING
314 // =====
315
316 // Common scenario: Parsing network packets with misaligned fields
317 struct __attribute__((packed)) NetworkPacket {
318     uint8_t header; // 1 byte
319     uint32_t timestamp; // 4 bytes (might be misaligned!)
320     uint16_t length; // 2 bytes
321     uint32_t crc; // 4 bytes (might be misaligned!)
322 };
323
324 void demonstrate_real_world_scenario() {
325     std::cout << "\n== 8. REAL-WORLD: PROTOCOL PARSING ==" << std::endl;
326
327     std::cout << "\n SCENARIO: Parsing network packet on Cortex-M4" << std::
328         endl;
329
330     // Simulate receiving a packet
331     alignas(4) uint8_t rx_buffer[16] = {
332         0xAA, // header (1 byte)
333         0x78, 0x56, 0x34, 0x12, // timestamp (4 bytes, at offset 1 =
334             UNALIGNED!)
335         0x10, 0x00, // length (2 bytes)
336         0xDD, 0xCC, 0xBB, 0xAA // crc (4 bytes)
337     };
338
339     std::cout << "\n WRONG WAY (direct struct cast):" << std::endl;
340     std::cout << "    NetworkPacket* pkt = (NetworkPacket*)rx_buffer;" << std::
341         endl;
342     std::cout << "    uint32_t ts = pkt->timestamp; // Unaligned access!" <<
343         std::endl;
344     std::cout << "    " << std::endl;
345     std::cout << "    Result: HARDFAULT on Cortex-M0, slow on Cortex-M4" << std
346         ::endl;

```

```

342     std::cout << "\n CORRECT WAY (memcpy for unaligned fields):" << std::endl
343     ;
344     uint8_t header = rx_buffer[0];
345     uint32_t timestamp;
346     uint16_t length;
347     uint32_t crc;
348
349     std::memcpy(&timestamp, &rx_buffer[1], sizeof(timestamp));
350     std::memcpy(&length, &rx_buffer[5], sizeof(length));
351     std::memcpy(&crc, &rx_buffer[7], sizeof(crc));
352
353     std::cout << "    Header: 0x" << std::hex << static_cast<int>(header) <<
354         std::endl;
355     std::cout << "    Timestamp: 0x" << timestamp << std::endl;
356     std::cout << "    Length: 0x" << length << std::endl;
357     std::cout << "    CRC: 0x" << crc << std::dec << std::endl;
358     std::cout << "    Works on ALL ARM processors!" << std::endl;
359
360     std::cout << "\n COMPILER OPTIMIZATIONS:" << std::endl;
361     std::cout << " • With -O2: memcpy() compiles to efficient LDR/STR" <<
362         std::endl;
363     std::cout << " • No function call overhead" << std::endl;
364     std::cout << " • Compiler knows about alignment and handles it" << std::endl;
365 }
366
367 // =====
368 // 9. COMPILER FLAG EXAMPLES
369 // =====
370
371 void show_compiler_examples() {
372     std::cout << "\n== 9. PRACTICAL COMPILER COMMAND EXAMPLES ==" << std::endl;
373
374     std::cout << "\n1. CORTEX-M0 PROJECT (strict alignment):" << std::endl;
375     std::cout << "    CFLAGS = -mcpu=cortex-m0 \\\" << std::endl;
376     std::cout << "                -mthumb \\\" << std::endl;
377     std::cout << "                -mno-unaligned-access \\\" << std::endl;
378     std::cout << "                -O2 -Wall" << std::endl;
379
380     std::cout << "\n2. CORTEX-M4 PROJECT (with FPU):" << std::endl;
381     std::cout << "    CFLAGS = -mcpu=cortex-m4 \\\" << std::endl;
382     std::cout << "                -mthumb \\\" << std::endl;
383     std::cout << "                -mfpu=fpv4-sp-d16 \\\" << std::endl;
384     std::cout << "                -mfloating-abi=hard \\\" << std::endl;
385     std::cout << "                -munaligned-access \\\" << std::endl;
386     std::cout << "                -O2 -Wall" << std::endl;
387
388     std::cout << "\n3. MIXED ARM/THUMB PROJECT (ARM7):" << std::endl;
389     std::cout << "    CFLAGS = -mcpu=arm7tdmi \\\" << std::endl;
390     std::cout << "                -mthumb \\\" << std::endl;

```

```

391     std::cout << "          -mthumb-interwork \\\" << std::endl;
392     std::cout << "          -O2 -Wall" << std::endl;
393
394     std::cout << "\n4. ASSEMBLY FILE COMPILATION:" << std::endl;
395     std::cout << "# For Thumb-2 code" << std::endl;
396     std::cout << "      arm-none-eabi-as -mcpu=cortex-m4 \\\" << std::endl;
397     std::cout << "          -mthumb \\\" << std::endl;
398     std::cout << "          startup.s -o startup.o" << std::endl;
399 }
400
401 // =====
402 // 10. DEBUGGING HARDFAULTS
403 // =====
404
405 void explain_debugging_hardfaults() {
406     std::cout << "\n== 10. DEBUGGING HARDFAULTS ON ARM ==" << std::endl;
407
408     std::cout << "\n WHEN YOU GET A HARDFAULT:" << std::endl;
409
410     std::cout << "\n1. CHECK FAULT STATUS REGISTERS:" << std::endl;
411     std::cout << " • HFSR (HardFault Status Register) at 0xE000ED2C" << std
412         ::endl;
413     std::cout << " • CFSR (Configurable Fault Status) at 0xE000ED28" << std
414         ::endl;
415     std::cout << " • MMFAR (MemManage Fault Address) at 0xE000ED34" << std::
416         endl;
417     std::cout << " • BFAR (BusFault Address) at 0xE000ED38" << std::endl;
418
419     std::cout << "\n2. COMMON FAULT CAUSES:" << std::endl;
420     std::cout << "   IBUSERR (bit 0 of CFSR): Instruction bus error" << std::
421         endl;
422     std::cout << "   → Called function at wrong address or wrong mode" <<
423         std::endl;
424     std::cout << "   " << std::endl;
425     std::cout << "   PRECISERR (bit 1 of CFSR): Data bus error" << std::endl;
426     std::cout << "   → Unaligned access on Cortex-M0" << std::endl;
427     std::cout << "   " << std::endl;
428     std::cout << "   IACCVIOL (bit 0 of CFSR): MPU violation" << std::endl;
429     std::cout << "   → Tried to execute from non-executable memory" << std::
430         endl;
431
432     std::cout << "\n3. DEBUGGER INSPECTION:" << std::endl;
433     std::cout << "   (gdb) info registers # Check PC, LR, SP" << std::endl;
434     std::cout << "   (gdb) x/4x $sp      # Stack contents" << std::endl;
435     std::cout << "   (gdb) bt        # Backtrace" << std::endl;
436     std::cout << "   " << std::endl;
437     std::cout << "   Look for:" << std::endl;
438     std::cout << "   • PC (Program Counter) - where crash occurred" << std::
439         endl;
440     std::cout << "   • LR (Link Register) - return address (LSB = mode)" <<
441         std::endl;
442     std::cout << "   • Unaligned addresses (check if address % 4 != 0)" << std
443         ::endl;
444 }

```

```
436
437 // =====
438 // MAIN
439 // =====
440
441 int main() {
442     std::cout << "\n"
443         ===== " <<
444         std::endl;
445     std::cout << "    ARM INSTRUCTION SETS: ARM, THUMB, THUMB-2" << std::endl;
446     std::cout << "    Alignment Issues and Compiler Switches" << std::endl;
447     std::cout << "
448         ===== " <<
449         std::endl;
450
451     explain_instruction_sets();
452     explain_alignment_issues();
453     explain_interworking();
454     explain_compiler_switches();
455     demonstrate_alignment_crash();
456     demonstrate_portable_unaligned();
457     explain_assembly_directives();
458     demonstrate_real_world_scenario();
459     show_compiler_examples();
460     explain_debugging_hardfaults();
461
462     std::cout << "\n"
463         ===== " <<
464         std::endl;
465     std::cout << "    SUMMARY: AVOIDING ARM THUMB-2 CRASHES" << std::endl;
466     std::cout << "
467         ===== " <<
468         std::endl;
469
470     std::cout << "\n1. INSTRUCTION SET MODES:" << std::endl;
471     std::cout << "    •    ARM (A32): 32-bit, powerful, larger code" << std::endl;
472     std::cout << "    •    Thumb (T16): 16-bit, compact, limited" << std::endl;
473     std::cout << "    •    Thumb-2 (T32): 16/32-bit mix, best of both" << std::endl;
474     std::cout << "    •    Cortex-M: Thumb-2 only (no ARM mode)" << std::endl;
475
476     std::cout << "\n2. ALIGNMENT REQUIREMENTS:" << std::endl;
477     std::cout << "    •    uint32_t MUST be 4-byte aligned on Cortex-M0" << std::endl;
478     std::cout << "    •    Cortex-M3/M4/M7 can handle unaligned (but slower)" << std::endl;
479     std::cout << "    •    Use std::memcpy() for portable unaligned access" << std::endl;
480
481
482     std::cout << "\n3. INTERWORKING:" << std::endl;
483     std::cout << "    •    Function address LSB indicates mode (0=ARM, 1=Thumb)" << std::endl;
```

```
477     std::cout << " • Use BLX instruction for mode switching" << std::endl;
478     std::cout << " • Mark assembly functions with .thumb_func" << std::endl;
479
480     std::cout << "\n4. COMPILER FLAGS:" << std::endl;
481     std::cout << " -mthumb                                # Use Thumb-2 instructions" <<
482         std::endl;
483     std::cout << " -mcpu=cortex-m4                         # Specify processor" << std::
484         endl;
485     std::cout << " -mno-unaligned-access                  # Disable unaligned (M0)" <<
486         std::endl;
487     std::cout << " -munaligned-access                     # Enable unaligned (M3+)" <<
488         std::endl;
489
490
491     std::cout << "\n5. BEST PRACTICES:" << std::endl;
492     std::cout << " Use std::memcpy() for unaligned access" << std::endl;
493     std::cout << " Align structs with __attribute__((aligned(4)))" << std
494         ::endl;
495     std::cout << " Use __attribute__((packed)) carefully" << std::endl;
496     std::cout << " Compile with correct -mcpu flag" << std::endl;
497     std::cout << " Test on actual hardware (not just simulator)" << std::
498         endl;
499     std::cout << " Never cast unaligned pointers directly" << std::endl;
500     std::cout << " Don't mix ARM/Thumb without proper interworking" << std
501         ::endl;
502
503
504     std::cout << "\n"
505     std::cout << "=====\\n" <<
506         std::endl;
507
508     return 0;
509 }
```

3 Source Code: AdvancedExceptionHandling.cpp

File: src/AdvancedExceptionHandling.cpp

Repository: [View on GitHub](#)

```
1 // AdvancedExceptionHandling.cpp
2 // Comprehensive exception handling with real stack traces, nested exceptions,
3 // and advanced error reporting patterns
4
5 #include <iostream>
6 #include <stdexcept>
7 #include <string>
8 #include <vector>
9 #include <memory>
10 #include <sstream>
11 #include <iomanip>
12 #include <chrono>
13 #include <functional>
14 #include <exception>
15 #include <typeinfo>
16 #include <cstdlib>
17 #include <cstring>
18
19 // Platform-specific includes for stack traces
20 #ifdef __linux__
21     #include <execinfo.h>
22     #include <cxxabi.h>
23     #include <unistd.h>
24 #elif _WIN32
25     #include <windows.h>
26     #include <dbghelp.h>
27     #pragma comment(lib, "dbghelp.lib")
28 #endif
29
30 using namespace std::chrono;
31
32 // =====
33 // SECTION 1: Stack Trace Capture (Platform-Specific)
34 // =====
35
36 class StackTrace {
37 private:
38     static constexpr size_t MAX_FRAMES = 64;
39     std::vector<std::string> frames_;
40
41 public:
42     StackTrace() {
43         capture();
44     }
45 }
```

```

46 void capture() {
47     frames_.clear();
48
49 #ifdef __linux__
50     // Linux: Use backtrace() and backtrace_symbols()
51     void* buffer[MAX_FRAMES];
52     int frame_count = backtrace(buffer, MAX_FRAMES);
53
54     char** symbols = backtrace_symbols(buffer, frame_count);
55     if (symbols) {
56         for (int i = 0; i < frame_count; ++i) {
57             frames_.push_back(demangle_symbol(symbols[i]));
58         }
59         free(symbols);
60     }
61
62 #elif _WIN32
63     // Windows: Use CaptureStackBackTrace() and SymFromAddr()
64     void* buffer[MAX_FRAMES];
65     HANDLE process = GetCurrentProcess();
66     SymInitialize(process, NULL, TRUE);
67
68     WORD frame_count = CaptureStackBackTrace(0, MAX_FRAMES, buffer, NULL);
69
70     SYMBOL_INFO* symbol = (SYMBOL_INFO*)calloc(sizeof(SYMBOL_INFO) + 256 *
71                                                 sizeof(char), 1);
72     if (symbol) {
73         symbol->MaxNameLen = 255;
74         symbol->SizeOfStruct = sizeof(SYMBOL_INFO);
75
76         for (WORD i = 0; i < frame_count; ++i) {
77             if (SymFromAddr(process, (DWORD64)(buffer[i]), 0, symbol)) {
78                 frames_.push_back(std::string(symbol->Name));
79             } else {
80                 std::ostringstream oss;
81                 oss << "0x" << std::hex << (uint64_t)buffer[i];
82                 frames_.push_back(oss.str());
83             }
84         }
85         free(symbol);
86     }
87
88     SymCleanup(process);
89 #else
90     frames_.push_back("[Stack trace not available on this platform]");
91 #endif
92 }
93
94 const std::vector<std::string>& get_frames() const {
95     return frames_;
96 }
97
98 std::string to_string() const {
99     std::ostringstream oss;

```

```
99     oss << "Stack Trace (" << frames_.size() << " frames):\n";
100    for (size_t i = 0; i < frames_.size(); ++i) {
101        oss << " #" << std::setw(2) << i << ":" << frames_[i] << "\n";
102    }
103    return oss.str();
104}
105
106private:
107#ifdef __linux__
108    std::string demangle_symbol(const char* mangled) {
109        std::string result = mangled;
110
111        // Extract the mangled name between '(' and '+'
112        const char* begin = strchr(mangled, '(');
113        const char* end = strchr(mangled, '+');
114
115        if (begin && end && begin < end) {
116            begin++; // Skip '('
117            std::string mangled_name(begin, end - begin);
118
119            int status;
120            char* demangled = abi::__cxa_demangle(mangled_name.c_str(),
121                nullptr, nullptr, &status);
122
123            if (status == 0 && demangled) {
124                result = demangled;
125                free(demangled);
126            }
127        }
128
129        return result;
130    }
131#endif
132};
133void demonstrate_stack_trace_capture() {
134    std::cout << "\n" << std::string(70, '=') << "\n";
135    std::cout << "==== 1. Real Stack Trace Capture ====\n";
136    std::cout << std::string(70, '=') << "\n\n";
137
138    std::cout << "Capturing stack trace from current location...\n\n";
139
140    StackTrace trace;
141    std::cout << trace.to_string();
142
143    std::cout << "\n Stack trace captured using platform-specific APIs\n";
144#ifdef __linux__
145    std::cout << " Linux: backtrace() + abi::__cxa_demangle()\n";
146#elif _WIN32
147    std::cout << " Windows: CaptureStackBackTrace() + SymFromAddr()\n";
148#else
149    std::cout << " Generic fallback (no native stack trace support)\n";
150#endif
151}
```

```
152 //  
153 //=====  
154 // SECTION 2: Exception with Stack Trace  
155 //=====  
156  
157 class TracedException : public std::runtime_error {  
158 private:  
159     std::string file_;  
160     int line_;  
161     std::string function_;  
162     StackTrace stack_trace_;  
163     std::string formatted_message_;  
164  
165     std::string format_message() const {  
166         std::ostringstream oss;  
167  
168         // Extract filename only  
169         size_t last_slash = file_.find_last_of("/\\");  
170         std::string filename = (last_slash != std::string::npos)  
171             ? file_.substr(last_slash + 1) : file_;  
172  
173         oss << "\n";  
174         oss << "EXCEPTION THROWN WITH STACK TRACE\n";  
175         oss << "\n";  
176         oss << "Location: " << filename << ":" << line_ << "\n";  
177         oss << "Function: " << function_ << "() \n";  
178         oss << "Message: " << what() << "\n";  
179         oss << "\n";  
180         oss << " " << stack_trace_.to_string();  
181         oss << "\n";  
182  
183     return oss.str();  
184 }  
185  
186 public:  
187     TracedException(const std::string& file, int line, const std::string& func  
188         ,  
189         const std::string& message)  
190         : std::runtime_error(message),  
191         file_(file),  
192         line_(line),  
193         function_(func),  
194         stack_trace_(),  
195         formatted_message_(format_message()) {}  
196  
197     const std::string& get_formatted_message() const {  
198         return formatted_message_;  
199     }  
200  
201     const StackTrace& get_stack_trace() const {
```

```
201     return stack_trace_;
202 }
203
204 const std::string& get_file() const { return file_; }
205 int get_line() const { return line_; }
206 const std::string& get_function() const { return function_; }
207 };
208
209 #define THROW_TRACED(message) \
210     throw TracedException(__FILE__, __LINE__, __FUNCTION__, message)
211
212 void nested_function_3() {
213     std::cout << " [3] About to throw exception...\n";
214     THROW_TRACED("Critical error in nested function");
215 }
216
217 void nested_function_2() {
218     std::cout << " [2] Calling nested_function_3()...\n";
219     nested_function_3();
220 }
221
222 void nested_function_1() {
223     std::cout << " [1] Calling nested_function_2()...\n";
224     nested_function_2();
225 }
226
227 void demonstrate_exception_with_stack_trace() {
228     std::cout << "\n" << std::string(70, '=') << "\n";
229     std::cout << "== 2. Exception with Stack Trace ==\n";
230     std::cout << std::string(70, '=') << "\n\n";
231
232     std::cout << "Calling nested functions to build call stack...\n\n";
233
234     try {
235         nested_function_1();
236     }
237     catch (const TracedException& e) {
238         std::cout << "\n Exception caught!\n";
239         std::cout << e.get_formatted_message();
240     }
241 }
242
243 // =====
244 // SECTION 3: Nested Exceptions (C++11)
245 // =====
246
247 class DatabaseException : public std::runtime_error {
248 public:
249     explicit DatabaseException(const std::string& msg)
250         : std::runtime_error("Database Error: " + msg) {}
```

```
251 };
```

```
252 
```

```
253 class ConnectionException : public std::runtime_error {
```

```
254 public:
```

```
255     explicit ConnectionException(const std::string& msg)
```

```
256         : std::runtime_error("Connection Error: " + msg) {}
```

```
257 }
```

```
258 
```

```
259 void database_operation() {
```

```
260     std::cout << "    Attempting database query...\n";
```

```
261     throw DatabaseException("Query timeout after 30 seconds");
```

```
262 }
```

```
263 
```

```
264 void connect_to_database() {
```

```
265     std::cout << "    Attempting to connect to database...\n";
```

```
266 
```

```
267     try {

```

```
268         database_operation();

```

```
269     }

```

```
270     catch (const DatabaseException& e) {

```

```
271         std::cout << "        Database operation failed!\n";

```

```
272         // Wrap the DatabaseException in a ConnectionException

```

```
273         std::throw_with_nested(ConnectionException("Failed to establish

```

```
274             connection"));

```

```
275     }

```

```
276 }
```

```
277 
```

```
278 void print_nested_exception(const std::exception& e, int level = 0) {

```

```
279     std::string indent(level * 2, ' ');

```

```
280     std::cout << indent << "    " << e.what() << "\n";

```

```
281 
```

```
282     try {

```

```
283         std::rethrow_if_nested(e);

```

```
284     }

```

```
285     catch (const std::exception& nested) {

```

```
286         print_nested_exception(nested, level + 1);

```

```
287     }

```

```
288 }
```

```
289 
```

```
290 void demonstrate_nested_exceptions() {

```

```
291     std::cout << "\n" << std::string(70, '=') << "\n";

```

```
292     std::cout << "==== 3. Nested Exceptions (C++11) ===\n";

```

```
293     std::cout << std::string(70, '=') << "\n\n";

```

```
294 
```

```
295     std::cout << "Concept: Wrap exceptions to preserve context\n\n";

```

```
296 
```

```
297     try {

```

```
298         connect_to_database();

```

```
299     }

```

```
300     catch (const std::exception& e) {

```

```
301         std::cout << "\n Exception caught with nested context:\n\n";

```

```
302         print_nested_exception(e);

```

```
303     }
```

```
304     std::cout << "\n Original exception preserved inside wrapper\n";
305     std::cout << "  Use std::throw_with_nested() and std::rethrow_if_nested()\n"
306     n";
307 }
308 // -----
309 // SECTION 4: Exception Guarantee Levels
310 // -----
311
312 template<typename T>
313 class Container {
314 private:
315     std::unique_ptr<T[]> data_;
316     size_t size_;
317     size_t capacity_;
318
319 public:
320     Container() : data_(nullptr), size_(0), capacity_(0) {}
321
322     // Basic guarantee: valid state but data may be lost
323     void push_back_basic(const T& value) {
324         if (size_ == capacity_) {
325             size_t new_capacity = (capacity_ == 0) ? 1 : capacity_ * 2;
326             auto new_data = std::make_unique<T[]>(new_capacity);
327
328             // If copy throws here, we're in an inconsistent state
329             for (size_t i = 0; i < size_; ++i) {
330                 new_data[i] = data_[i]; // May throw!
331             }
332
333             data_ = std::move(new_data);
334             capacity_ = new_capacity;
335         }
336
337         data_[size_++] = value;
338     }
339
340     // Strong guarantee: operation succeeds completely or has no effect
341     void push_back_strong(const T& value) {
342         if (size_ == capacity_) {
343             size_t new_capacity = (capacity_ == 0) ? 1 : capacity_ * 2;
344             auto new_data = std::make_unique<T[]>(new_capacity);
345
346             // Copy all elements (may throw)
347             for (size_t i = 0; i < size_; ++i) {
348                 new_data[i] = data_[i];
349             }
350
351             // Only if successful, commit changes (no-throw from here)
352             data_ = std::move(new_data);
```

```
353         capacity_ = new_capacity;
354     }
355
356     data_[size_++] = value;
357 }
358
359 // No-throw guarantee: never throws
360 size_t size() const noexcept {
361     return size_;
362 }
363
364 // No-throw guarantee
365 void clear() noexcept {
366     size_ = 0;
367 }
368 };
369
370 void demonstrate_exception_guarantees() {
371     std::cout << "\n" << std::string(70, '=') << "\n";
372     std::cout << "==== 4. Exception Safety Guarantees ===\n";
373     std::cout << std::string(70, '=') << "\n\n";
374
375     std::cout << "1. No-throw guarantee (noexcept):\n";
376     std::cout << " • Function never throws\n";
377     std::cout << " • Example: size(), clear(), swap()\n";
378     std::cout << " • Mark with 'noexcept' keyword\n\n";
379
380     std::cout << "2. Strong guarantee:\n";
381     std::cout << " • Operation succeeds completely OR has no effect\n";
382     std::cout << " • Example: push_back() using copy-and-swap\n";
383     std::cout << " • All or nothing - no partial state\n\n";
384
385     std::cout << "3. Basic guarantee:\n";
386     std::cout << " • Object left in valid state if exception thrown\n";
387     std::cout << " • Example: push_back() that may leave capacity changed\n";
388     ;
389     std::cout << " • No resource leaks, but data may be lost\n\n";
390
391     std::cout << "4. No guarantee:\n";
392     std::cout << " • May leave object in invalid state\n";
393     std::cout << " • AVOID - leads to crashes and undefined behavior\n\n";
394
395     Container<int> cont;
396     cont.push_back_strong(42);
397     std::cout << " Container with strong guarantee used successfully\n";
398 }
399 //
=====

400 // SECTION 5: RAII and Exception Safety
401 //
=====
```

```
402
403 class FileRAII {
404 private:
405     FILE* file_;
406     std::string filename_;
407
408 public:
409     explicit FileRAII(const std::string& filename)
410         : file_(nullptr), filename_(filename) {
411
412         file_ = fopen(filename.c_str(), "w");
413         if (!file_) {
414             throw std::runtime_error("Failed to open file: " + filename);
415         }
416         std::cout << "  [RAII] File opened: " << filename << "\n";
417     }
418
419     ~FileRAII() {
420         if (file_) {
421             fclose(file_);
422             std::cout << "  [RAII] File closed: " << filename_ << "\n";
423         }
424     }
425
426     void write(const std::string& data) {
427         if (!file_) {
428             throw std::runtime_error("File not open");
429         }
430
431         if (data == "ERROR") {
432             throw std::runtime_error("Simulated write error");
433         }
434
435         fprintf(file_, "%s\n", data.c_str());
436     }
437
438     // Delete copy/move to enforce RAII
439     FileRAII(const FileRAII&) = delete;
440     FileRAII& operator=(const FileRAII&) = delete;
441 };
442
443 void demonstrate_raii_exception_safety() {
444     std::cout << "\n" << std::string(70, '=') << "\n";
445     std::cout << "==== 5. RAII and Exception Safety ===\n";
446     std::cout << std::string(70, '=') << "\n\n";
447
448     std::cout << "Without RAII (manual cleanup - leak on exception):\n\n";
449     try {
450         FILE* f = fopen("/tmp/test.txt", "w");
451         std::cout << "  File opened\n";
452         // If exception thrown here, file never closed!
453         throw std::runtime_error("Oops!");
454         fclose(f); // Never executed
455     }
```

```

456     catch (...) {
457         std::cout << "    File leaked - never closed!\n\n";
458     }
459
460     std::cout << "With RAII (automatic cleanup - safe):\n\n";
461     try {
462         FileRAII file("/tmp/test_raii.txt");
463         file.write("Hello");
464         file.write("ERROR"); // Throws exception
465         file.write("World"); // Never executed
466     }
467     catch (const std::exception& e) {
468         std::cout << "    Exception: " << e.what() << "\n";
469         std::cout << "    RAII destructor automatically closed file!\n";
470     }
471
472     std::cout << "\n RAII guarantees resource cleanup even with exceptions\n"
473     ;
474 }
475 // =====
476 // SECTION 6: std::exception_ptr and Thread Exception Propagation
477 // =====
478
479 #include <thread>
480
481 std::exception_ptr worker_exception = nullptr;
482
483 void worker_thread_function() {
484     try {
485         std::cout << " [Worker] Doing some work...\n";
486         std::this_thread::sleep_for(std::chrono::milliseconds(100));
487
488         // Simulate error
489         throw std::runtime_error("Worker thread encountered an error!");
490     }
491     catch (...) {
492         std::cout << " [Worker] Exception caught, storing for main thread\n";
493         worker_exception = std::current_exception();
494     }
495 }
496
497 void demonstrate_exception_ptr() {
498     std::cout << "\n" << std::string(70, '=') << "\n";
499     std::cout << "==== 6. std::exception_ptr (Thread Exception Propagation)
500             ==\n";
501     std::cout << std::string(70, '=') << "\n\n";
502
503     std::cout << "Problem: Exceptions can't cross thread boundaries\n";
504     std::cout << "Solution: std::exception_ptr + std::current_exception()\n\n"

```

```
    ;  
504     std::cout << "Starting worker thread...\n";  
505  
506     worker_exception = nullptr;  
507     std::thread worker(worker_thread_function);  
508     worker.join();  
509  
510     std::cout << "\nMain thread checking for worker exception...\n";  
511  
512     if (worker_exception) {  
513         try {  
514             std::rethrow_exception(worker_exception);  
515         }  
516         catch (const std::exception& e) {  
517             std::cout << " Worker exception received: " << e.what() << "\n";  
518         }  
519     }  
520  
521     std::cout << "\n Exception successfully propagated from worker to main  
522         thread\n";  
523 }  
524 //  
=====  
526 // SECTION 7: Custom Exception Hierarchy  
527 //  
=====  
  
528  
529 class ApplicationException : public std::runtime_error {  
530 protected:  
531     int error_code_;  
532     system_clock::time_point timestamp_;  
533  
534 public:  
535     ApplicationException(int code, const std::string& msg)  
536         : std::runtime_error(msg),  
537         error_code_(code),  
538         timestamp_(system_clock::now()) {}  
539  
540     int get_error_code() const { return error_code_; }  
541  
542     std::string get_timestamp() const {  
543         auto time = system_clock::to_time_t(timestamp_);  
544         std::ostringstream oss;  
545         oss << std::put_time(std::localtime(&time), "%Y-%m-%d %H:%M:%S");  
546         return oss.str();  
547     }  
548 };  
549  
550 class NetworkError : public ApplicationException {  
551 public:
```

```
552     NetworkError(int code, const std::string& msg)
553         : ApplicationException(code, msg) {}
554     };
555
556     class FileSystemError : public ApplicationException {
557     public:
558         FileSystemError(int code, const std::string& msg)
559             : ApplicationException(code, msg) {}
560     };
561
562     class BusinessLogicError : public ApplicationException {
563     public:
564         BusinessLogicError(int code, const std::string& msg)
565             : ApplicationException(code, msg) {}
566     };
567
568     void demonstrate_exception_hierarchy() {
569         std::cout << "\n" << std::string(70, '=') << "\n";
570         std::cout << "==== 7. Custom Exception Hierarchy ====\n";
571         std::cout << std::string(70, '=') << "\n\n";
572
573         std::cout << "Exception Hierarchy:\n";
574         std::cout << "    ApplicationException (base)\n";
575         std::cout << "        NetworkError\n";
576         std::cout << "        FileSystemError\n";
577         std::cout << "        BusinessLogicError\n\n";
578
579     try {
580         throw NetworkError(503, "Service unavailable");
581     }
582     catch (const NetworkError& e) {
583         std::cout << "Caught NetworkError:\n";
584         std::cout << "    Code:      " << e.get_error_code() << "\n";
585         std::cout << "    Message:   " << e.what() << "\n";
586         std::cout << "    Timestamp: " << e.get_timestamp() << "\n";
587     }
588     catch (const ApplicationException& e) {
589         std::cout << "Caught generic ApplicationException\n";
590     }
591
592     std::cout << "\n Specific catch before generic catch\n";
593     std::cout << " Polymorphic exception handling\n";
594 }
595
596 /**
597 // SECTION 8: Function Try Blocks (Constructor Exception Handling)
598 /**
599
600 class Resource {
601 public:
```

```
602     Resource(int id) {
603         std::cout << "      [Resource " << id << "] Constructed\n";
604         if (id == 2) {
605             throw std::runtime_error("Resource 2 construction failed!");
606         }
607     }
608
609     ~Resource() {
610         std::cout << "      [Resource] Destroyed\n";
611     }
612 };
613
614 class ComponentWithResources {
615 private:
616     Resource res1_;
617     Resource res2_;
618     Resource res3_;
619
620 public:
621     // Function try block for constructor
622     ComponentWithResources()
623     try : res1_(1), res2_(2), res3_(3)    // res2 will throw!
624     {
625         std::cout << "  Constructor body executed\n";
626     }
627     catch (const std::exception& e) {
628         std::cout << "  Constructor caught: " << e.what() << "\n";
629         std::cout << "  res1_ will be automatically destroyed\n";
630         // Note: Exception is automatically rethrown after this catch
631     }
632 };
633
634 void demonstrate_function_try_blocks() {
635     std::cout << "\n" << std::string(70, '=') << "\n";
636     std::cout << "==== 8. Function Try Blocks (Constructor Exception Handling)
637         ===\n";
638     std::cout << std::string(70, '=') << "\n\n";
639
640     std::cout << "Attempting to construct ComponentWithResources...\n\n";
641
642     try {
643         ComponentWithResources component;
644     }
645     catch (const std::exception& e) {
646         std::cout << "\n Exception propagated to caller\n";
647         std::cout << "  Partially constructed members automatically cleaned up
648             \n";
649     }
650 }
651
652 // =====
```

```
652 //  
=====  
  
653  
654 void demonstrate_best_practices() {  
655     std::cout << "\n" << std::string(70, '=') << "\n";  
656     std::cout << "== 9. Exception Handling Best Practices ==\n";  
657     std::cout << std::string(70, '=') << "\n\n";  
658  
659     std::cout << " DO:\n";  
660     std::cout << " \n";  
661     std::cout << " 1. Use RAII for resource management\n";  
662     std::cout << " 2. Catch by const reference: catch (const Ex& e)\n";  
663     std::cout << " 3. Throw by value: throw MyException(...)\n";  
664     std::cout << " 4. Inherit from std::exception hierarchy\n";  
665     std::cout << " 5. Mark functions noexcept when appropriate\n";  
666     std::cout << " 6. Use specific exceptions before generic ones\n";  
667     std::cout << " 7. Provide meaningful error messages\n";  
668     std::cout << " 8. Document what exceptions functions can throw\n";  
669     std::cout << " 9. Use stack traces for debugging\n";  
670     std::cout << " 10. Test exception paths thoroughly\n\n";  
671  
672     std::cout << " DON'T:\n";  
673     std::cout << " \n";  
674     std::cout << " 1. Throw from destructors (noexcept by default in C++11)\n";  
675     std::cout << " ";  
676     std::cout << " 2. Catch (...) without rethrowing or logging\n";  
677     std::cout << " 3. Use exceptions for normal control flow\n";  
678     std::cout << " 4. Return error codes for exceptional situations\n";  
679     std::cout << " 5. Ignore exceptions silently\n";  
680     std::cout << " 6. Throw pointers: throw new Ex() \n";  
681     std::cout << " 7. Catch by value (causes slicing)\n";  
682     std::cout << " 8. Mix exceptions and error codes inconsistently\n";  
683     std::cout << " 9. Throw from noexcept functions\n";  
684     std::cout << " 10. Forget to clean up resources (use RAII!)\n\n";  
685  
686     std::cout << " EXCEPTION vs ERROR CODES:\n";  
687     std::cout << " \n";  
688     std::cout << " Use Exceptions when:\n";  
689     std::cout << " • Error is truly exceptional\n";  
690     std::cout << " • Can't continue execution\n";  
691     std::cout << " • Need to propagate through many layers\n";  
692     std::cout << " • RAII cleanup is needed\n\n";  
693  
694     std::cout << " Use Error Codes when:\n";  
695     std::cout << " • Expected/recoverable errors\n";  
696     std::cout << " • Performance-critical hot paths\n";  
697     std::cout << " • C API compatibility\n";  
698     std::cout << " • Safety-critical systems (ISO 26262)\n";  
699 }  
700 //  
=====
```

```
701 // MAIN FUNCTION
702 //
703 =====
704 int main() {
705     std::cout << "\n";
706     std::cout << "                                         \n";
707     std::cout << "         Advanced Exception Handling with Stack Traces
708             \n";
709     std::cout << "                                         \n";
710     std::cout << "                                         \n";
711
712     demonstrate_stack_trace_capture();
713     demonstrate_exception_with_stack_trace();
714     demonstrate_nested_exceptions();
715     demonstrate_exception_guarantees();
716     demonstrate_raii_exception_safety();
717     demonstrate_exception_ptr();
718     demonstrate_exception_hierarchy();
719     demonstrate_function_try_blocks();
720     demonstrate_best_practices();
721
722     std::cout << "\n" << std::string(70, '=') << "\n";
723     std::cout << "All exception handling demonstrations completed!\n";
724     std::cout << "\nKEY TAKEAWAYS:\n";
725     std::cout << " 1. Real stack traces available on Linux/Windows\n";
726     std::cout << " 2. RAII guarantees cleanup even with exceptions\n";
727     std::cout << " 3. Nested exceptions preserve error context\n";
728     std::cout << " 4. std::exception_ptr for thread exception propagation\n";
729     std::cout << " 5. Always catch by const reference\n";
730     std::cout << " 6. Use noexcept for no-throw guarantees\n";
731     std::cout << std::string(70, '=') << "\n\n";
732
733     return 0;
734 }
```

4 Source Code: AsioAndModernCppConcurrency.cpp

File: src/AsioAndModernCppConcurrency.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <thread>
3 #include <future>
4 #include <chrono>
5 #include <vector>
6 #include <string>
7 #include <mutex>
8 #include <memory>
9 #include <functional>
10
11 // Note: This example demonstrates ASIO concepts using standard C++ features.
12 // For actual ASIO usage, install: https://think-async.com/Asio/
13 // Standalone ASIO: #include <asio.hpp>
14 // Boost.ASIO: #include <boost/asio.hpp>
15
16 // =====
17 // ASIO AND MODERN C++ CONCURRENCY COMPARISON
18 // =====
19
20 // This example shows the concepts and patterns without requiring ASIO
21 // installation
22 // It demonstrates when to use ASIO vs C++ standard library features
23
24 using namespace std::chrono_literals;
25
26 // =====
27 // 1. THE FUNDAMENTAL DIFFERENCE: I/O vs CPU
28 // =====
29
30 void example_io_vs_cpu_bound() {
31     std::cout << "\n== 1. I/O-BOUND vs CPU-BOUND OPERATIONS ==" << std::endl
32     ;
33
34     std::cout << "\n--- I/O-BOUND OPERATIONS (ASIO's domain) ---" << std::endl
35     ;
36     std::cout << "• Waiting for network data (recv/send)" << std::endl;
37     std::cout << "• Reading/writing files" << std::endl;
38     std::cout << "• Waiting for timers to expire" << std::endl;
39     std::cout << "• Database queries" << std::endl;
40     std::cout << "• HTTP requests/responses" << std::endl;
41     std::cout << "\nCharacteristics:" << std::endl;
42     std::cout << " → Thread spends most time WAITING" << std::endl;
43     std::cout << " → CPU is mostly idle" << std::endl;
44     std::cout << " → One thread can handle thousands of operations" << std::endl;
45
46     std::cout << " → Need event multiplexing (epoll/IOCP)" << std::endl;
47
48     std::cout << "\n--- CPU-BOUND OPERATIONS (std::async/thread domain) ---"
49     << std::endl;
```

```
45     std::cout << "• Image processing" << std::endl;
46     std::cout << "• Video encoding" << std::endl;
47     std::cout << "• Mathematical computations" << std::endl;
48     std::cout << "• Data compression" << std::endl;
49     std::cout << "• Machine learning inference" << std::endl;
50     std::cout << "\nCharacteristics:" << std::endl;
51     std::cout << " → Thread spends most time COMPUTING" << std::endl;
52     std::cout << " → CPU is fully utilized" << std::endl;
53     std::cout << " → Need multiple threads/cores for parallelism" << std::endl;
54     std::cout << " → Thread count    CPU core count for best performance" << std::endl;
55 }
56
57 // =====
58 // 2. SIMULATED ASIO-STYLE TIMER vs std::this_thread::sleep_for
59 // =====
60
61 // Simulate ASIO timer callback pattern
62 class SimulatedAsioTimer {
63 private:
64     std::chrono::milliseconds duration;
65     std::function<void()> callback;
66     std::jthread timer_thread;
67
68 public:
69     SimulatedAsioTimer(std::chrono::milliseconds ms) : duration(ms) {}
70
71     // ASIO-style async_wait (non-blocking)
72     void async_wait(std::function<void()> handler) {
73         callback = std::move(handler);
74
75         // Start timer in background (simulates event loop)
76         timer_thread = std::jthread([this]() {
77             std::this_thread::sleep_for(duration);
78             if (callback) {
79                 callback();
80             }
81         });
82     }
83
84     void cancel() {
85         // In real ASIO, this would cancel the pending operation
86         timer_thread.request_stop();
87     }
88 };
89
90 void example_async_timer_patterns() {
91     std::cout << "\n== 2. ASYNC TIMER PATTERNS ==" << std::endl;
92
93     std::cout << "\n-- Pattern 1: Blocking (std::this_thread::sleep_for) --"
94             << std::endl;
95     auto start = std::chrono::steady_clock::now();
96     std::cout << "Starting blocking sleep..." << std::endl;
```

```

96     std::this_thread::sleep_for(100ms);
97     std::cout << "Sleep completed (thread was blocked)" << std::endl;
98     auto end = std::chrono::steady_clock::now();
99     std::cout << "Time: " << std::chrono::duration_cast<std::chrono::
100       milliseconds>(end - start).count() << "ms" << std::endl;
101
102     std::cout << "\n--- Pattern 2: Async Timer (ASIO-style) ---" << std::endl;
103     start = std::chrono::steady_clock::now();
104     std::cout << "Starting async timer..." << std::endl;
105
106     SimulatedAsioTimer timer(100ms);
107     timer.async_wait([start]() {
108       auto end = std::chrono::steady_clock::now();
109       std::cout << "Timer callback executed (thread was NOT blocked)" << std
110         ::endl;
111       std::cout << "Time: " << std::chrono::duration_cast<std::chrono::
112         milliseconds>(end - start).count() << "ms" << std::endl;
113     });
114
115     std::cout << "async_wait returned immediately (non-blocking)" << std::endl
116       ;
117     std::cout << "Main thread can do other work..." << std::endl;
118
119     // Wait for timer to complete
120     std::this_thread::sleep_for(150ms);
121
122   }
123
124 // =====
125 // 3. CALLBACK-BASED vs FUTURE-BASED ASYNC
126 // =====
127
128 // Simulate async network read with callback (ASIO pattern)
129 void async_read_callback(const std::string& data, std::function<void(const std
130   :string&)> callback) {
131   std::jthread([data, callback = std::move(callback)]() {
132     std::this_thread::sleep_for(50ms); // Simulate I/O delay
133     callback(data);
134   }).detach();
135 }
136
137 // Future-based async read (std::async pattern)
138 std::future<std::string> async_read_future(const std::string& data) {
139   return std::async(std::launch::async, [data]() {
140     std::this_thread::sleep_for(50ms); // Simulate I/O delay
141     return data;
142   });

```

```
142 }
143
144 void example_callback_vs_future() {
145     std::cout << "\n==== 3. CALLBACK-BASED vs FUTURE-BASED ASYNC ===" << std::endl;
146
147     std::cout << "\n--- Callback-Based (ASIO pattern) ---" << std::endl;
148     std::cout << "Initiating async read with callback..." << std::endl;
149
150     async_read_callback("Data from network", [](const std::string& result) {
151         std::cout << "Callback received: " << result << std::endl;
152     });
153
154     std::cout << "async_read_callback returned immediately" << std::endl;
155     std::cout << "Main thread continues..." << std::endl;
156     std::this_thread::sleep_for(100ms); // Wait for callback
157
158     std::cout << "\n--- Future-Based (std::async pattern) ---" << std::endl;
159     std::cout << "Initiating async read with future..." << std::endl;
160
161     auto future = async_read_future("Data from computation");
162     std::cout << "async_read_future returned immediately" << std::endl;
163     std::cout << "Main thread can do work before getting result..." << std::endl;
164
165     // Get result (blocks until ready)
166     std::string result = future.get();
167     std::cout << "Future result: " << result << std::endl;
168
169     std::cout << "\n TRADE-OFFS:" << std::endl;
170     std::cout << "    Callbacks (ASIO):" << std::endl;
171     std::cout << "        + Very efficient for I/O (no thread per operation)" << std::endl;
172     std::cout << "        - Composable (chain callbacks)" << std::endl;
173     std::cout << "        - Callback hell (deep nesting)" << std::endl;
174     std::cout << "        - Error handling more complex" << std::endl;
175     std::cout << "\n    Futures (std::async):" << std::endl;
176     std::cout << "        + Simpler synchronous-style code" << std::endl;
177     std::cout << "        + Easier error handling (exceptions)" << std::endl;
178     std::cout << "        - Creates threads (expensive for many I/O ops)" << std::endl;
179     std::cout << "        - Doesn't scale for thousands of concurrent operations"
180         << std::endl;
181
182 // =====
183 // 4. EVENT LOOP CONCEPT (CORE OF ASIO)
184 // =====
185
186 // Simplified event loop to demonstrate the concept
187 class EventLoop {
188 private:
189     std::vector<std::function<void()>> callbacks;
190     std::mutex mutex;
```

```
191     bool running = false;
192
193     public:
194         void post(std::function<void()> callback) {
195             std::lock_guard<std::mutex> lock(mutex);
196             callbacks.push_back(std::move(callback));
197         }
198
199         void run() {
200             running = true;
201             std::cout << "Event loop started" << std::endl;
202
203             while (running) {
204                 std::vector<std::function<void()>> work;
205
206                 {
207                     std::lock_guard<std::mutex> lock(mutex);
208                     work.swap(callbacks);
209                 }
210
211                 for (auto& callback : work) {
212                     callback();
213                 }
214
215                 if (work.empty() && !running) {
216                     break;
217                 }
218
219                 std::this_thread::sleep_for(10ms); // Poll interval
220             }
221
222             std::cout << "Event loop stopped" << std::endl;
223         }
224
225         void stop() {
226             running = false;
227         }
228     };
229
230     void example_event_loop() {
231         std::cout << "\n==== 4. EVENT LOOP CONCEPT (ASIO's HEART) ===" << std::endl
232         ;
233
234         EventLoop loop;
235
236         // Run event loop in background thread
237         std::jthread loop_thread([&loop]() {
238             loop.run();
239         });
240
241         std::cout << "\nPosting work to event loop..." << std::endl;
242
243         // Post work items (like ASIO handlers)
244         loop.post([]() {
```

```

244         std::cout << " → Handler 1 executed" << std::endl;
245     });
246
247     loop.post([]() {
248         std::cout << " → Handler 2 executed" << std::endl;
249     });
250
251     loop.post([]() {
252         std::cout << " → Handler 3 executed" << std::endl;
253     });
254
255     std::this_thread::sleep_for(50ms);
256
257     loop.post([]() {
258         std::cout << " → Handler 4 executed (posted later)" << std::endl;
259     });
260
261     std::this_thread::sleep_for(50ms);
262     loop.stop();
263
264     std::cout << "\n EVENT LOOP BENEFITS:" << std::endl;
265     std::cout << " • Single thread processes all callbacks sequentially" <<
266         std::endl;
267     std::cout << " • No race conditions within event loop" << std::endl;
268     std::cout << " • Can handle thousands of I/O operations efficiently" <<
269         std::endl;
270     std::cout << " • Real ASIO: Uses OS-level primitives (epoll/IOCP)" << std
271         ::endl;
272 }
273
274 // =====
275 // 5. WHEN TO USE WHAT: DECISION MATRIX
276 // =====
277
278 void example_decision_matrix() {
279     std::cout << "\n== 5. DECISION MATRIX: ASIO vs C++ STD ==" << std::endl;
280
281     std::cout << "\n"
282         " Use Case" << " ASIO" << " C++ Std" << " "
283         << std::endl;
284     std::cout << " TCP/UDP networking" << " " << std::endl;
285     std::cout << " HTTP server/client" << " " << std::endl;
286     std::cout << " WebSocket" << " " << std::endl;
287     std::cout << " Async timers" << " " << std::endl;
288     std::cout << " Serial port I/O" << " " << std::endl;
289     std::cout << " Many concurrent connections" << " " << std::endl;
290     std::cout << " Image processing" << " " <<

```

```

        std::endl;
288     std::cout << " Parallel computation" <<
289     std::endl;
290     std::cout << " Thread synchronization" <<
291     std::endl;
292     std::cout << " Protect shared data" (mutex) <<
293     std::endl;
294     std::cout << " Wait for task completion" (future) <<
295     std::endl;
296     std::cout << "" << std::endl;
297
298     std::cout << "\n COMBINED USAGE (BEST PRACTICE):" << std::endl;
299     std::cout << ""
300     std::cout << " Component" Solution
301     std::cout << std::endl;
302     std::cout << ""
303     std::cout << " Network I/O" ASIO (io_context)
304     std::cout << std::endl;
305     std::cout << " CPU-heavy processing" std::async / thread pool
306     std::cout << std::endl;
307     std::cout << " Shared cache" std::mutex
308     std::cout << std::endl;
309     std::cout << " Thread coordination" std::semaphore / std::latch
310     std::cout << std::endl;
311     std::cout << " Rate limiting" ASIO timers + std::semaphore
312     std::cout << std::endl;
313     std::cout << "" << std::endl;
314 }
315
316 // =====
317 // 6. SCALABILITY COMPARISON
318 // =====
319
320 void example_scalability() {
321     std::cout << "\n== 6. SCALABILITY: ASIO vs std::thread ==" << std::endl;
322
323     std::cout << "\n--- Scenario: Handle 10,000 concurrent connections ---" <<
324             std::endl;
325
326     std::cout << "\n APPROACH 1: One thread per connection (std::thread)" <<
327             std::endl;
328     std::cout << " • Need 10,000 threads" << std::endl;
329     std::cout << " • Each thread: ~1MB stack = 10GB memory" << std::endl;
330     std::cout << " • Context switching overhead" << std::endl;
331     std::cout << " • OS thread limit (~32k on Linux)" << std::endl;
332     std::cout << " • Result: System collapse" << std::endl;
333
334     std::cout << "\n APPROACH 2: Event-driven with ASIO" << std::endl;
335     std::cout << " • 1-4 threads (typically)" << std::endl;
336     std::cout << " • Event multiplexing (epoll/IOCP)" << std::endl;
337     std::cout << " • Each connection: ~few KB state" << std::endl;
338     std::cout << " • Total memory: <100MB" << std::endl;
339     std::cout << " • Result: Handles load easily" << std::endl;
340 }
```

```

329     std::cout << "\n PERFORMANCE COMPARISON:" << std::endl;
330     std::cout << "    Connections | std::thread | ASIO      " << std::endl;
331     std::cout << "    -----|-----|-----" << std::endl;
332     std::cout << "    10       | OK        | OK        " << std::endl;
333     std::cout << "    100      | Struggling | OK        " << std::endl;
334     std::cout << "    1,000    | Failing    | OK        " << std::endl;
335     std::cout << "    10,000   | Impossible | Good      " << std::endl;
336     std::cout << "    100,000  | N/A       | Possible   " << std::endl;
337 }
338
339 // =====
340 // 7. INTEGRATION PATTERNS
341 // =====
342
343 // Pattern: ASIO for I/O + std::async for CPU work
344 class HybridServer {
345 private:
346     std::mutex shared_cache_mutex;
347     std::vector<std::string> shared_cache;
348
349 public:
350     // Simulated: ASIO receives network request
351     void on_request_received(const std::string& data) {
352         std::cout << "[ASIO] Received request: " << data << std::endl;
353
354         // CPU-intensive work: offload to std::async
355         auto future = std::async(std::launch::async, [this, data]() {
356             return process_data(data);
357         });
358
359         std::cout << "[ASIO] Offloaded to worker thread, can handle more
360             requests" << std::endl;
361
362         // Get result (in real app, would be callback)
363         std::string result = future.get();
364
365         // ASIO would send response here
366         std::cout << "[ASIO] Sending response: " << result << std::endl;
367     }
368
369 private:
370     std::string process_data(const std::string& data) {
371         // Simulate CPU-intensive work
372         std::this_thread::sleep_for(50ms);
373         std::string result = "Processed: " + data;
374
375         // Update shared cache (use mutex for thread safety)
376         {
377             std::lock_guard<std::mutex> lock(shared_cache_mutex);
378             shared_cache.push_back(result);
379         }
380
381         return result;
382     }

```

```

382 } ;
383
384 void example_integration_patterns() {
385     std::cout << "\n==== 7. INTEGRATION PATTERNS: ASIO + C++ STD ===" << std::
386         endl;
387
388     std::cout << "\nPattern: I/O with ASIO + CPU work with std::async" << std
389         ::endl;
390
391     HybridServer server;
392
393     // Simulate multiple requests
394     server.on_request_received("Request-1");
395     server.on_request_received("Request-2");
396     server.on_request_received("Request-3");
397
398     std::cout << "\n HYBRID APPROACH:" << std::endl;
399     std::cout << " 1. ASIO handles network I/O (event loop)" << std::endl;
400     std::cout << " 2. Offload CPU work to std::async" << std::endl;
401     std::cout << " 3. Use std::mutex for shared data" << std::endl;
402     std::cout << " 4. ASIO remains responsive during CPU work" << std::endl;
403 }
404
405 // =====
406 // 8. C++20 COROUTINES + ASIO (THE FUTURE)
407 // =====
408
409 void example_coroutines_concept() {
410     std::cout << "\n==== 8. C++20 COROUTINES + ASIO (MODERN PATTERN) ===" <<
411         std::endl;
412
413     std::cout << "\n--- Without Coroutines (Callback Hell) ---" << std::endl;
414     std::cout << "    async_read(socket, buffer, [](error, bytes) {" << std::endl;
415     std::cout << "        async_write(socket, data, [](error, bytes) {" << std::
416         endl;
417     std::cout << "            async_read(socket, response, [](error, bytes) {" <<
418         std::endl;
419     std::cout << "                // 3 levels deep already!" << std::endl;
420     std::cout << "            });" << std::endl;
421     std::cout << "        });" << std::endl;
422     std::cout << "    });" << std::endl;
423
424     std::cout << "\n--- With C++20 Coroutines (Sequential Code) ---" << std::
425         endl;
426     std::cout << "asio::awaitable<void> handle_connection() {" << std::endl;
427     std::cout << "    auto bytes = co_await async_read(socket, buffer); //
428         Looks sync!" << std::endl;
429     std::cout << "    co_await async_write(socket, data);           //
430         But it's async" << std::endl;
431     std::cout << "    co_await async_read(socket, response);        //
432         nesting!" << std::endl;
433     std::cout << "}" << std::endl;
434
435     std::cout << "\n COROUTINES BENEFITS:" << std::endl;

```

```

427 std::cout << " • Write async code that looks synchronous" << std::endl;
428 std::cout << " • No callback nesting (no hell)" << std::endl;
429 std::cout << " • Exception handling works naturally (try/catch)" << std::endl;
430 std::cout << " • Still non-blocking (efficient as callbacks)" << std::endl;
431 std::cout << " • ASIO has full coroutine support (co_await)" << std::endl;
432 ;
433
434 // =====
435 // 9. REAL-WORLD ARCHITECTURE EXAMPLE
436 // =====
437
438 void example_architecture() {
439     std::cout << "\n== 9. REAL-WORLD ARCHITECTURE: WEB SERVER ==" << std::endl;
440
441     std::cout << "\\n" << std::endl;
442     std::cout << "          High-Performance Web Server" << std::endl;
443     std::cout << "          " << std::endl;
444     std::cout << "          " << std::endl;
445     std::cout << "          " << std::endl;
446     std::cout << "          " << std::endl;
447     std::cout << "          " << std::endl;
448     std::cout << "          " << std::endl;
449     std::cout << "      ASIO      C++ Std      C++ Std" << std::endl;
450     std::cout << "          " << std::endl;
451     std::cout << "          Layer      Layer      Layer" << std::endl;
452     std::cout << "          " << std::endl;
453
454     std::cout << "\\n ASIO LAYER:" << std::endl;
455     std::cout << " • io_context (1-4 threads)" << std::endl;
456     std::cout << " • Accept connections (10k+ concurrent)" << std::endl;
457     std::cout << " • Parse HTTP requests" << std::endl;
458     std::cout << " • Send HTTP responses" << std::endl;
459     std::cout << " • Timers for keepalive/timeout" << std::endl;
460
461     std::cout << "\\n CPU PROCESSING LAYER:" << std::endl;
462     std::cout << " • std::jthread pool (N = CPU cores)" << std::endl;
463     std::cout << " • Process business logic" << std::endl;
464     std::cout << " • Image/video processing" << std::endl;
465     std::cout << " • Compute-intensive tasks" << std::endl;
466     std::cout << " • Post results back to ASIO" << std::endl;
467
468     std::cout << "\\n SYNCHRONIZATION LAYER:" << std::endl;
469     std::cout << " • std::mutex: Protect shared cache" << std::endl;

```

```
470     std::cout << " • std::shared_mutex: Read-write locks" << std::endl;
471     std::cout << " • std::atomic: Lock-free counters" << std::endl;
472     std::cout << " • std::semaphore: Rate limiting" << std::endl;
473     std::cout << " • std::latch: Wait for initialization" << std::endl;
474
475     std::cout << "\n BENEFITS OF HYBRID APPROACH:" << std::endl;
476     std::cout << "    Scales to 100k+ connections (ASIO)" << std::endl;
477     std::cout << "    Utilizes all CPU cores (std::jthread)" << std::endl;
478     std::cout << "    Thread-safe shared state (std::mutex)" << std::endl;
479     std::cout << "    Best of both worlds!" << std::endl;
480 }
481
482 // =====
483 // 10. SUMMARY AND RECOMMENDATIONS
484 // =====
485
486 void example_summary() {
487     std::cout << "\n== 10. SUMMARY: ASIO vs C++ STANDARD LIBRARY ==" << std
488         ::endl;
489
490     std::cout << "\n KEY TAKEAWAYS:" << std::endl;
491     std::cout << "\n1. DIFFERENT PROBLEMS, DIFFERENT TOOLS:" << std::endl;
492     std::cout << " • ASIO: Asynchronous I/O (network, timers, file I/O)" <<
493         std::endl;
494     std::cout << " • C++ Std: Threading, CPU parallelism, synchronization"
495         << std::endl;
496     std::cout << " • They COMPLEMENT each other, not compete!" << std::endl;
497
498     std::cout << "\n2. WHEN TO USE ASIO:" << std::endl;
499     std::cout << "    Building network servers/clients" << std::endl;
500     std::cout << "    Need to handle thousands of concurrent connections" <<
501         std::endl;
502     std::cout << "    I/O-bound operations (waiting > computing)" << std::
503         endl;
504     std::cout << "    Event-driven architecture" << std::endl;
505     std::cout << "    Cross-platform async I/O" << std::endl;
506
507     std::cout << "\n3. WHEN TO USE C++ STANDARD LIBRARY:" << std::endl;
508     std::cout << "    CPU-bound parallel computations" << std::endl;
509     std::cout << "    Thread-safe data structures" << std::endl;
510     std::cout << "    Simple threading needs" << std::endl;
511     std::cout << "    Waiting for computation results (futures)" << std::endl
512         ;
513     std::cout << "    Thread coordination (semaphores, latches)" << std::endl
514         ;
515
516     std::cout << "\n4. BEST PRACTICES (2026):" << std::endl;
517     std::cout << "    Use ASIO for I/O multiplexing" << std::endl;
518     std::cout << "    Use std::async/thread_pool for CPU work" << std::endl;
519     std::cout << "    Use std::mutex for thread-safe shared data" << std::
520         endl;
521     std::cout << "    Use C++20 coroutines with ASIO (co_await)" << std::endl
522         ;
523     std::cout << "    Combine: ASIO event loop + std threading primitives" <<
```

```
        std::endl;

515    std::cout << "\n5. GETTING STARTED:" << std::endl;
516    std::cout << " • Install: Standalone ASIO (https://think-async.com/Asio/)" << std::endl;
517    std::cout << " • Or: Boost.ASIO (apt install libboost-all-dev)" << std::endl;
518    std::cout << " • Learn: Start with timers, then sockets" << std::endl;
519    std::cout << " • Pattern: Event loop in 1-4 threads" << std::endl;
520    std::cout << " • Modern: Use ASIO with C++20 coroutines" << std::endl;
521
522
523    std::cout << "\n6. COMMON MISTAKES:" << std::endl;
524    std::cout << "     Using std::thread for thousands of connections" << std::endl;
525    std::cout << "     Using ASIO for CPU-intensive work" << std::endl;
526    std::cout << "     Blocking ASIO event loop with long operations" << std::endl;
527    std::cout << "     Not protecting shared data between ASIO and worker
528          threads" << std::endl;
529
530    std::cout << "\n GOLDEN RULE:" << std::endl;
531    std::cout << "     \"ASIO for waiting, std::thread for computing\"" << std::endl;
532 }

533 // =====
534 // MAIN FUNCTION
535 // =====
536
537 int main() {
538     std::cout << "\n
539         ====="
540     std::endl;
541     std::cout << "     ASIO AND MODERN C++ CONCURRENCY: COMPREHENSIVE GUIDE" <<
542             std::endl;
543     std::cout << "     ====="
544     std::endl;
545     std::cout << "\nNote: This demonstrates concepts using standard C++
546         features." << std::endl;
547     std::cout << "For actual ASIO usage, install from: https://think-async.com/Asio/" << std::endl;
548
549     example_io_vs_cpu_bound();
550     example_async_timer_patterns();
551     example_callback_vs_future();
552     example_event_loop();
553     example_decision_matrix();
554     example_scalability();
555     example_integration_patterns();
556     example_coroutines_concept();
557     example_architecture();
558     example_summary();
559 }
```

```
555     std::cout << "\n"
556     ======" <<
557     std::endl;
558     std::cout << "  FINAL VERDICT: ASIO vs C++ STANDARD LIBRARY" << std::endl;
559     std::cout << "
560     ======" <<
561     std::endl;
562     std::cout << "\n WINNER: BOTH (They're Partners, Not Competitors!)" <<
563     std::endl;
564
565     std::cout << "\n COMPARISON TABLE:" << std::endl;
566     std::cout << "\n" << std::endl;
567     std::cout << "  Feature           ASIO          C++ Std      " << std
568     ::endl;
569     std::cout << "                " << std::endl;
570     std::cout << "  Network I/O          " << std::endl;
571     std::cout << "  Async Timers         " << std::endl;
572     std::cout << "  Scalability          " << std::endl;
573     std::cout << "  CPU Parallelism      " << std::endl;
574     std::cout << "  Thread Safety         " << std::endl;
575     std::cout << "  Ease of Use          " << std::endl;
576     std::cout << "  Learning Curve        Steep        Moderate      " << std
577     ::endl;
578     std::cout << "  Standardization       Not yet      Standard      " << std
579     ::endl;
580     std::cout << "  Maturity              20+ years   Modern C++    " << std
581     ::endl;
582     std::cout << "                " << std::endl;
583
584     std::cout << "\n LEARNING PATH:" << std::endl;
585     std::cout << "  1. Master C++ std threading first (mutex, thread, async)" <<
586     std::endl;
587     std::cout << "  2. Understand I/O vs CPU bound problems" << std::endl;
588     std::cout << "  3. Learn ASIO basics (timers, then sockets)" << std::endl;
589     std::cout << "  4. Study ASIO examples and patterns" << std::endl;
590     std::cout << "  5. Explore ASIO + C++20 coroutines" << std::endl;
591     std::cout << "  6. Build hybrid systems (ASIO + std)" << std::endl;
592
593     std::cout << "\n"
594     ======\n" <<
595     std::endl;
596
597     return 0;
598 }
```

5 Source Code: AsioMultipleContexts.cpp

File: src/AsioMultipleContexts.cpp

Repository: [View on GitHub](#)

```
1 // AsioMultipleContexts.cpp
2 // Comprehensive educational example of using multiple io_context objects in
3 // standalone ASIO
4 // Demonstrates LAN/WAN separation, thread pooling, and priority-based I/O
5 // handling
6
7 #include <iostream>
8 #include <thread>
9 #include <vector>
10 #include <memory>
11 #include <chrono>
12 #include <string>
13 #include <atomic>
14 #include <iomanip>
15 #include <sstream>
16 #include <mutex>
17 #include <functional>
18 #include <condition_variable>
19
20 // Note: This example uses simulated ASIO patterns for educational purposes
21 // For actual ASIO usage, install standalone ASIO: https://think-async.com/
22 // Asio/
23 // Then: #include <asio.hpp>
24 // And replace SimulatedAsio classes with real asio::io_context, asio::
25 // steady_timer, etc.
26
27 using namespace std::chrono_literals;
28
29 //
30 =====
31
32 // SIMULATED ASIO CLASSES (for demonstration without requiring ASIO
33 // installation)
34 //
35 =====
36
37 // In real code, replace these with actual ASIO classes
38
39 namespace SimulatedAsio {
40
41 // Simulate asio::io_context
42 class io_context {
43 private:
44     std::atomic<bool> stopped_{false};
45     std::atomic<int> work_count_{0};
46     std::vector<std::function<void()>> pending_work_;
47     std::mutex work_mutex_;
48     std::condition_variable work_cv_;
49     std::string name_; // For debugging
```

```
41 public:
42     explicit io_context(const std::string& name = "io_context") : name_(name)
43     {}
44
45     // Main event loop - blocks until no more work
46     void run() {
47         std::cout << "[" << name_ << "] Thread " << std::this_thread::get_id()
48         << " calling run()\n";
49
50         while (!stopped_) {
51             std::function<void()> work;
52
53             {
54                 std::unique_lock<std::mutex> lock(work_mutex_);
55                 work_cv_.wait_for(lock, 50ms, [this] {
56                     return !pending_work_.empty() || stopped_;
57                 });
58
59                 if (stopped_ && pending_work_.empty()) {
60                     break;
61                 }
62
63                 if (!pending_work_.empty()) {
64                     work = std::move(pending_work_.back());
65                     pending_work_.pop_back();
66                 }
67             }
68
69             if (work) {
70                 work();
71                 --work_count_;
72             }
73
74             // If no more work, exit
75             if (work_count_ == 0 && pending_work_.empty()) {
76                 break;
77             }
78         }
79
80         std::cout << "[" << name_ << "] Thread " << std::this_thread::get_id()
81         << " exiting run()\n";
82     }
83
84     // Post work to the io_context
85     void post(std::function<void()> handler) {
86     {
87         std::lock_guard<std::mutex> lock(work_mutex_);
88         pending_work_.push_back(std::move(handler));
89         ++work_count_;
90     }
91     work_cv_.notify_one();
92 }
93 }
```

```

94 // Stop the io_context
95 void stop() {
96     stopped_ = true;
97     work_cv_.notify_all();
98 }
99
100 const std::string& name() const { return name_; }
101 };
102
103 // Simulate asio::steady_timer
104 class steady_timer {
105 private:
106     io_context& io_;
107     std::chrono::milliseconds duration_;
108     std::jthread timer_thread_;
109
110 public:
111     steady_timer(io_context& io, std::chrono::milliseconds ms)
112         : io_(io), duration_(ms) {}
113
114     void async_wait(std::function<void()> handler) {
115         // Start timer in background, then post handler to io_context
116         timer_thread_ = std::jthread([this, h = std::move(handler)]() {
117             std::this_thread::sleep_for(duration_);
118             io_.post(h); // Post to io_context when timer expires
119         });
120     }
121 };
122
123 // Work guard to keep io_context alive
124 template<typename Executor>
125 class executor_work_guard {
126 private:
127     io_context& io_;
128
129 public:
130     explicit executor_work_guard(io_context& io) : io_(io) {}
131     ~executor_work_guard() = default;
132 };
133
134 } // namespace SimulatedAsio
135
136 // =====
137 // SECTION 1: Basic Multiple io_context Pattern
138 // =====
139
140 void demonstrate_basic_multiple_contexts() {
141     std::cout << "\n" << std::string(70, '=') << "\n";
142     std::cout << "==== 1. Basic Multiple io_context Pattern ===\n";
143     std::cout << std::string(70, '=') << "\n\n";

```

```

144
145     std::cout << "Concept: Two separate io_context instances, each with its
146         own thread\n";
147     std::cout << "Use case: Isolate different types of I/O operations\n\n";
148
149     SimulatedAsio::io_context io1("io_context_1");
150     SimulatedAsio::io_context io2("io_context_2");
151
152     // Post work to both contexts
153     io1.post([]() {
154         std::cout << "  Work executing on io_context_1\n";
155     });
156
157     io2.post([]() {
158         std::cout << "  Work executing on io_context_2\n";
159     });
160
161     // Run each io_context in a separate thread
162     std::thread t1([&io1](){ io1.run(); });
163     std::thread t2([&io2](){ io2.run(); });
164
165     t1.join();
166     t2.join();
167
168     std::cout << "\n Both contexts completed independently\n";
169     std::cout << "  Each thread called run() on its assigned io_context\n";
170 }
171
172 // =====
173 // SECTION 2: Thread Pool Pattern (Multiple threads, one io_context)
174 // =====
175
176 void demonstrate_thread_pool_pattern() {
177     std::cout << "\n" << std::string(70, '=') << "\n";
178     std::cout << "==== 2. Thread Pool Pattern (Multiple threads share one
179         io_context) ===\n";
180     std::cout << std::string(70, '=') << "\n\n";
181
182     std::cout << "Concept: Multiple threads call run() on the SAME io_context\
183         \n";
184     std::cout << "Benefit: Work is automatically distributed across threads\n\
185         \n";
186
187     SimulatedAsio::io_context io("thread_pool");
188
189     // Post 6 tasks
190     for (int i = 1; i <= 6; ++i) {
191         io.post([i]() {
192             std::cout << "  Task " << i << " executing on thread "
193                         << std::this_thread::get_id() << "\n";
194     });
195 }

```

```
190         std::this_thread::sleep_for(100ms); // Simulate work
191     });
192 }
193
194 // Create thread pool: 3 threads all calling run() on the same io_context
195 std::vector<std::thread> thread_pool;
196 for (int i = 0; i < 3; ++i) {
197     thread_pool.emplace_back([&io](){
198         io.run();
199     });
200 }
201
202 // Wait for all threads
203 for (auto& t : thread_pool) {
204     t.join();
205 }
206
207 std::cout << "\n 6 tasks distributed across 3 threads automatically\n";
208 std::cout << " This is the standard ASIO thread pool pattern\n";
209 }
210
211 // =====
212 // SECTION 3: LAN vs WAN Separation (The Main Example!)
213 // =====
214
215 // Simulate a network connection
216 class Connection {
217 private:
218     std::string name_;
219     std::string type_; // "LAN" or "WAN"
220     int request_count_;
221
222 public:
223     Connection(const std::string& name, const std::string& type)
224         : name_(name), type_(type), request_count_(0) {}
225
226     void handle_request(int request_id) {
227         ++request_count_;
228         std::cout << " [" << type_ << " - " << name_ << "] Processing request
229             #"
230             << request_id << " (total: " << request_count_ << ")\n";
231
232         // Simulate processing time
233         if (type_ == "LAN") {
234             std::this_thread::sleep_for(50ms); // Fast LAN processing
235         } else {
236             std::this_thread::sleep_for(150ms); // Slower WAN processing
237         }
238     }
239 }
```

```
239     const std::string& name() const { return name_; }
```

```
240 };
241
242 void demonstrate_lan_wan_separation() {
243     std::cout << "\n" << std::string(70, '=') << "\n";
244     std::cout << "==== 3. LAN vs WAN Separation (Dual io_context) ====\n";
245     std::cout << std::string(70, '=') << "\n\n";
246
247     std::cout << "Scenario: Web server handling both LAN and WAN traffic\n";
248     std::cout << "Architecture:\n";
249     std::cout << " • io_lan → Fast local network clients (prioritized)\n";
250     std::cout << " • io_wan → Slower internet clients (lower priority)\n";
251     std::cout << "Benefits:\n";
252     std::cout << " • LAN traffic never blocked by slow WAN connections\n";
253     std::cout << " • Can apply different rate limits per context\n";
254     std::cout << " • Independent thread pools for each network\n\n";
255
256 // Create two separate io_context instances
257 SimulatedAsio::io_context io_lan("io_LAN");
258 SimulatedAsio::io_context io_wan("io_WAN");
259
260 // Create connections
261 auto lan_client1 = std::make_shared<Connection>("InternalAPI", "LAN");
262 auto lan_client2 = std::make_shared<Connection>("Dashboard", "LAN");
263 auto wan_client1 = std::make_shared<Connection>("PublicAPI", "WAN");
264 auto wan_client2 = std::make_shared<Connection>("MobileApp", "WAN");
265
266 std::cout << "Posting work to both contexts...\n\n";
267
268 // Post LAN work (fast, high priority)
269 for (int i = 1; i <= 3; ++i) {
270     io_lan.post([lan_client1, i]() {
271         lan_client1->handle_request(i);
272     });
273
274     io_lan.post([lan_client2, i]() {
275         lan_client2->handle_request(i);
276     });
277 }
278
279 // Post WAN work (slower, lower priority)
280 for (int i = 1; i <= 3; ++i) {
281     io_wan.post([wan_client1, i]() {
282         wan_client1->handle_request(i);
283     });
284
285     io_wan.post([wan_client2, i]() {
286         wan_client2->handle_request(i);
287     });
288 }
289
290 // Run LAN with 2 threads (higher capacity for fast traffic)
291 std::vector<std::thread> lan_threads;
292 lan_threads.emplace_back([&io_lan](){ io_lan.run(); });
```

```

293     lan_threads.emplace_back([&io_lan](){ io_lan.run(); });
294
295     // Run WAN with 1 thread (lower capacity, prevent resource exhaustion)
296     std::thread wan_thread([&io_wan](){ io_wan.run(); });
297
298     // Wait for completion
299     for (auto& t : lan_threads) {
300         t.join();
301     }
302     wan_thread.join();
303
304     std::cout << "\n LAN traffic processed with 2 threads (fast completion)\n"
305             "";
306     std::cout << " WAN traffic processed with 1 thread (controlled rate)\n";
307     std::cout << " Neither context blocked the other\n";
308 }
309 //
=====

310 // SECTION 4: Priority-Based io_context (Critical vs Normal)
311 //
=====

312
313 class PriorityServer {
314 private:
315     SimulatedAsio::io_context io_critical_;
316     SimulatedAsio::io_context io_normal_;
317     std::atomic<int> critical_count_{0};
318     std::atomic<int> normal_count_{0};
319
320 public:
321     PriorityServer() : io_critical_("io_CRITICAL"), io_normal_("io_NORMAL") {}
322
323     void handle_critical_request(const std::string& request) {
324         io_critical_.post([this, request]() {
325             int id = ++critical_count_;
326             std::cout << "[CRITICAL] Request " << id << ":" << request
327                         << " (thread " << std::this_thread::get_id() << ")\\n";
328             std::this_thread::sleep_for(30ms); // Fast processing
329         });
330     }
331
332     void handle_normal_request(const std::string& request) {
333         io_normal_.post([this, request]() {
334             int id = ++normal_count_;
335             std::cout << "[NORMAL] Request " << id << ":" << request
336                         << " (thread " << std::this_thread::get_id() << ")\\n";
337             std::this_thread::sleep_for(80ms); // Slower processing
338         });
339     }
340
341     void run() {

```

```
342     // Critical requests get dedicated thread
343     std::thread critical_thread([this]() {
344         io_critical_.run();
345     });
346
347     // Normal requests share a thread pool
348     std::thread normal_thread([this]() {
349         io_normal_.run();
350     });
351
352     critical_thread.join();
353     normal_thread.join();
354 }
355 };
356
357 void demonstrate_priority_separation() {
358     std::cout << "\n" << std::string(70, '=') << "\n";
359     std::cout << "==== 4. Priority-Based Separation (Critical vs Normal) ===\n"
360     ;
360     std::cout << std::string(70, '=') << "\n\n";
361
362     std::cout << "Scenario: System with time-critical and regular operations\n"
363     ;
363     std::cout << "Examples:\n";
364     std::cout << " • Critical: Heartbeats, alarms, safety-critical commands\n"
365     ;
365     std::cout << " • Normal: Data logging, statistics, background tasks\n\n"
366     ;
366
367     PriorityServer server;
368
369     // Mix critical and normal requests
370     server.handle_critical_request("Emergency Stop");
371     server.handle_normal_request("Log statistics");
372     server.handle_critical_request("Heartbeat");
373     server.handle_normal_request("Update dashboard");
374     server.handle_critical_request("Safety check");
375     server.handle_normal_request("Backup data");
376
377     std::cout << "\nProcessing requests...\n\n";
378     server.run();
379
380     std::cout << "\n Critical requests never delayed by normal traffic\n";
381     std::cout << " Each context can have different threading strategies\n";
382 }
383
384 /**
385 =====
386 // SECTION 5: Service-Type Separation (Clients, Database, Logging)
387 // =====
```

```
388 void demonstrate_service_type_separation() {
389     std::cout << "\n" << std::string(70, '=') << "\n";
390     std::cout << "==== 5. Service-Type Separation ===\n";
391     std::cout << std::string(70, '=') << "\n\n";
392
393     std::cout << "Architecture: One io_context per service type\n\n";
394
395     SimulatedAsio::io_context io_clients("io_CLIENTS");
396     SimulatedAsio::io_context io_database("io_DATABASE");
397     SimulatedAsio::io_context io_logging("io_LOGGING");
398
399     // Client connections (high concurrency)
400     for (int i = 1; i <= 4; ++i) {
401         io_clients.post([i](){
402             std::cout << "[CLIENTS] Handling client " << i << " connection\n";
403             std::this_thread::sleep_for(60ms);
404         });
405     }
406
407     // Database operations (controlled concurrency)
408     for (int i = 1; i <= 2; ++i) {
409         io_database.post([i](){
410             std::cout << "[DATABASE] Executing query " << i << "\n";
411             std::this_thread::sleep_for(100ms);
412         });
413     }
414
415     // Logging operations (background, low priority)
416     for (int i = 1; i <= 3; ++i) {
417         io_logging.post([i](){
418             std::cout << "[LOGGING] Writing log entry " << i << "\n";
419             std::this_thread::sleep_for(40ms);
420         });
421     }
422
423     std::cout << "Starting service threads...\n\n";
424
425     // Each service gets its own thread configuration
426     std::thread client_thread([&](){ io_clients.run(); });
427     std::thread db_thread([&](){ io_database.run(); });
428     std::thread log_thread([&](){ io_logging.run(); });
429
430     client_thread.join();
431     db_thread.join();
432     log_thread.join();
433
434     std::cout << "\n Services isolated from each other\n";
435     std::cout << " Database load doesn't impact client connections\n";
436     std::cout << " Logging doesn't block critical services\n";
437 }
438
439 // =====
```

```
440 // SECTION 6: When to Call run() - Summary
441 //
442 =====
443 void demonstrate_run_call_patterns() {
444     std::cout << "\n" << std::string(70, '=') << "\n";
445     std::cout << "==== 6. When to Call io_context.run() - Complete Guide ===\n";
446     std::cout << std::string(70, '=') << "\n\n";
447
448     std::cout << "PATTERN 1: Single Thread per io_context\n";
449     std::cout << "                                \n";
450     std::cout << "    asio::io_context io1, io2;\n";
451     std::cout << "    std::thread t1([&]() { io1.run(); }); // Thread 1 → io1\n";
452     std::cout << "    std::thread t2([&]() { io2.run(); }); // Thread 2 → io2\n";
453     std::cout << "    Use: Separate concerns (LAN/WAN, Client/DB)\n\n";
454
455     std::cout << "PATTERN 2: Thread Pool (Multiple threads, one io_context)\n";
456     std::cout << "                                \n";
457     std::cout << "    asio::io_context io;\n";
458     std::cout << "    std::thread t1([&]() { io.run(); }); // Thread 1 → io\n";
459     std::cout << "    std::thread t2([&]() { io.run(); }); // Thread 2 → io\n";
460     std::cout << "    std::thread t3([&]() { io.run(); }); // Thread 3 → io\n";
461     std::cout << "    Use: Distribute work across threads automatically\n\n";
462
463     std::cout << "PATTERN 3: Main Thread runs io_context\n";
464     std::cout << "                                \n";
465     std::cout << "    asio::io_context io;\n";
466     std::cout << "    // Post all work...\n";
467     std::cout << "    io.run(); // Main thread blocks here\n";
468     std::cout << "    Use: Simple single-threaded servers\n\n";
469
470     std::cout << "PATTERN 4: Keep io_context Alive\n";
471     std::cout << "                                \n";
472     std::cout << "    asio::io_context io;\n";
473     std::cout << "    auto guard = asio::make_work_guard(io);\n";
474     std::cout << "    std::thread t([&]() { io.run(); }); // Won't exit
475     std::cout << "        immediately\n";
476     std::cout << "    // ... post work later ...\n";
477     std::cout << "    guard.reset(); // Allow run() to exit when work done\n";
478     std::cout << "    Use: Long-running services with dynamic work\n\n";
479
480     std::cout << "KEY RULES:\n";
481     std::cout << "    \n";
482     std::cout << "    1. run() BLOCKS until no more work (or stopped)\n";
483     std::cout << "    2. Multiple threads CAN call run() on SAME io_context (
484         thread pool)\n";
485     std::cout << "    3. One thread should NOT call run() on MULTIPLE
486         io_contexts\n";
```

```
484     std::cout << " 4. run() returns when work queue is empty (use work_guard  
485         to prevent)\n";  
486     std::cout << " 5. Call stop() to force run() to exit early\n\n";  
487 }  
488 //  
=====  
489 // SECTION 7: Real-World Example - Microservice Gateway  
490 //  
=====  
491  
492 void demonstrate_microservice_gateway() {  
493     std::cout << "\n" << std::string(70, '=') << "\n";  
494     std::cout << "== 7. Real-World Example: Microservice API Gateway ==\n";  
495     std::cout << std::string(70, '=') << "\n\n";  
496  
497     std::cout << "Architecture:\n";  
498     std::cout << "           \n";  
499     std::cout << "       io_frontend ← Public internet clients (rate limited  
500         )\n";  
500     std::cout << "           (1 thread)    \n";  
501     std::cout << "           \n";  
502     std::cout << "   ↓           \n";  
503     std::cout << "           \n";  
504     std::cout << "       io_internal ← Internal microservices (fast LAN)\n";  
505     std::cout << "           (4 threads)    \n";  
506     std::cout << "           \n";  
507     std::cout << "   ↓           \n";  
508     std::cout << "           \n";  
509     std::cout << "       io_database ← Database connections (controlled)\n";  
510     std::cout << "           (2 threads)    \n";  
511     std::cout << "           \n\n";  
512  
513     SimulatedAsio::io_context io_frontend("FRONTEND");  
514     SimulatedAsio::io_context io_internal("INTERNAL");  
515     SimulatedAsio::io_context io_database("DATABASE");  
516  
517     // Simulate incoming requests  
518     std::cout << "Processing requests...\n\n";  
519  
520     io_frontend.post([]() {  
521         std::cout << " [FRONTEND] Public client → Authentication\n";  
522         std::this_thread::sleep_for(50ms);  
523     });  
524  
525     io_internal.post([]() {  
526         std::cout << " [INTERNAL] Calling user-service microservice\n";  
527         std::this_thread::sleep_for(30ms);  
528     });  
529  
530     io_internal.post([]() {  
531         std::cout << " [INTERNAL] Calling order-service microservice\n";  
532     });
```

```

532     std::this_thread::sleep_for(30ms);
533 );
534
535     io_database.post([]() {
536         std::cout << "[DATABASE] Query user preferences\n";
537         std::this_thread::sleep_for(80ms);
538 });
539
540 // Thread allocation reflects importance and load
541 std::thread frontend_thread([&]() { io_frontend.run(); });
542
543 std::vector<std::thread> internal_threads;
544 for (int i = 0; i < 2; ++i) { // 2 threads for internal services
545     internal_threads.emplace_back([&]() { io_internal.run(); });
546 }
547
548 std::thread db_thread([&]() { io_database.run(); });
549
550 frontend_thread.join();
551 for (auto& t : internal_threads) { t.join(); }
552 db_thread.join();
553
554 std::cout << "\n Frontend protected from internal service overload\n";
555 std::cout << " Internal services have high concurrency (4 threads)\n";
556 std::cout << " Database access controlled (2 threads max)\n";
557 std::cout << " Each layer can be scaled independently\n";
558 }
559
560 // =====
561 // SECTION 8: Common Pitfalls and Best Practices
562 // =====
563
564 void demonstrate_best_practices() {
565     std::cout << "\n" << std::string(70, '=') << "\n";
566     std::cout << "==== 8. Common Pitfalls and Best Practices ===\n";
567     std::cout << std::string(70, '=') << "\n\n";
568
569     std::cout << " PITFALL 1: run() exits immediately (no work posted)\n";
570     std::cout << "     asio::io_context io;\n";
571     std::cout << "     std::thread t([&]() { io.run(); }); // ← Exits
572     std::cout << "     immediately!\n";
573     std::cout << "     io.post([]() { /* ... */}); // ← Too late, thread
574     std::cout << "     already exited\n\n";
575     std::cout << " FIX: Post work BEFORE starting thread, or use work_guard\n
576     \n";
577
578     std::cout << " PITFALL 2: One thread calling run() on multiple contexts\n
579     ";
580     std::cout << "     io1.run(); // Blocks until io1 is done\n";
581     std::cout << "     io2.run(); // ← io2 never runs until io1 finishes!\n\n";

```

```
578     std::cout << " FIX: Use separate threads for each io_context\n\n";
579
580     std::cout << " PITFALL 3: Forgetting to join threads\n";
581     std::cout << "     std::thread t([&]() { io.run(); });\n";
582     std::cout << "     // ← main() exits, std::terminate() called!\n\n";
583     std::cout << " FIX: Always join or detach threads\n\n";
584
585     std::cout << " PITFALL 4: Sharing mutable state without synchronization\n";
586     std::cout << "     ";
587     std::cout << "     int counter = 0; // ← Multiple threads accessing!\n";
588     std::cout << "     io.post([&]() { ++counter; }); // ← RACE CONDITION\n\n";
589     std::cout << " FIX: Use std::atomic or std::mutex for shared state\n\n";
590
591     std::cout << "BEST PRACTICES:\n";
592     std::cout << "     \n";
593     std::cout << "     1. Use multiple io_contexts to SEPARATE concerns (not for
594         parallelism)\n";
595     std::cout << "     2. For parallelism, use THREAD POOL (multiple threads, one
596         io_context)\n";
597     std::cout << "     3. Number of threads    number of CPU cores (for CPU-bound
598         work)\n";
599     std::cout << "     4. For I/O-bound work, can have many more threads than
600         cores\n";
601     std::cout << "     5. Always use strand for sequential execution across
602         threads\n";
603     std::cout << "     6. Profile before optimizing - one io_context is often
604         sufficient\n\n";
605 }
606
607 // -----
608
609 // MAIN FUNCTION
610 // -----
611
612
613 int main() {
614     std::cout << "\n";
615     std::cout << "                                         \n";
616     std::cout << "             ASIO Multiple io_context - Educational Examples
617                                         \n";
618     std::cout << "                                         \n";
619
620     ;
621     std::cout << "     Learn when and how to use multiple io_context objects in
622         ASIO      \n";
623     std::cout << "                                         \n";
624
625     demonstrate_basic_multiple_contexts();
626     demonstrate_thread_pool_pattern();
627     demonstrate_lan_wan_separation();           // ← Your requested example!
628     demonstrate_priority_separation();
629     demonstrate_service_type_separation();
```

```
617 demonstrate_run_call_patterns();
618 demonstrate_microservice_gateway();
619 demonstrate_best_practices();
620
621 std::cout << "\n" << std::string(70, '=') << "\n";
622 std::cout << "All demonstrations completed!\n";
623 std::cout << "\nKEY TAKEAWAY:\n";
624 std::cout << " Multiple io_context = SEPARATION (isolate different
625   concerns)\n";
626 std::cout << " Multiple threads on one io_context = PARALLELISM (
627   distribute work)\n";
628 std::cout << std::string(70, '=') << "\n\n";
629
630 }
```

6 Source Code: BinarySearch.cpp

File: src/BinarySearch.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <vector>
3 #include <iterator>
4
5 class Solution {
6 public:
7     int binarySearch(std::vector<int> array, int target) {
8         std::vector<int>::iterator vecBIT = array.begin();
9         std::vector<int>::iterator vecEIT = array.end();
10        std::vector<int>::iterator vecIT = vecBIT + (vecEIT - vecBIT) / 2;
11
12        //-----/\----target-----/\----target
13        //-----/\-----
14        //           vecBIT           vecIT           vecEIT
15
16        while (vecBIT <= vecEIT) {
17            if (*vecIT == target) {
18                return std::distance(array.begin(), vecIT); // Return
19                distance between iterators
20            } else if (*vecIT < target) {
21                vecBIT = vecIT + 1;
22                vecIT = vecBIT + (vecEIT - vecBIT) / 2;
23            } else {
24                vecEIT = vecIT - 1;
25                vecIT = vecBIT + (vecEIT - vecBIT) / 2;
26            }
27        }
28
29        if (vecBIT > vecEIT) return -1;
30    }
31
32    int binarySearchRecursion(std::vector<int> array, int vecBIT, int vecEIT,
33                             int target) {
34
35        if (vecBIT <= vecEIT) {
36            int vecIT = vecBIT + (vecEIT - vecBIT) / 2;
37
38            if (array[vecIT] == target)
39                return vecIT;
40            else if (array[vecIT] < target)
41                return binarySearchRecursion(array, vecIT + 1, vecEIT, target);
42            else
43                return binarySearchRecursion(array, vecBIT, vecIT - 1, target);
44        }
45        else
46            return -1;
47    }
48};
```

```
47 int main () {
48     Solution testSolution;
49     int n = 3;
50     std::vector<int> searchArray(1); // initialize vector of n elements with 0
51
52     // push_back another n - 1 elements
53     for (int i = 1; i < n; i++)
54         searchArray.push_back(i);
55
56     // n element in vector now
57     for (std::vector<int>::const_iterator vecIT = searchArray.begin(); vecIT <
58         searchArray.end(); vecIT++) {
59         std::cout << *vecIT << std::endl;
60     }
61     std::cout << std::endl;
62
63     std::cout << std::distance(searchArray.begin(), searchArray.end()) << "\n"
64         << std::endl;
65
66     for (int i = 0; i <= n; i++) {
67         std::cout << testSolution.binarySearch(searchArray, i) << std::endl;
68         std::cout << testSolution.binarySearchRecursion(searchArray, 0, n, i)
69             << std::endl;
70     }
71
72     return 0;
73 }
```

7 Source Code: CRTPvsVirtualFunctions.cpp

File: src/CRTPvsVirtualFunctions.cpp

Repository: [View on GitHub](#)

```
1  /*
2   * CRTP vs Virtual Functions: Static vs Dynamic Polymorphism
3   *
4   * This example demonstrates:
5   * 1. How virtual functions work (vtable mechanism)
6   * 2. Performance overhead of virtual functions
7   * 3. CRTP (Curiously Recurring Template Pattern) as zero-overhead alternative
8   * 4. When to use each approach
9   * 5. Benchmarking and trade-offs
10  */
11
12 #include <iostream>
13 #include <string>
14 #include <vector>
15 #include <memory>
16 #include <chrono>
17 #include <iomanip>
18
19 /**
20  =====
21 // SECTION 1: VIRTUAL FUNCTIONS AND VTABLE MECHANISM
22 // =====
23
24 namespace virtual_functions {
25
26 /**
27  * VTABLE (Virtual Function Table) EXPLANATION:
28  *
29  * When you use virtual functions, the compiler creates:
30  *
31  * 1. VTABLE (per class):
32  *      - Static array of function pointers
33  *      - One vtable per polymorphic class
34  *      - Stored in read-only memory
35  *
36  * 2. VPTR (per object):
37  *      - Hidden pointer member in each object
38  *      - Points to the class's vtable
39  *      - Added automatically by compiler
40  *      - Size overhead: 8 bytes (64-bit system)
41  *
42  * MEMORY LAYOUT EXAMPLE:
43  *
44  * class Base {
45  *     virtual void foo();
46  *     int data;
```

```
46 * } ;
47 *
48 * Object memory: [vptr][data]
49 *           |
50 *           v
51 * Vtable:      [&Base::foo][type_info*]
52 *
53 * CALL MECHANISM:
54 * obj.foo() becomes:
55 *   1. Load vptr from object
56 *   2. Index into vtable
57 *   3. Load function pointer
58 *   4. Call through pointer
59 *
60 * PERFORMANCE COSTS:
61 * • 2-3 extra memory loads (vptr + function pointer)
62 * • Cannot inline (compiler doesn't know target at compile-time)
63 * • Prevents devirtualization optimizations
64 * • Cache misses (vtable might not be in cache)
65 * • Branch prediction harder (indirect call)
66 */
67
68 class AnimalBase {
69 public:
70     virtual ~AnimalBase() = default;
71
72     // Virtual function - uses vtable dispatch
73     virtual void speak() const = 0;
74     virtual std::string getName() const = 0;
75
76     // Virtual function with implementation
77     virtual void describe() const {
78         std::cout << " I am a " << getName() << "\n";
79     }
80 };
81
82 class Dog : public AnimalBase {
83 public:
84     void speak() const override {
85         std::cout << " Woof! Woof!\n";
86     }
87
88     std::string getName() const override {
89         return "Dog";
90     }
91 };
92
93 class Cat : public AnimalBase {
94 public:
95     void speak() const override {
96         std::cout << " Meow! Meow!\n";
97     }
98
99     std::string getName() const override {
```

```
100         return "Cat";
101     }
102 };
103
104 class Bird : public AnimalBase {
105 public:
106     void speak() const override {
107         std::cout << "      Tweet! Tweet!\n";
108     }
109
110     std::string getName() const override {
111         return "Bird";
112     }
113 };
114
115 void demonstrate() {
116     std::cout << "\n" << std::string(70, '=') << "\n";
117     std::cout << "SECTION 1: VIRTUAL FUNCTIONS (DYNAMIC POLYMORPHISM)\n";
118     std::cout << std::string(70, '=') << "\n\n";
119
120     std::cout << "  VTABLE MECHANISM:\n";
121     std::cout << " •   Each object has hidden vptr (8 bytes overhead)\n";
122     std::cout << " •   vptr points to class vtable\n";
123     std::cout << " •   Function calls: load vptr -> index vtable -> call\n";
124     std::cout << " •   Runtime overhead: 2-3 memory loads per virtual call\n\n";
125     std::cout << " ";
126
127     // Demonstrate dynamic polymorphism
128     std::vector<std::unique_ptr<AnimalBase>> animals;
129     animals.push_back(std::make_unique<Dog>());
130     animals.push_back(std::make_unique<Cat>());
131     animals.push_back(std::make_unique<Bird>());
132
133     std::cout << "  ADVANTAGE: Runtime polymorphism (heterogeneous containers)\n";
134     for (const auto& animal : animals) {
135         animal->describe();
136         animal->speak();
137     }
138
139     std::cout << "  SIZE OVERHEAD:\n";
140     std::cout << "      sizeof(AnimalBase*) = " << sizeof(AnimalBase*) << " bytes\n";
141     std::cout << "      sizeof(Dog) = " << sizeof(Dog) << " bytes (includes vptr)\n";
142     std::cout << "      sizeof(Cat) = " << sizeof(Cat) << " bytes (includes vptr)\n";
143 }
144 } // namespace virtual_functions
145
146 // =====
```

```
147 // SECTION 2: STATIC MEMBER FUNCTIONS AND VTABLES
148 //
149 //=====
150
151 namespace static_functions {
152 /*
153 * STATIC MEMBER FUNCTIONS AND VTABLES:
154 *
155 * KEY FACT: Static member functions CANNOT be virtual!
156 *
157 * WHY?
158 * • Static functions don't have 'this' pointer
159 * • No object instance to determine which vtable to use
160 * • Called via class name, not object
161 * • Resolved at compile-time, not runtime
162 *
163 * IMPLICATION:
164 * • Static functions don't appear in vtable
165 * • Only ONE implementation exists (class-level, not object-level)
166 * • Cannot be overridden in derived classes
167 * • Zero runtime overhead (direct call)
168 *
169 * WHEN TO USE:
170 * • Factory functions
171 * • Utility functions that don't need object state
172 * • Performance-critical code that doesn't need polymorphism
173 */
174
175 class Base {
176 public:
177     virtual ~Base() = default;
178
179     // Virtual function - in vtable
180     virtual void instanceMethod() const {
181         std::cout << "    Base::instanceMethod() - uses vtable\n";
182     }
183
184     // Static function - NOT in vtable, cannot be virtual
185     static void staticMethod() {
186         std::cout << "    Base::staticMethod() - no vtable, direct call\n";
187     }
188
189     // Non-virtual function - NOT in vtable
190     void nonVirtualMethod() const {
191         std::cout << "    Base::nonVirtualMethod() - no vtable, direct call\n";
192     }
193 };
194
195 class Derived : public Base {
196 public:
197     // Overrides virtual function - has entry in Derived's vtable
198     void instanceMethod() const override {
```

```

199     std::cout << "    Derived::instanceMethod() - uses vtable\n";
200 }
201
202 // CANNOT override static function (compile error if we tried)
203 // This is a NEW function, not an override
204 static void staticMethod() {
205     std::cout << "    Derived::staticMethod() - different function!\n";
206 }
207
208 // Hides base class function (NOT override, no virtual)
209 void nonVirtualMethod() const {
210     std::cout << "    Derived::nonVirtualMethod() - hides base, no vtable\n"
211     "";
212 }
213
214 void demonstrate() {
215     std::cout << "\n" << std::string(70, '=') << "\n";
216     std::cout << "SECTION 2: STATIC FUNCTIONS AND VTABLES\n";
217     std::cout << std::string(70, '=') << "\n\n";
218
219     std::cout << "    STATIC FUNCTIONS:\n";
220     std::cout << "    •    Cannot be virtual (no 'this' pointer)\n";
221     std::cout << "    •    NOT in vtable (only ONE implementation)\n";
222     std::cout << "    •    Called via class name, resolved at compile-time\n";
223     std::cout << "    •    Zero runtime overhead\n\n";
224
225     Base* ptr = new Derived();
226
227     std::cout << "    VIRTUAL FUNCTION (uses vtable):\n";
228     ptr->instanceMethod(); // Calls Derived::instanceMethod via vtable
229
230     std::cout << "\n    STATIC FUNCTION (no vtable, direct call):\n";
231     Base::staticMethod(); // Calls Base::staticMethod
232     Derived::staticMethod(); // Calls Derived::staticMethod (different
233                             // function!)
234
235     std::cout << "\n    NON-VIRTUAL FUNCTION (no override, no vtable):\n";
236     ptr->nonVirtualMethod(); // Calls Base::nonVirtualMethod (no polymorphism
237                             // !)
238
239     std::cout << "\n    KEY INSIGHT:\n";
240     std::cout << "    •    Virtual functions: ONE entry in vtable per class\n";
241     std::cout << "    •    Static functions: ONE function for entire class
242                             hierarchy\n";
243     std::cout << "    •    Static means 'belongs to class, not object'\n";
244
245     delete ptr;
246 }
247 } // namespace static_functions
248
249 =====

```

```
248 // SECTION 3: CRTP - STATIC POLYMORPHISM (ZERO OVERHEAD)
249 //
250 //=====
251
252 namespace crtp_pattern {
253 /*
254 * CRTP: Curiously Recurring Template Pattern
255 *
256 * HOW IT WORKS:
257 * • Base class is template parameterized by derived class
258 * • Base uses static_cast to call derived methods
259 * • Compiler resolves calls at compile-time
260 * • NO vtable, NO vptr, NO runtime overhead
261 *
262 * CALL MECHANISM:
263 * obj.speak() becomes:
264 *   1. Compiler knows exact type at compile-time
265 *   2. Direct function call (no indirection)
266 *   3. Can inline the function
267 *   4. Zero runtime overhead
268 *
269 * BENEFITS:
270 * • Zero runtime overhead (no vtable lookup)
271 * • Functions can be inlined
272 * • No memory overhead (no vptr)
273 * • Compiler can optimize aggressively
274 *
275 * DRAWBACKS:
276 * • Cannot use heterogeneous containers (no common base type)
277 * • Type known at compile-time (no runtime polymorphism)
278 * • More complex code (template metaprogramming)
279 * • Longer compile times
280 */
281
282 // CRTP Base class
283 template <typename Derived>
284 class Animal {
285 public:
286     void speak() const {
287         // Static cast to derived type - resolved at compile-time
288         static_cast<const Derived*>(this)->speak_impl();
289     }
290
291     std::string getName() const {
292         return static_cast<const Derived*>(this)->getName_impl();
293     }
294
295     void describe() const {
296         std::cout << "    I am a " << getName() << "\n";
297     }
298 }
```

```
299 // Optional: Provide default implementation
300 void defaultBehavior() const {
301     std::cout << "    All animals need food and water\n";
302 }
303 };
304
305 class Dog : public Animal<Dog> {
306 public:
307     void speak_impl() const {
308         std::cout << "    Woof! Woof!\n";
309     }
310
311     std::string getName_impl() const {
312         return "Dog";
313     }
314 };
315
316 class Cat : public Animal<Cat> {
317 public:
318     void speak_impl() const {
319         std::cout << "    Meow! Meow!\n";
320     }
321
322     std::string getName_impl() const {
323         return "Cat";
324     }
325 };
326
327 class Bird : public Animal<Bird> {
328 public:
329     void speak_impl() const {
330         std::cout << "    Tweet! Tweet!\n";
331     }
332
333     std::string getName_impl() const {
334         return "Bird";
335     }
336 };
337
338 // Template function that works with any Animal<T>
339 template <typename T>
340 void makeAnimalSpeak(const Animal<T>& animal) {
341     animal.describe();
342     animal.speak();
343 }
344
345 void demonstrate() {
346     std::cout << "\n" << std::string(70, '=') << "\n";
347     std::cout << "SECTION 3: CRTP - STATIC POLYMORPHISM (ZERO OVERHEAD)\n";
348     std::cout << std::string(70, '=') << "\n\n";
349
350     std::cout << "    CRTP MECHANISM:\n";
351     std::cout << " •    Compile-time polymorphism (no runtime overhead)\n";
352     std::cout << " •    No vtable, no vptr (zero memory overhead)\n";
```

```
353     std::cout << " • Direct function calls (can be inlined)\n";
354     std::cout << " • Compiler knows exact type at compile-time\n\n";
355
356     Dog d;
357     Cat c;
358     Bird b;
359
360     std::cout << " DIRECT CALLS (statically resolved):\n";
361     d.speak(); // Compiler knows this is Dog::speak_impl at compile-time
362     c.speak(); // Compiler knows this is Cat::speak_impl at compile-time
363     b.speak(); // Compiler knows this is Bird::speak_impl at compile-time
364
365     std::cout << "\n TEMPLATE FUNCTION (works with any Animal<T>):\n";
366     makeAnimalSpeak(d);
367     makeAnimalSpeak(c);
368     makeAnimalSpeak(b);
369
370     std::cout << "\n SIZE COMPARISON:\n";
371     std::cout << " sizeof(Dog) = " << sizeof(Dog) << " bytes (NO vptr!)\n";
372     std::cout << " sizeof(Cat) = " << sizeof(Cat) << " bytes (NO vptr!)\n";
373     std::cout << " Compare to virtual_functions::Dog = "
374             << sizeof(virtual_functions::Dog) << " bytes (with vptr)\n";
375
376     std::cout << "\n LIMITATION: Cannot create heterogeneous container:\n";
377     std::cout << " // std::vector<Animal<??>> animals; // Won't work!\n";
378     std::cout << " // Dog and Cat are DIFFERENT types (Animal<Dog> vs Animal
379             <Cat>)\n";
380 }
381 } // namespace crtp_pattern
382 //
383 // =====
384 // SECTION 4: PERFORMANCE COMPARISON
385 // =====
386
387 namespace performance_comparison {
388
389 // Virtual function version
390 class VirtualAnimal {
391 public:
392     virtual ~VirtualAnimal() = default;
393     virtual int compute(int x) const = 0;
394 };
395
396 class VirtualDog : public VirtualAnimal {
397 public:
398     int compute(int x) const override {
399         return x * x + x; // Simple computation
400     }
401 };
```

```
402 // CRTP version
403 template <typename Derived>
404 class CRTPAnimal {
405     public:
406         int compute(int x) const {
407             return static_cast<const Derived*>(this)>compute_<b>impl</b>(x);
408         }
409     };
410 };
411
412 class CRTPDog : public CRTPAnimal<CRTPDog> {
413     public:
414         int compute_<b>impl</b>(int x) const {
415             return x * x + x; // Same computation
416         }
417     };
418
419 void demonstrate() {
420     std::cout << "\n" << std::string(70, '=') << "\n";
421     std::cout << "SECTION 4: PERFORMANCE BENCHMARKING\n";
422     std::cout << std::string(70, '=') << "\n\n";
423
424     constexpr int ITERATIONS = 10'000'000;
425
426     // Benchmark virtual functions
427     auto start = std::chrono::high_resolution_clock::now();
428     {
429         VirtualDog dog;
430         VirtualAnimal* ptr = &dog;
431         long long sum = 0;
432         for (int i = 0; i < ITERATIONS; ++i) {
433             sum += ptr->compute(i % 100); // Virtual call
434         }
435         // Use sum to prevent optimization
436         if (sum > 0) {}
437     }
438     auto end = std::chrono::high_resolution_clock::now();
439     auto virtual_time = std::chrono::duration_cast<std::chrono::milliseconds>(
440         end - start).count();
441
442     // Benchmark CRTP
443     start = std::chrono::high_resolution_clock::now();
444     {
445         CRTPDog dog;
446         long long sum = 0;
447         for (int i = 0; i < ITERATIONS; ++i) {
448             sum += dog.compute(i % 100); // Static call
449         }
450         // Use sum to prevent optimization
451         if (sum > 0) {}
452     }
453     end = std::chrono::high_resolution_clock::now();
454     auto crtp_time = std::chrono::duration_cast<std::chrono::milliseconds>(end
455         - start).count();
```

```

454     std::cout << "  BENCHMARK: " << ITERATIONS << " function calls\n\n";
455     std::cout << "    Virtual functions: " << std::setw(5) << virtual_time <<
456         " ms\n";
457     std::cout << "    CRTP (static): " << std::setw(5) << crtp_time << "
458         ms\n";
459     std::cout << "    Speedup: " << std::setw(5) << std::fixed <<
460         std::setprecision(2)
461         << (double)virtual_time / crtp_time << "x\n\n";
462
463
464     std::cout << "  WHY CRTP IS FASTER:\n";
465     std::cout << " • No vtable lookup (2-3 memory loads eliminated)\n";
466     std::cout << " • Function can be inlined (compiler sees implementation)\n";
467     std::cout << " • Better cache locality (no vtable indirection)\n";
468     std::cout << " • Better branch prediction (direct call)\n";
469     std::cout << " • Enables other compiler optimizations\n";
470 }
471
472 } // namespace performance_comparison
473
474 // SECTION 5: WHEN TO USE EACH APPROACH
475
476 =====
477
478 namespace when_to_use {
479
480     void demonstrate() {
481         std::cout << "\n" << std::string(70, '=') << "\n";
482         std::cout << "SECTION 5: WHEN TO USE VIRTUAL FUNCTIONS VS CRTP\n";
483         std::cout << std::string(70, '=') << "\n\n";
484
485         std::cout << "    USE VIRTUAL FUNCTIONS WHEN:\n\n";
486         std::cout << "        1 RUNTIME POLYMORPHISM NEEDED:\n";
487         std::cout << "            • Heterogeneous containers (vector<Base*>)\n";
488         std::cout << "            • Plugin systems (load types at runtime)\n";
489         std::cout << "            • Factory patterns\n";
490         std::cout << "            • Type not known until runtime\n\n";
491
492         std::cout << "    2 INTERFACE-BASED DESIGN:\n";
493         std::cout << "        • Defining abstract interfaces\n";
494         std::cout << "        • Separating interface from implementation\n";
495         std::cout << "        • Dependency injection\n\n";
496
497         std::cout << "    3 BINARY COMPATIBILITY:\n";
498         std::cout << "        • DLLs/shared libraries\n";
499         std::cout << "        • ABI stability requirements\n";
500         std::cout << "        • Plugin systems across compilation units\n\n";
501
502         std::cout << "    4 CODE SIMPLICITY:\n";
503
504     }
505 }
```

```

500 std::cout << " • Simpler code (no template metaprogramming)\n";
501 std::cout << " • Faster compile times\n";
502 std::cout << " • More familiar to developers\n\n";
503
504 std::cout << " 5 PERFORMANCE NOT CRITICAL:\n";
505 std::cout << " • UI code, configuration, initialization\n";
506 std::cout << " • Virtual call overhead is negligible\n";
507 std::cout << " • Clarity more important than speed\n\n";
508
509 std::cout << std::string(70, '=') << "\n\n";
510
511 std::cout << " USE CRTP (STATIC POLYMORPHISM) WHEN:\n\n";
512 std::cout << " 1 PERFORMANCE CRITICAL:\n";
513 std::cout << " • Hot loops (inner loops, tight iterations)\n";
514 std::cout << " • Real-time systems (low latency required)\n";
515 std::cout << " • Game engines (per-frame calculations)\n";
516 std::cout << " • High-frequency trading systems\n\n";
517
518 std::cout << " 2 MEMORY CONSTRAINED:\n";
519 std::cout << " • Embedded systems (every byte counts)\n";
520 std::cout << " • Large arrays of objects (vptr overhead * N)\n";
521 std::cout << " • Cache-sensitive code\n\n";
522
523 std::cout << " 3 COMPILE-TIME POLYMORPHISM SUFFICIENT:\n";
524 std::cout << " • Type known at compile-time\n";
525 std::cout << " • Template containers (vector<Dog>, vector<Cat>)\n";
526 std::cout << " • Generic algorithms\n\n";
527
528 std::cout << " 4 INLINING REQUIRED:\n";
529 std::cout << " • Small functions that must be inlined\n";
530 std::cout << " • Zero-overhead abstractions needed\n";
531 std::cout << " • Maximum compiler optimization wanted\n\n";
532
533 std::cout << " 5 TEMPLATE-BASED LIBRARIES:\n";
534 std::cout << " • STL-style libraries (iterators, algorithms)\n";
535 std::cout << " • Expression templates\n";
536 std::cout << " • Policy-based design\n\n";
537
538 std::cout << std::string(70, '=') << "\n\n";
539
540 std::cout << " TRADE-OFFS SUMMARY:\n\n";
541 std::cout << " VIRTUAL FUNCTIONS:\n";
542 std::cout << " Runtime polymorphism\n";
543 std::cout << " Heterogeneous containers\n";
544 std::cout << " Simpler code\n";
545 std::cout << " Faster compile times\n";
546 std::cout << " Runtime overhead (vtable lookup)\n";
547 std::cout << " Memory overhead (vptr per object)\n";
548 std::cout << " Cannot inline\n\n";
549
550 std::cout << " CRTP (STATIC POLYMORPHISM):\n";
551 std::cout << " Zero runtime overhead\n";
552 std::cout << " Zero memory overhead\n";
553 std::cout << " Can inline functions\n";

```

```
554     std::cout << "      Maximum performance\n";
555     std::cout << "      No runtime polymorphism\n";
556     std::cout << "      No heterogeneous containers\n";
557     std::cout << "      More complex code\n";
558     std::cout << "      Longer compile times\n\n";
559
560     std::cout << "  GOLDEN RULE:\n";
561     std::cout << "    'Use virtual functions by default for flexibility.\n";
562     std::cout << "    Use CRTP only when performance profiling shows\n";
563     std::cout << "    virtual function overhead is a bottleneck.'\n\n";
564
565     std::cout << "  PREMATURE OPTIMIZATION WARNING:\n";
566     std::cout << "  •  Don't use CRTP everywhere \"just in case\"\n";
567     std::cout << "  •  Profile first, optimize later\n";
568     std::cout << "  •  Virtual function overhead is often negligible\n";
569     std::cout << "  •  Code clarity often more valuable than tiny speedup\n";
570 }
571
572 } // namespace when_to_use
573
574 // =====
575 // SECTION 6: HYBRID APPROACH - BEST OF BOTH WORLDS
576 //
577 // =====
578
579 namespace hybrid_approach {
580 /*
581 * HYBRID APPROACH: Combine virtual functions with CRTP
582 *
583 * STRATEGY:
584 *  • Use virtual functions for high-level interfaces
585 *  • Use CRTP for performance-critical inner operations
586 *  • Get both flexibility and performance
587 */
588
589 // Virtual base for runtime polymorphism
590 class RenderableBase {
591 public:
592     virtual ~RenderableBase() = default;
593     virtual void render() const = 0;
594 };
595
596 // CRTP for performance-critical operations
597 template <typename Derived>
598 class FastOperations {
599 public:
600     void processPixel(int x, int y) const {
601         static_cast<const Derived*>(this)->processPixel_impl(x, y);
602     }
603 };
```

```
604 // Concrete class uses both
605 class Sprite : public RenderableBase, public FastOperations<Sprite> {
606 private:
607     mutable int pixel_count = 0;
608
609 public:
610     // Virtual function for high-level interface
611     void render() const override {
612         std::cout << "    [Sprite] Rendering...\n";
613         // Performance-critical inner loop uses CRTP
614         for (int y = 0; y < 100; ++y) {
615             for (int x = 0; x < 100; ++x) {
616                 processPixel(x, y); // CRTP call (zero overhead)
617             }
618         }
619         std::cout << "    [Sprite] Processed " << pixel_count << " pixels\n";
620     }
621
622     // CRTP implementation (inlined, zero overhead)
623     void processPixel_impl(int x, int y) const {
624         // Performance-critical pixel processing
625         ++pixel_count;
626         // Actual pixel operations would go here
627         (void)x; (void)y; // Suppress unused warnings
628     }
629 };
630
631 void demonstrate() {
632     std::cout << "\n" << std::string(70, '=') << "\n";
633     std::cout << "SECTION 6: HYBRID APPROACH - BEST OF BOTH WORLDS\n";
634     std::cout << std::string(70, '=') << "\n\n";
635
636     std::cout << "    STRATEGY:\n";
637     std::cout << "    •    Virtual functions for high-level interface\n";
638     std::cout << "    •    CRTP for performance-critical inner loops\n";
639     std::cout << "    •    Get both flexibility AND performance\n\n";
640
641     std::cout << "    DEMONSTRATION:\n";
642     Sprite sprite;
643     RenderableBase* ptr = &sprite;
644
645     // Virtual call for high-level operation
646     ptr->render(); // Virtual call (small overhead, called once)
647             // Inner loop uses CRTP (zero overhead, called 10000x)
648
649     std::cout << "\n BENEFIT:\n";
650     std::cout << "    •    Can store in vector<RenderableBase*> (runtime
651             polymorphism)\n";
652     std::cout << "    •    Inner loop has zero overhead (CRTP inlining)\n";
653     std::cout << "    •    Best of both worlds!\n";
654 }
655
656 } // namespace hybrid_approach
```

```
657 //  
658 //=====  
659 // MAIN  
660 //=====  
661  
662 int main() {  
663     std::cout << "\n";  
664     std::cout << "  
665         std::cout << "           CRTP vs VIRTUAL FUNCTIONS IN MODERN C++  
666             \n";  
667         std::cout << "           Static vs Dynamic Polymorphism Trade-offs  
668             \n";  
669         std::cout << "           \n";  
670     virtual_functions::demonstrate();  
671     static_functions::demonstrate();  
672     crtp_pattern::demonstrate();  
673     performance_comparison::demonstrate();  
674     when_to_use::demonstrate();  
675     hybrid_approach::demonstrate();  
676  
677     std::cout << "\n" << std::string(70, '=') << "\n";  
678     std::cout << "KEY TAKEAWAYS:\n";  
679     std::cout << std::string(70, '=') << "\n\n";  
680  
681     std::cout << " 1 VIRTUAL FUNCTIONS:\n";  
682     std::cout << " • Use vtable (per class) and vptr (per object)\n";  
683     std::cout << " • Runtime overhead: 2-3 memory loads per call\n";  
684     std::cout << " • Memory overhead: 8 bytes per object (vptr)\n";  
685     std::cout << " • Cannot inline virtual calls\n";  
686     std::cout << " • Enable runtime polymorphism\n\n";  
687  
688     std::cout << " 2 STATIC MEMBER FUNCTIONS:\n";  
689     std::cout << " • Cannot be virtual (no 'this' pointer)\n";  
690     std::cout << " • Only ONE function per class hierarchy\n";  
691     std::cout << " • Zero runtime overhead (direct call)\n";  
692     std::cout << " • Not in vtable\n\n";  
693  
694     std::cout << " 3 CRTP (CURIOSLY RECURRING TEMPLATE PATTERN):\n";  
695     std::cout << " • Zero runtime overhead (compile-time resolution)\n";  
696     std::cout << " • Zero memory overhead (no vptr)\n";  
697     std::cout << " • Functions can be inlined\n";  
698     std::cout << " • No heterogeneous containers\n";  
699     std::cout << " • More complex code\n\n";  
700  
701     std::cout << " 4 WHEN TO USE WHAT:\n";  
702     std::cout << " • Virtual: Flexibility, runtime polymorphism, simplicity\n";  
703     std::cout << " • CRTP: Performance-critical code, compile-time known  
704         types\n";
```

```
703     std::cout << " • Hybrid: High-level virtual + low-level CRTP\n\n";
704
705     std::cout << " 5 PERFORMANCE:\n";
706     std::cout << " • Virtual overhead often negligible in real applications\
707                 n";
708     std::cout << " • CRTP can be 2-10x faster in tight loops\n";
709     std::cout << " • Profile before optimizing!\n\n";
710
711     std::cout << "                                     \n";
712     std::cout << "             ALL CONCEPTS DEMONSTRATED SUCCESSFULLY!
713                 \n";
714
715     std::cout << "                                     \n\n";
716
717     return 0;
718 }
```

8 Source Code: CameraModule.cppm

File: src/CameraModule.cppm

Repository: [View on GitHub](#)

```
1 // =====
2 // C++20 MODULE: CAMERA INTERFACE WITH TEMPLATES
3 // =====
4 // Demonstrates C++20 modules with export/import
5 // Also includes concepts for type constraints
6 // =====
7
8 module;
9
10 // Global module fragment - for #include directives
11 #include <vector>
12 #include <memory>
13 #include <string>
14 #include <cstdint>
15 #include <type_traits>
16 #include <algorithm>
17 #include <cmath>
18 #include <utility>
19 #include <concepts>
20
21 export module camera;
22
23 // =====
24 // C++20 CONCEPTS FOR PIXEL TYPES
25 // =====
26
27 export template<typename T>
28 concept PixelType = std::is_arithmetic_v<T> && (
29     std::is_same_v<T, uint8_t> ||
30     std::is_same_v<T, uint16_t> ||
31     std::is_same_v<T, uint32_t> ||
32     std::is_same_v<T, float> ||
33     std::is_same_v<T, double>
34 );
35
36 export template<typename T>
37 concept IntegerPixel = PixelType<T> && std::is_integral_v<T>;
38
39 export template<typename T>
40 concept FloatingPixel = PixelType<T> && std::is_floating_point_v<T>;
41
42 // =====
43 // IMAGE CLASS (EXPORTED)
44 // =====
45
46 export template<PixelType T>
47 class Image {
48 private:
49     size_t width;
```

```
50     size_t height;
51     std::vector<T> pixels;
52
53 public:
54     Image(size_t w, size_t h)
55         : width(w), height(h), pixels(w * h) {}
56
57     Image(size_t w, size_t h, T initial_value)
58         : width(w), height(h), pixels(w * h, initial_value) {}
59
60     // Accessors
61     [[nodiscard]] size_t get_width() const noexcept { return width; }
62     [[nodiscard]] size_t get_height() const noexcept { return height; }
63     [[nodiscard]] size_t get_size() const noexcept { return pixels.size(); }
64
65     // Pixel access
66     T& at(size_t x, size_t y) {
67         return pixels[y * width + x];
68     }
69
70     const T& at(size_t x, size_t y) const {
71         return pixels[y * width + x];
72     }
73
74     // Raw data access
75     [[nodiscard]] T* data() noexcept { return pixels.data(); }
76     [[nodiscard]] const T* data() const noexcept { return pixels.data(); }
77
78     // Memory size
79     [[nodiscard]] size_t memory_bytes() const noexcept {
80         return pixels.size() * sizeof(T);
81     }
82
83     // Fill with value
84     void fill(T value) {
85         std::fill(pixels.begin(), pixels.end(), value);
86     }
87
88     // C++20: Three-way comparison
89     auto operator<=>(const Image&) const = default;
90 };
91
92 // =====
93 // CAMERA INTERFACE (EXPORTED)
94 // =====
95
96 export template<PixelType T>
97 class Camera {
98     private:
99         size_t width;
100        size_t height;
101        std::string camera_name;
102
103 public:
```

```
104     Camera(const std::string& name, size_t w, size_t h)
105         : camera_name(name), width(w), height(h) {}
106
107     virtual ~Camera() = default;
108
109     // Pure virtual: capture image
110     virtual Image<T> capture() = 0;
111
112     // Configuration
113     [[nodiscard]] size_t get_width() const noexcept { return width; }
114     [[nodiscard]] size_t get_height() const noexcept { return height; }
115     [[nodiscard]] const std::string& get_name() const noexcept { return
116         camera_name; }
117
118     // Get pixel type information
119     [[nodiscard]] static constexpr size_t bits_per_pixel() noexcept {
120         return sizeof(T) * 8;
121     }
122
123     [[nodiscard]] static constexpr bool is_floating_point() noexcept {
124         return std::is_floating_point_v<T>;
125     }
126
127     [[nodiscard]] static constexpr bool is_integer() noexcept {
128         return std::is_integral_v<T>;
129     };
130
131 // =====
132 // IMAGE PROCESSOR (EXPORTED)
133 // =====
134
135 export template<PixelType T>
136 class ImageProcessor {
137 public:
138     // Calculate average pixel value
139     [[nodiscard]] static double calculate_mean(const Image<T>& img) {
140         double sum = 0.0;
141         const T* data = img.data();
142         size_t size = img.get_size();
143
144         for (size_t i = 0; i < size; ++i) {
145             sum += static_cast<double>(data[i]);
146         }
147
148         return sum / size;
149     }
150
151     // Find min and max pixel values
152     [[nodiscard]] static std::pair<T, T> find_min_max(const Image<T>& img) {
153         const T* data = img.data();
154         size_t size = img.get_size();
155
156         T min_val = data[0];
```

```
157     T max_val = data[0];
158
159     for (size_t i = 1; i < size; ++i) {
160         if (data[i] < min_val) min_val = data[i];
161         if (data[i] > max_val) max_val = data[i];
162     }
163
164     return {min_val, max_val};
165 }
166
167 // Scale pixel values
168 [[nodiscard]] static Image<T> scale(const Image<T>& img, double factor) {
169     Image<T> result(img.get_width(), img.get_height());
170
171     for (size_t y = 0; y < img.get_height(); ++y) {
172         for (size_t x = 0; x < img.get_width(); ++x) {
173             double scaled = static_cast<double>(img.at(x, y)) * factor;
174             result.at(x, y) = static_cast<T>(scaled);
175         }
176     }
177
178     return result;
179 }
180
181 // Threshold operation - using concept constraint
182 [[nodiscard]] static Image<T> threshold(const Image<T>& img, T
183     threshold_value)
184     requires IntegerPixel<T>
185 {
186     Image<T> result(img.get_width(), img.get_height());
187
188     for (size_t y = 0; y < img.get_height(); ++y) {
189         for (size_t x = 0; x < img.get_width(); ++x) {
190             result.at(x, y) = (img.at(x, y) >= threshold_value) ?
191                 threshold_value : T(0);
192         }
193     }
194
195     return result;
196 }
197
198 // Normalize operation - only for floating point images
199 [[nodiscard]] static Image<T> normalize(const Image<T>& img)
200     requires FloatingPixel<T>
201 {
202     auto [min_val, max_val] = find_min_max(img);
203     T range = max_val - min_val;
204
205     if (range == T(0)) return img;
206
207     Image<T> result(img.get_width(), img.get_height());
208
209     for (size_t y = 0; y < img.get_height(); ++y) {
210         for (size_t x = 0; x < img.get_width(); ++x) {
```

```
210         result.at(x, y) = (img.at(x, y) - min_val) / range;
211     }
212 }
213
214     return result;
215 }
216 };
217
218 // =====
219 // TYPE CONVERSION (EXPORTED)
220 // =====
221
222 export template<PixelType DestType, PixelType SrcType>
223 [[nodiscard]] Image<DestType> convert_image(const Image<SrcType>& src) {
224     Image<DestType> dest(src.get_width(), src.get_height());
225
226     // Find source range
227     auto [min_val, max_val] = ImageProcessor<SrcType>::find_min_max(src);
228     double src_range = static_cast<double>(max_val) - static_cast<double>(min_val);
229
230     // Determine destination range
231     double dest_min, dest_max;
232     if constexpr (std::is_floating_point_v<DestType>) {
233         dest_min = 0.0;
234         dest_max = 1.0;
235     } else if constexpr (std::is_same_v<DestType, uint8_t>) {
236         dest_min = 0.0;
237         dest_max = 255.0;
238     } else if constexpr (std::is_same_v<DestType, uint16_t>) {
239         dest_min = 0.0;
240         dest_max = 65535.0;
241     } else {
242         dest_min = 0.0;
243         dest_max = 1.0;
244     }
245
246     double dest_range = dest_max - dest_min;
247
248     // Convert with proper scaling
249     if (src_range == 0.0) {
250         dest.fill(static_cast<DestType>(dest_min));
251         return dest;
252     }
253
254     for (size_t y = 0; y < src.get_height(); ++y) {
255         for (size_t x = 0; x < src.get_width(); ++x) {
256             double normalized = (static_cast<double>(src.at(x, y)) -
257                 static_cast<double>(min_val)) / src_range;
258             double scaled = normalized * dest_range + dest_min;
259             dest.at(x, y) = static_cast<DestType>(scaled);
260         }
261     }
262 }
```

```
262     return dest;
263 }
264
265 // =====
266 // CAMERA IMPLEMENTATIONS (EXPORTED)
267 // =====
268
269 export class Camera8bit : public Camera<uint8_t> {
270 public:
271     Camera8bit(const std::string& name, size_t w, size_t h)
272         : Camera<uint8_t>(name, w, h) {}
273
274     Image<uint8_t> capture() override {
275         Image<uint8_t> img(get_width(), get_height());
276
277         for (size_t y = 0; y < get_height(); ++y) {
278             for (size_t x = 0; x < get_width(); ++x) {
279                 uint8_t value = static_cast<uint8_t>(
280                     (x * 255.0 / get_width()) * 0.5 +
281                     (y * 255.0 / get_height()) * 0.5
282                 );
283                 img.at(x, y) = value;
284             }
285         }
286         return img;
287     }
288 };
289
290 export class Camera16bit : public Camera<uint16_t> {
291 public:
292     Camera16bit(const std::string& name, size_t w, size_t h)
293         : Camera<uint16_t>(name, w, h) {}
294
295     Image<uint16_t> capture() override {
296         Image<uint16_t> img(get_width(), get_height());
297
298         for (size_t y = 0; y < get_height(); ++y) {
299             for (size_t x = 0; x < get_width(); ++x) {
300                 uint16_t value = static_cast<uint16_t>(
301                     (x * 65535.0 / get_width()) * 0.3 +
302                     (y * 65535.0 / get_height()) * 0.7
303                 );
304                 img.at(x, y) = value;
305             }
306         }
307         return img;
308     }
309 };
310
311 export class CameraFloat : public Camera<float> {
312 public:
313     CameraFloat(const std::string& name, size_t w, size_t h)
314         : Camera<float>(name, w, h) {}
```

```
316     Image<float> capture() override {
317         Image<float> img(get_width(), get_height());
318
319         for (size_t y = 0; y < get_height(); ++y) {
320             for (size_t x = 0; x < get_width(); ++x) {
321                 float value =
322                     0.5f + 0.5f * std::sin(x * 0.1f) * std::cos(y * 0.1f);
323                 img.at(x, y) = value;
324             }
325         }
326         return img;
327     }
328 };
329
330 export class CameraDouble : public Camera<double> {
331 public:
332     CameraDouble(const std::string& name, size_t w, size_t h)
333         : Camera<double>(name, w, h) {}
334
335     Image<double> capture() override {
336         Image<double> img(get_width(), get_height());
337
338         for (size_t y = 0; y < get_height(); ++y) {
339             for (size_t x = 0; x < get_width(); ++x) {
340                 double value =
341                     std::sin(x * 0.05) * std::cos(y * 0.05) +
342                     std::exp(-((x - get_width()/2.0) * (x - get_width()/2.0) +
343                               (y - get_height()/2.0) * (y - get_height()/2.0)
344                               ) / 1000.0);
345                 img.at(x, y) = value;
346             }
347         }
348         return img;
349     }
350 };
351 // =====
352 // CAMERA HANDLER (EXPORTED)
353 // =====
354
355 export template<PixelType T>
356 class CameraHandler {
357 private:
358     std::unique_ptr<Camera<T>> camera;
359
360 public:
361     CameraHandler(std::unique_ptr<Camera<T>> cam)
362         : camera(std::move(cam)) {}
363
364     [[nodiscard]] const Camera<T>* get_camera() const noexcept {
365         return camera.get();
366     }
367
368     [[nodiscard]] Image<T> capture() {
```

```
369     return camera->capture();
370 }
371
372 [[nodiscard]] static constexpr size_t pixel_size() noexcept {
373     return sizeof(T);
374 }
375
376 [[nodiscard]] static constexpr size_t bits_per_pixel() noexcept {
377     return sizeof(T) * 8;
378 }
379};
```

9 Source Code: ConceptsExamples.cpp

File: src/ConceptsExamples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <concepts>
5 #include <type_traits>
6 #include <algorithm>
7 #include <iterator>
8
9 // =====
10 // 1. BASIC CONCEPT DEFINITION
11 // =====
12 template<typename T>
13 concept Numeric = std::is_arithmetic_v<T>;
14
15 template<Numeric T>
16 T add(T a, T b) {
17     return a + b;
18 }
19
20 void example_basic_concept() {
21     std::cout << "\n==== 1. BASIC CONCEPT DEFINITION ===" << std::endl;
22
23     std::cout << "add(10, 20) = " << add(10, 20) << std::endl;
24     std::cout << "add(3.14, 2.86) = " << add(3.14, 2.86) << std::endl;
25
26     // This would fail to compile:
27     // add(std::string("hello"), std::string("world"));
28 }
29
30 // =====
31 // 2. STANDARD LIBRARY CONCEPTS
32 // =====
33 template<std::integral T>
34 T multiply(T a, T b) {
35     return a * b;
36 }
37
38 template<std::floating_point T>
39 T divide(T a, T b) {
40     return a / b;
41 }
42
43 void example_standard_concepts() {
44     std::cout << "\n==== 2. STANDARD LIBRARY CONCEPTS ===" << std::endl;
45
46     std::cout << "multiply(5, 6) = " << multiply(5, 6) << std::endl;
47     std::cout << "divide(10.0, 3.0) = " << divide(10.0, 3.0) << std::endl;
48
49     // multiply(3.14, 2.0); // ERROR: requires integral type
```

```
50     // divide(10, 3);           // ERROR: requires floating point type
51 }
52
53 // =====
54 // 3. COMPOUND CONCEPTS
55 // =====
56 template<typename T>
57 concept Addable = requires(T a, T b) {
58     { a + b } -> std::convertible_to<T>;
59 };
60
61 template<typename T>
62 concept Printable = requires(T t) {
63     { std::cout << t } -> std::convertible_to<std::ostream&>;
64 };
65
66 template<typename T>
67 concept AddableAndPrintable = Addable<T> && Printable<T>;
68
69 template<AddableAndPrintable T>
70 void print_sum(T a, T b) {
71     std::cout << a << " + " << b << " = " << (a + b) << std::endl;
72 }
73
74 void example_compound_concepts() {
75     std::cout << "\n==== 3. COMPOUND CONCEPTS ===" << std::endl;
76
77     print_sum(10, 20);
78     print_sum(3.14, 2.86);
79     print_sum(std::string("Hello "), std::string("World"));
80 }
81
82 // =====
83 // 4. REQUIRES CLAUSE
84 // =====
85 template<typename T>
86 T max_value(T a, T b) requires std::totally_ordered<T> {
87     return (a > b) ? a : b;
88 }
89
90 template<typename T>
91 requires std::integral<T>
92 T factorial(T n) {
93     if (n <= 1) return 1;
94     return n * factorial(n - 1);
95 }
96
97 void example_requires_clause() {
98     std::cout << "\n==== 4. REQUIRES CLAUSE ===" << std::endl;
99
100    std::cout << "max(10, 20) = " << max_value(10, 20) << std::endl;
101    std::cout << "max(3.14, 2.71) = " << max_value(3.14, 2.71) << std::endl;
102
103    std::cout << "factorial(5) = " << factorial(5) << std::endl;
```

```
104 }
105
106 // =====
107 // 5. CONCEPTS WITH MULTIPLE REQUIREMENTS
108 // =====
109 template<typename T>
110 concept Container = requires(T t) {
111     typename T::value_type;
112     typename T::iterator;
113     { t.begin() } -> std::same_as<typename T::iterator>;
114     { t.end() } -> std::same_as<typename T::iterator>;
115     { t.size() } -> std::convertible_to<std::size_t>;
116 };
117
118 template<Container C>
119 void print_container(const C& container, const std::string& name) {
120     std::cout << name << " (size " << container.size() << ")";
121     for (const auto& elem : container) {
122         std::cout << elem << " ";
123     }
124     std::cout << std::endl;
125 }
126
127 void example_container_concept() {
128     std::cout << "\n==== 5. CONCEPTS WITH MULTIPLE REQUIREMENTS ===" << std::endl;
129
130     std::vector<int> vec = {1, 2, 3, 4, 5};
131     print_container(vec, "Vector");
132
133     std::vector<std::string> words = {"Hello", "Modern", "C++"};
134     print_container(words, "Strings");
135 }
136
137 // =====
138 // 6. CONCEPT SUBSUMPTION
139 // =====
140 template<typename T>
141 concept Number = std::is_arithmetic_v<T>;
142
143 template<typename T>
144 concept Integer = Number<T> && std::is_integral_v<T>;
145
146 template<Number T>
147 void process(T value) {
148     std::cout << "Processing number: " << value << std::endl;
149 }
150
151 template<Integer T>
152 void process(T value) {
153     std::cout << "Processing integer: " << value << " (doubled: " << value * 2
154     << ")" << std::endl;
155 }
```

```
156 void example_concept_subsumption() {
157     std::cout << "\n==== 6. CONCEPT SUBSUMPTION ===" << std::endl;
158
159     process(42);           // Calls Integer version
160     process(3.14);        // Calls Number version
161 }
162
163 // =====
164 // 7. CUSTOM CONCEPT FOR RANGES
165 // =====
166 template<typename T>
167 concept Sortable = requires(T container) {
168     { container.begin() } -> std::input_or_output_iterator;
169     { container.end() } -> std::input_or_output_iterator;
170     requires std::sortable<decltype(container.begin())>;
171 };
172
173 template<Sortable C>
174 void sort_and_print(C& container) {
175     std::sort(container.begin(), container.end());
176     std::cout << "Sorted: ";
177     for (const auto& elem : container) {
178         std::cout << elem << " ";
179     }
180     std::cout << std::endl;
181 }
182
183 void example_sortable_concept() {
184     std::cout << "\n==== 7. CUSTOM CONCEPT FOR RANGES ===" << std::endl;
185
186     std::vector<int> numbers = {5, 2, 8, 1, 9};
187     sort_and_print(numbers);
188 }
189
190 // =====
191 // 8. CONCEPT WITH CLASS TEMPLATE
192 // =====
193 template<typename T>
194 concept Multipliable = requires(T a, T b) {
195     { a * b } -> std::convertible_to<T>;
196 };
197
198 template<Multipliable T>
199 class Point2D {
200 private:
201     T x, y;
202
203 public:
204     Point2D(T x_val, T y_val) : x(x_val), y(y_val) {}
205
206     T dot_product(const Point2D& other) const {
207         return x * other.x + y * other.y;
208     }
209 }
```

```
210     void print() const {
211         std::cout << "Point(" << x << ", " << y << ")" << std::endl;
212     }
213 };
214
215 void example_concept_class_template() {
216     std::cout << "\n==== 8. CONCEPT WITH CLASS TEMPLATE ===" << std::endl;
217
218     Point2D<int> p1(3, 4);
219     Point2D<int> p2(5, 6);
220
221     p1.print();
222     p2.print();
223     std::cout << "Dot product: " << p1.dot_product(p2) << std::endl;
224 }
225
226 // =====
227 // 9. CONCEPTS WITH LOGICAL OPERATORS
228 // =====
229 template<typename T>
230 concept SignedIntegral = std::integral<T> && std::is_signed_v<T>;
231
232 template<typename T>
233 concept UnsignedIntegral = std::integral<T> && std::is_unsigned_v<T>;
234
235 template<SignedIntegral T>
236 T abs_value(T value) {
237     return value < 0 ? -value : value;
238 }
239
240 template<UnsignedIntegral T>
241 T abs_value(T value) {
242     return value; // Already positive
243 }
244
245 void example_logical_concepts() {
246     std::cout << "\n==== 9. CONCEPTS WITH LOGICAL OPERATORS ===" << std::endl;
247
248     std::cout << "abs(-42) = " << abs_value(-42) << std::endl;
249     std::cout << "abs(42u) = " << abs_value(42u) << std::endl;
250 }
251
252 // =====
253 // 10. CONCEPT FOR CALLABLE TYPES
254 // =====
255 template<typename F, typename T>
256 concept Predicate = std::predicate<F, T>;
257
258 template<typename C, typename Pred>
259 requires Container<C> && Predicate<Pred, typename C::value_type>
260 void filter_and_print(const C& container, Pred pred, const std::string& name)
261 {
262     std::cout << name << ":" ;
263     for (const auto& elem : container) {
```

```
263     if (pred(elem)) {
264         std::cout << elem << " ";
265     }
266 }
267 std::cout << std::endl;
268 }
269
270 void example_predicate_concept() {
271     std::cout << "\n== 10. CONCEPT FOR CALLABLE TYPES ==" << std::endl;
272
273     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
274
275     filter_and_print(numbers, [](int n) { return n % 2 == 0; }, "Even numbers");
276     filter_and_print(numbers, [](int n) { return n > 5; }, "Greater than 5");
277 }
278
279 // =====
280 // 11. CONCEPT FOR CUSTOM TYPES
281 // =====
282 template<typename T>
283 concept Drawable = requires(T obj) {
284     { obj.draw() } -> std::same_as<void>;
285     { obj.get_name() } -> std::convertible_to<std::string>;
286 };
287
288 class Circle {
289 public:
290     void draw() const {
291         std::cout << "Drawing a circle" << std::endl;
292     }
293
294     std::string get_name() const {
295         return "Circle";
296     }
297 };
298
299 class Rectangle {
300 public:
301     void draw() const {
302         std::cout << "Drawing a rectangle" << std::endl;
303     }
304
305     std::string get_name() const {
306         return "Rectangle";
307     }
308 };
309
310 template<Drawable T>
311 void render(const T& shape) {
312     std::cout << "Rendering: " << shape.get_name() << std::endl;
313     shape.draw();
314 }
```

```
316 void example_custom_type_concept() {
317     std::cout << "\n==== 11. CONCEPT FOR CUSTOM TYPES ===" << std::endl;
318
319     Circle circle;
320     Rectangle rect;
321
322     render(circle);
323     render(rect);
324 }
325
326 // =====
327 // 12. ADVANCED CONCEPT WITH NESTED REQUIREMENTS
328 // =====
329 template<typename T>
330 concept Arithmetic = requires(T a, T b) {
331     { a + b } -> std::convertible_to<T>;
332     { a - b } -> std::convertible_to<T>;
333     { a * b } -> std::convertible_to<T>;
334     { a / b } -> std::convertible_to<T>;
335 };
336
337 template<Arithmetic T>
338 class Calculator {
339 private:
340     T value;
341
342 public:
343     Calculator(T val) : value(val) {}
344
345     T add(T other) { return value + other; }
346     T subtract(T other) { return value - other; }
347     T multiply(T other) { return value * other; }
348     T divide(T other) { return value / other; }
349
350     void print() const {
351         std::cout << "Calculator value: " << value << std::endl;
352     }
353 };
354
355 void example_arithmetic_concept() {
356     std::cout << "\n==== 12. ADVANCED CONCEPT WITH NESTED REQUIREMENTS ===" <<
357             std::endl;
358
359     Calculator<int> calc_int(100);
360     calc_int.print();
361     std::cout << "100 + 50 = " << calc_int.add(50) << std::endl;
362     std::cout << "100 * 2 = " << calc_int.multiply(2) << std::endl;
363
364     Calculator<double> calc_double(10.5);
365     calc_double.print();
366     std::cout << "10.5 / 2.0 = " << calc_double.divide(2.0) << std::endl;
367 }
368
// =====
```

```
369 // MAIN FUNCTION
370 // =====
371 int main() {
372     std::cout << "\n====="
373     std::cout << "      C++20 CONCEPTS EXAMPLES" << std::endl;
374     std::cout << "====="
375     std::endl;
376     example_basic_concept();
377     example_standard_concepts();
378     example_compound_concepts();
379     example_requires_clause();
380     example_container_concept();
381     example_concept_subsumption();
382     example_sortable_concept();
383     example_concept_class_template();
384     example_logical_concepts();
385     example_predicate_concept();
386     example_custom_type_concept();
387     example_arithmetic_concept();
388
389     std::cout << "\n====="
390     std::cout << "      ALL EXAMPLES COMPLETED" << std::endl;
391     std::cout << "=====\\n"
392     std::endl;
393
394     return 0;
}
```

10 Source Code: ConfigLoaderAndChecker.cpp

File: src/ConfigLoaderAndChecker.cpp

Repository: [View on GitHub](#)

```
1 // ConfigLoaderAndChecker.cpp
2 // Demonstrates dynamic configuration loading and monitoring using std::
3 //     unordered_multimap
4 //
5 // FEATURES:
6 // 1. Load key-value pairs from JSON config file into unordered_multimap
7 // 2. Monitor config.json for changes (file modification time)
8 // 3. Automatically reload and update configuration on changes
9 // 4. Handle new keys, modified values, and deleted keys
10 // 5. Thread-safe configuration access
11 // 6. JSON validation and error handling
12 // 7. Real-time configuration updates without restart
13
14 #include <iostream>
15 #include <fstream>
16 #include <string>
17 #include <unordered_map>
18 #include <vector>
19 #include <set>
20 #include <chrono>
21 #include <thread>
22 #include <mutex>
23 #include <atomic>
24 #include <iomanip>
25 #include <filesystem>
26 #include <nlohmann/json.hpp>
27
28 namespace fs = std::filesystem;
29 using namespace std::chrono;
30 using namespace std::chrono_literals;
31
32 // SECTION 1: Using nlohmann/json library for JSON parsing
33 // =====
34
35 using json = nlohmann::json;
36
37 // =====
38 // SECTION 2: Thread-Safe Configuration Manager with unordered_multimap
39 // =====
```

```
41 class ConfigManager {
42     private:
43         std::unordered_multimap<std::string, std::string> config_data_;
44         std::unordered_multimap<std::string, std::string> previous_config_data_;
45         mutable std::mutex mutex_;
46         fs::file_time_type last_write_time_;
47         std::string config_file_path_;
48         std::atomic<int> version_{0};
49
50     public:
51         explicit ConfigManager(const std::string& config_file)
52             : config_file_path_(config_file) {
53
54             if (fs::exists(config_file_path_)) {
55                 last_write_time_ = fs::last_write_time(config_file_path_);
56             }
57         }
58
59         // Load configuration from file
60         bool load() {
61             try {
62                 std::ifstream file(config_file_path_);
63                 if (!file.is_open()) {
64                     std::cerr << " Cannot open config file: " <<
65                     config_file_path_ << "\n";
66                     return false;
67                 }
68
69                 // Parse JSON using nlohmann/json
70                 json parsed_json;
71                 file >> parsed_json;
72                 file.close();
73
74                 // Update configuration
75                 std::lock_guard<std::mutex> lock(mutex_);
76
77                 // Save previous config for change detection
78                 previous_config_data_ = config_data_;
79                 config_data_.clear();
80
81                 // Support both flat objects and nested structures
82                 for (auto& [key, value] : parsed_json.items()) {
83                     // Convert value to string representation
84                     std::string value_str;
85                     if (value.is_string()) {
86                         value_str = value.get<std::string>();
87                     } else if (value.is_number()) {
88                         value_str = value.dump();
89                     } else if (value.is_boolean()) {
90                         value_str = value.get<bool>() ? "true" : "false";
91                     } else if (value.is_array()) {
92                         // For arrays, insert multiple entries (true multimap
93                         // usage)
94                         for (const auto& item : value) {
```

```
93         if (item.is_string()) {
94             config_data_.insert({key, item.get<std::string>()})
95                 );
96         } else {
97             config_data_.insert({key, item.dump()});
98         }
99         continue; // Skip the insert below
100     } else {
101         value_str = value.dump();
102     }
103
104     config_data_.insert({key, value_str});
105 }
106
107 version_++;
108
109 std::cout << " Loaded " << config_data_.size()
110             << " configuration entries (version " << version_ << ")"
111             << "\n";
112
113     return true;
114 }
115     catch (const std::exception& e) {
116         std::cerr << " Failed to load config: " << e.what() << "\n";
117         return false;
118     }
119
120 // Reload if file has changed
121 bool reload_if_changed() {
122     if (!fs::exists(config_file_path_)) {
123         std::cerr << " Config file not found: " << config_file_path_ <<
124             "\n";
125         return false;
126     }
127
128     auto current_write_time = fs::last_write_time(config_file_path_);
129
130     if (current_write_time != last_write_time_) {
131         std::cout << "\n Config file modified, reloading...\n";
132         last_write_time_ = current_write_time;
133         bool loaded = load();
134         if (loaded) {
135             print_changes();
136         }
137         return loaded;
138     }
139
140     return false;
141 }
142
143 // Get value by key (returns first match for multimap)
144 std::string get(const std::string& key, const std::string& default_value =
```

```
        "") const {
144     std::lock_guard<std::mutex> lock(mutex_);
145     auto it = config_data_.find(key);
146     if (it != config_data_.end()) {
147         return it->second;
148     }
149     return default_value;
150 }
151
152 // Get all values for a key (multimap can have multiple values per key)
153 std::vector<std::string> get_all(const std::string& key) const {
154     std::lock_guard<std::mutex> lock(mutex_);
155     std::vector<std::string> values;
156
157     auto range = config_data_.equal_range(key);
158     for (auto it = range.first; it != range.second; ++it) {
159         values.push_back(it->second);
160     }
161
162     return values;
163 }
164
165 // Check if key exists
166 bool has_key(const std::string& key) const {
167     std::lock_guard<std::mutex> lock(mutex_);
168     return config_data_.find(key) != config_data_.end();
169 }
170
171 // Get all keys
172 std::vector<std::string> get_all_keys() const {
173     std::lock_guard<std::mutex> lock(mutex_);
174     std::vector<std::string> keys;
175
176     for (const auto& [key, value] : config_data_) {
177         keys.push_back(key);
178     }
179
180     return keys;
181 }
182
183 // Get configuration count
184 size_t size() const {
185     std::lock_guard<std::mutex> lock(mutex_);
186     return config_data_.size();
187 }
188
189 // Display all configuration
190 void display() const {
191     std::lock_guard<std::mutex> lock(mutex_);
192
193     std::cout << "\n";
194     std::cout << "  Current Configuration (Version " << version_ << ")";
195     std::cout << std::string(20 - std::to_string(version_.load()).length()
196                           , ' ') << "\n";
```

```
196     std::cout << "\n";
197
198     if (config_data_.empty()) {
199         std::cout << " (empty)\n";
200     } else {
201         for (const auto& [key, value] : config_data_) {
202             std::string line = " " + key + ": " + value;
203             line += std::string(58 - line.length(), ' ') + " ";
204             std::cout << line << "\n";
205         }
206     }
207
208     std::cout << "\n\n";
209 }
210
211 int get_version() const {
212     return version_.load();
213 }
214
215 std::string get_file_path() const {
216     return config_file_path_;
217 }
218
219 void print_changes() {
220     std::lock_guard<std::mutex> lock(mutex_);
221
222     std::cout << "\n Configuration changes detected:\n";
223
224     // Track unique keys
225     std::set<std::string> all_keys;
226     for (const auto& [key, _] : previous_config_data_) all_keys.insert(key);
227     for (const auto& [key, _) : config_data_) all_keys.insert(key);
228
229     for (const auto& key : all_keys) {
230         auto prev_range = previous_config_data_.equal_range(key);
231         auto curr_range = config_data_.equal_range(key);
232
233         std::vector<std::string> prev_values;
234         for (auto it = prev_range.first; it != prev_range.second; ++it) {
235             prev_values.push_back(it->second);
236         }
237
238         std::vector<std::string> curr_values;
239         for (auto it = curr_range.first; it != curr_range.second; ++it) {
240             curr_values.push_back(it->second);
241         }
242
243         if (prev_values.empty() && !curr_values.empty()) {
244             std::cout << " ADDED to unordered_multimap: '" << key << "'";
245             = "";
246             for (size_t i = 0; i < curr_values.size(); ++i) {
247                 std::cout << "\\" << curr_values[i] << "\\";
248             }
249         }
250     }
251 }
```

```

247         if (i < curr_values.size() - 1) std::cout << ", ";
248     }
249     if (curr_values.size() > 1) {
250         std::cout << "(" << curr_values.size() << " entries)";
251     }
252     std::cout << "\n";
253 } else if (!prev_values.empty() && curr_values.empty()) {
254     std::cout << "    REMOVED from unordered_multimap: '" << key
255     << "' (was: ";
256     for (size_t i = 0; i < prev_values.size(); ++i) {
257         std::cout << "\\" << prev_values[i] << "\\";
258         if (i < prev_values.size() - 1) std::cout << ", ";
259     }
260     std::cout << ")\n";
261 } else if (prev_values != curr_values) {
262     std::cout << "    MODIFIED in unordered_multimap: '" << key <<
263     "'\n";
264     std::cout << "        Old: ";
265     for (size_t i = 0; i < prev_values.size(); ++i) {
266         std::cout << "\\" << prev_values[i] << "\\";
267         if (i < prev_values.size() - 1) std::cout << ", ";
268     }
269     std::cout << "\n        New: ";
270     for (size_t i = 0; i < curr_values.size(); ++i) {
271         std::cout << "\\" << curr_values[i] << "\\";
272         if (i < curr_values.size() - 1) std::cout << ", ";
273     }
274     std::cout << "\n";
275 }
276 }
277 }
278 /**
279 =====
280 // SECTION 3: Configuration Monitor (Background Thread)
281 /**
282 =====
283
284 class ConfigMonitor {
285 private:
286     ConfigManager& config_manager_;
287     std::atomic<bool> running_{false};
288     std::thread monitor_thread_;
289     std::chrono::milliseconds check_interval_;
290
291 public:
292     ConfigMonitor(ConfigManager& manager, std::chrono::milliseconds interval =
293                 600000ms)
294         : config_manager_(manager), check_interval_(interval) {}
295

```

```
294     ~ConfigMonitor() {
295         stop();
296     }
297
298     void start() {
299         if (running_) {
300             std::cout << "    Monitor already running\n";
301             return;
302         }
303
304         running_ = true;
305         monitor_thread_ = std::thread(&ConfigMonitor::monitor_loop, this);
306
307         std::cout << " Configuration monitor started (checking every "
308             << check_interval_.count() << "ms)\n";
309     }
310
311     void stop() {
312         if (!running_) return;
313
314         running_ = false;
315         if (monitor_thread_.joinable()) {
316             monitor_thread_.join();
317         }
318
319         std::cout << " Configuration monitor stopped\n";
320     }
321
322 private:
323     void monitor_loop() {
324         while (running_) {
325             config_manager_.reload_if_changed();
326             std::this_thread::sleep_for(check_interval_);
327         }
328     }
329 };
330 /**
331 =====
332 // SECTION 4: Demonstration Application
333 /**
334 =====
335
336 void demonstrate_basic_loading() {
337     std::cout << "\n" << std::string(70, '=') << "\n";
338     std::cout << "==== Demo 1: Basic Configuration Loading ===\n";
339     std::cout << std::string(70, '=') << "\n\n";
340
341     ConfigManager config("../config.json");
342
343     std::cout << "Loading initial configuration...\n";
344     if (config.load()) {
```

```
344     config.display();
345
346     // Access individual values
347     std::cout << "Accessing specific values:\n";
348     std::cout << "    server_host: " << config.get("server_host", "not found"
349             " ") << "\n";
350     std::cout << "    server_port: " << config.get("server_port", "not found"
351             " ") << "\n";
352     std::cout << "    debug_mode: " << config.get("debug_mode", "not found")
353             " << "\n";
354     std::cout << "    max_connections: " << config.get("max_connections", " "
355             "not found") << "\n";
356
357     // Check if keys exist
358     std::cout << "\nKey existence checks:\n";
359     std::cout << "    has 'server_host': " << (config.has_key("server_host")
360             ? "Yes" : "No") << "\n";
361     std::cout << "    has 'nonexistent': " << (config.has_key("nonexistent")
362             ? "Yes" : "No") << "\n";
363
364     // Get all keys
365     std::cout << "\nAll keys: ";
366     auto keys = config.get_all_keys();
367     for (size_t i = 0; i < keys.size(); ++i) {
368         std::cout << keys[i];
369         if (i < keys.size() - 1) std::cout << ", ";
370     }
371     std::cout << "\n";
372 }
373
374 void demonstrate_live_monitoring() {
375     std::cout << "\n" << std::string(70, '=') << "\n";
376     std::cout << "==== Demo 2: Live Configuration Monitoring ===\n";
377     std::cout << std::string(70, '=') << "\n\n";
378
379     ConfigManager config("../config.json");
380     std::cout << "    Reading config from: " << fs::absolute("../config.json")
381             << "\n\n";
382     config.load();
383     config.display();
384
385     // Start monitoring in background - use 10 seconds for demo (production:
386     // 10 minutes)
387     ConfigMonitor monitor(config, 10000ms); // Check every 10 seconds for
388     // demo
389     monitor.start();
390
391     // Read demoTime from config (default to 120 seconds)
392     int demo_time = 120;
393     std::string demo_time_str = config.get("demoTime");
394     if (!demo_time_str.empty()) {
395         try {
396             demo_time = std::stoi(demo_time_str);
397         }
```

```
389         std::cout << " Using demoTime from config: " << demo_time << "
390             seconds\n";
391     } catch (...) {
392         std::cout << " Invalid demoTime in config, using default: 120
393             seconds\n";
394     }
395
396     std::cout << "\n Instructions:\n";
397     std::cout << " 1. Edit config.json file while this program is running\n";
398     std::cout << " 2. Add new key-value pairs: \"new_key\": \"new_value\"\n";
399     std::cout << " 3. Modify existing values: \"server_port\": \"9090\"\n";
400     std::cout << " 4. Add arrays: \"allowed_ips\": [\"192.168.1.1\",
401             \"10.0.0.1\"]\n";
402     std::cout << " 5. Change \"demoTime\": 60 to adjust monitoring duration
403             dynamically\n";
404     std::cout << " 6. Save the file and watch for automatic reload!\n";
405     std::cout << "\n App will run for " << demo_time << " seconds (checks
406             config every 10 seconds)...\n";
407     std::cout << " (In production: use 10 minutes / 600000ms)\n\n";
408
409 // Simulate application running and accessing config
410 int elapsed = 0;
411 while (elapsed < demo_time) {
412     std::this_thread::sleep_for(1s);
413     elapsed++;
414
415     // Periodically show current config version
416     if (elapsed % 10 == 0) {
417         std::cout << " " << elapsed << "s - Config version: " << config.
418             get_version()
419                 << " | Entries: " << config.size();
420
421     // Check if demoTime has changed
422     std::string current_demo_time_str = config.get("demoTime");
423     if (!current_demo_time_str.empty()) {
424         try {
425             int new_demo_time = std::stoi(current_demo_time_str);
426             if (new_demo_time != demo_time) {
427                 std::cout << " | demoTime changed: " << demo_time << "
428                     →" << new_demo_time << "s";
429                 demo_time = new_demo_time;
430                 std::cout << "\n Runtime adjusted! Will now run until
431                     " << demo_time << " seconds\n";
432             } else {
433                 std::cout << "\n";
434             }
435         } catch (...) {
436             std::cout << "\n";
437         }
438     } else {
439         std::cout << "\n";
440     }
441 }
```

```
435     }
436
437     monitor.stop();
438
439     std::cout << "\nFinal configuration state:\n";
440     config.display();
441 }
442
443 void demonstrate_error_handling() {
444     std::cout << "\n" << std::string(70, '=') << "\n";
445     std::cout << "==== Demo 3: Error Handling ===\n";
446     std::cout << std::string(70, '=') << "\n\n";
447
448     // Test with non-existent file
449     std::cout << "1. Loading non-existent file:\n";
450     ConfigManager config1("nonexistent.json");
451     config1.load();
452
453     // Test with invalid JSON
454     std::cout << "\n2. Creating and loading invalid JSON:\n";
455     std::ofstream bad_file("bad_config.json");
456     bad_file << "{ invalid json without quotes }";
457     bad_file.close();
458
459     ConfigManager config2("bad_config.json");
460     config2.load();
461
462     // Cleanup
463     fs::remove("bad_config.json");
464
465     std::cout << "\n Error handling demonstrated\n";
466     std::cout << " • File not found: gracefully handled\n";
467     std::cout << " • Invalid JSON: exception caught and reported\n";
468 }
469
470 void demonstrate_multimap_features() {
471     std::cout << "\n" << std::string(70, '=') << "\n";
472     std::cout << "==== Demo 4: unordered_multimap Features ===\n";
473     std::cout << std::string(70, '=') << "\n\n";
474
475     std::cout << "Concept: unordered_multimap allows multiple values per key\n";
476     std::cout << "Use case: Configuration with arrays or multiple values\n\n";
477
478     std::cout << "Example JSON (if extended):\n";
479     std::cout << R"({
480         "server": "localhost",
481         "allowed_ip": "192.168.1.1",
482         "allowed_ip": "192.168.1.2",
483         "allowed_ip": "10.0.0.1"
484     })" << "\n\n";
485
486     std::cout << "With unordered_multimap, you can store multiple 'allowed_ip' values\n";
```

```
487     std::cout << "and retrieve them all using get_all('allowed_ip')\n\n";
488
489     std::cout << "Current implementation: Simple key-value pairs\n";
490     std::cout << "If duplicate keys in JSON: last one wins (map behavior)\n";
491     std::cout << "To enable true multimap: parse JSON arrays into separate
492         entries\n\n";
493
494     ConfigManager config("../config.json");
495     config.load();
496
497     std::cout << "Accessing all values for a key:\n";
498     auto values = config.get_all("server_host");
499     std::cout << "'server_host' has " << values.size() << " value(s):\n";
500     for (const auto& val : values) {
501         std::cout << "    - " << val << "\n";
502     }
503
504 void create_sample_config_if_not_exists() {
505     if (!fs::exists("config.json")) {
506         std::cout << " Creating sample config.json...\n";
507         std::ofstream config_file("config.json");
508         config_file << R"({
509             \"server_host\": \"localhost\",
510             \"server_port\": \"8080\",
511             \"debug_mode\": \"true\",
512             \"max_connections\": \"100\",
513             \"timeout_seconds\": \"30\",
514             \"database_url\": \"mongodb://localhost:27017\""
515         })";
516         config_file.close();
517         std::cout << " Sample config.json created\n\n";
518     }
519 }
520
521 // =====
522 // SECTION 5: Best Practices Guide
523 // =====
524
525 void show_best_practices() {
526     std::cout << "\n" << std::string(70, '=') << "\n";
527     std::cout << "==== Configuration Management Best Practices ===\n";
528     std::cout << std::string(70, '=') << "\n\n";
529
530     std::cout << " DESIGN PATTERNS:\n";
531     std::cout << " 1. Singleton pattern for global config access\n";
532     std::cout << " 2. Observer pattern for change notifications\n";
533     std::cout << " 3. Strategy pattern for different config sources\n";
534     std::cout << " 4. Builder pattern for complex configurations\n\n";
535 }
```

```
536     std::cout << " THREAD SAFETY:\n";
537     std::cout << "   1. Use std::mutex for protecting config access\n";
538     std::cout << "   2. std::shared_mutex for read-write locks (C++17)\n";
539     std::cout << "   3. std::atomic for version counters\n";
540     std::cout << "   4. Lock-free structures for high-performance\n\n";
541
542     std::cout << " FILE MONITORING:\n";
543     std::cout << "   1. Check file modification time (fs::last_write_time)\n";
544     std::cout << "   2. Use inotify (Linux) / ReadDirectoryChangesW (Windows)\n";
545     std::cout << "   ";
546     std::cout << "   3. Background thread with periodic checks\n";
547     std::cout << "   4. Debounce rapid changes (wait for settle)\n\n";
548
549     std::cout << " ERROR HANDLING:\n";
550     std::cout << "   1. Validate JSON syntax before parsing\n";
551     std::cout << "   2. Keep previous valid config on parse errors\n";
552     std::cout << "   3. Log all config changes and errors\n";
553     std::cout << "   4. Provide default values for missing keys\n\n";
554
555     std::cout << " PERFORMANCE:\n";
556     std::cout << "   1. Cache frequently accessed values\n";
557     std::cout << "   2. Use unordered_map for O(1) lookups\n";
558     std::cout << "   3. Minimize file I/O (check timestamp first)\n";
559     std::cout << "   4. Parse JSON incrementally for large files\n\n";
560
561     std::cout << " PRODUCTION CONSIDERATIONS:\n";
562     std::cout << "   1. Support multiple config sources (file, env, CLI)\n";
563     std::cout << "   2. Implement config versioning and rollback\n";
564     std::cout << "   3. Add config validation (schemas, constraints)\n";
565     std::cout << "   4. Enable hot-reload without service restart\n";
566     std::cout << "   5. Using nlohmann/json library (header-only, modern C++)\n";
567     std::cout << "   ";
568     std::cout << "   6. Implement config encryption for sensitive data\n";
569     std::cout << "   7. Set appropriate monitoring interval (10 min for\n";
570     std::cout << "       production)\n\n";
571 }
572 // =====
573 // MAIN FUNCTION
574 // =====
575
576 int main() {
577     std::cout << "\n";
578     std::cout << "                               \n";
579     std::cout << " Configuration Loader and Live Monitor\n";
580     std::cout << "                               \n";
581     std::cout << " Using std::unordered_multimap + File Watching\n";
582     std::cout << "                               \n";
583     std::cout << "                               \n";
```

```
581 // Create sample config if it doesn't exist
582 create_sample_config_if_not_exists();
583
584 // Run demonstrations
585 demonstrate_basic_loading();
586 demonstrate_multimap_features();
587 demonstrate_error_handling();
588
589 // Interactive monitoring demo
590 std::cout << "\n" << std::string(70, '=') << "\n";
591 std::cout << "Would you like to run the live monitoring demo? (y/n): ";
592 char choice;
593 std::cin >> choice;
594
595 if (choice == 'y' || choice == 'Y') {
596     demonstrate_live_monitoring();
597 } else {
598     std::cout << "\nSkipping live monitoring demo.\n";
599     std::cout << "To test manually:\n";
600     std::cout << " 1. Run this program\n";
601     std::cout << " 2. In another terminal: echo '{\"test\": \"value\"}' >
602         config.json\n";
603     std::cout << " 3. Watch the program detect changes!\n";
604 }
605
606 show_best_practices();
607
608 std::cout << "\n" << std::string(70, '=') << "\n";
609 std::cout << "All demonstrations completed!\n";
610 std::cout << "\nKEY FEATURES DEMONSTRATED:\n";
611 std::cout << "    std::unordered_multimap for config storage\n";
612 std::cout << "    JSON parsing and validation\n";
613 std::cout << "    File modification detection\n";
614 std::cout << "    Automatic config reloading\n";
615 std::cout << "    Thread-safe access with std::mutex\n";
616 std::cout << "    Background monitoring thread\n";
617 std::cout << "    Error handling and recovery\n";
618 std::cout << std::string(70, '=') << "\n\n";
619
620 return 0;
}
```

11 Source Code: Cpp11Examples.cpp

File: src/Cpp11Examples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <memory>
5 #include <thread>
6 #include <chrono>
7 #include <tuple>
8 #include <array>
9 #include <unordered_map>
10 #include <functional>
11 #include <algorithm>
12 #include <numeric>
13 #include <type_traits>
14
15 // =====
16 // C++11 COMPREHENSIVE EXAMPLES
17 // =====
18
19 // =====
20 // 1. AUTO TYPE DEDUCTION
21 // =====
22 void example_auto() {
23     std::cout << "\n== 1. AUTO TYPE DEDUCTION ==" << std::endl;
24
25     auto a = 42;           // int
26     auto b = 3.14;         // double
27     auto c = "hello";      // const char*
28     auto d = std::string("world"); // std::string
29
30     std::vector<int> vec = {1, 2, 3};
31     auto it = vec.begin(); // std::vector<int>::iterator
32
33     std::cout << "auto deduced types: int, double, const char*, std::string"
34             << std::endl;
35 }
36
37 // =====
38 // 2. NULLPTR
39 // =====
40 void foo(int) { std::cout << "Called foo(int)" << std::endl; }
41 void foo(int*) { std::cout << "Called foo(int*)" << std::endl; }
42
43 void example_nullptr() {
44     std::cout << "\n== 2. NULLPTR ==" << std::endl;
45
46     int* ptr = nullptr;
47     foo(nullptr); // Calls foo(int*)
48     std::cout << "nullptr is " << (ptr == nullptr ? "null" : "not null") <<
49         std::endl;
```

```
48 }
49
50 // =====
51 // 3. RANGE-BASED FOR LOOPS
52 // =====
53 void example_range_for() {
54     std::cout << "\n==== 3. RANGE-BASED FOR LOOPS ===" << std::endl;
55
56     std::vector<int> vec = {1, 2, 3, 4, 5};
57     std::cout << "Elements: ";
58     for (const auto& elem : vec) {
59         std::cout << elem << " ";
60     }
61     std::cout << std::endl;
62 }
63
64 // =====
65 // 4. LAMBDA EXPRESSIONS
66 // =====
67 void example_lambdas() {
68     std::cout << "\n==== 4. LAMBDA EXPRESSIONS ===" << std::endl;
69
70     int x = 10;
71     auto add_x = [x](int y) { return x + y; };
72     std::cout << "Lambda add_x(5) = " << add_x(5) << std::endl;
73
74     auto square = [] (int n) { return n * n; };
75     std::cout << "Lambda square(7) = " << square(7) << std::endl;
76
77     std::vector<int> vec = {1, 2, 3, 4, 5};
78     int sum = 0;
79     std::for_each(vec.begin(), vec.end(), [&sum](int n) { sum += n; });
80     std::cout << "Sum using lambda: " << sum << std::endl;
81 }
82
83 // =====
84 // 5. RVALUE REFERENCES AND MOVE SEMANTICS
85 // =====
86 class MoveableResource {
87 private:
88     int* data;
89     size_t size;
90 public:
91     MoveableResource(size_t s) : size(s) {
92         data = new int[size];
93         std::cout << "Allocated resource of size " << size << std::endl;
94     }
95
96     ~MoveableResource() {
97         delete[] data;
98     }
99
100    // Move constructor
101    MoveableResource(MoveableResource&& other) noexcept
```

```
102     : data(other.data), size(other.size) {
103     other.data = nullptr;
104     other.size = 0;
105     std::cout << "Moved resource" << std::endl;
106 }
107
108 // Move assignment
109 MoveableResource& operator=(MoveableResource&& other) noexcept {
110     if (this != &other) {
111         delete [] data;
112         data = other.data;
113         size = other.size;
114         other.data = nullptr;
115         other.size = 0;
116     }
117     return *this;
118 }
119 };
120
121 void example_move_semantics() {
122     std::cout << "\n== 5. MOVE SEMANTICS ==" << std::endl;
123
124     MoveableResource res1(100);
125     MoveableResource res2 = std::move(res1); // Move constructor
126 }
127
128 // =====
129 // 6. VARIADIC TEMPLATES
130 // =====
131 template <typename... Args>
132 void print_args(Args... args) {
133     (void)std::initializer_list<int>{
134         (std::cout << args << " ", 0)...
135     };
136     std::cout << std::endl;
137 }
138
139 template <typename... T>
140 struct arity {
141     static constexpr int value = sizeof...(T);
142 };
143
144 void example_variadic_templates() {
145     std::cout << "\n== 6. VARIADIC TEMPLATES ==" << std::endl;
146
147     print_args(1, "hello", 3.14, "world");
148     std::cout << "arity<int, double, char>::value = "
149             << arity<int, double, char>::value << std::endl;
150 }
151
152 // =====
153 // 7. STRONGLY-TYPED ENUMS
154 // =====
155 enum class Color { Red, Green, Blue };
```

```
156 enum class Traffic { Red, Yellow, Green }; // No conflict!
157
158 void example_strongly_typedEnums() {
159     std::cout << "\n== 7. STRONGLY-TYPED ENUMS ==" << std::endl;
160
161     Color c = Color::Red;
162     Traffic t = Traffic::Red;
163
164     // Color and Traffic::Red don't conflict
165     std::cout << "Strongly-typed enums prevent naming conflicts" << std::endl;
166 }
167
168 // =====
169 // 8. INITIALIZER LISTS
170 // =====
171 int sum_list(const std::initializer_list<int>& list) {
172     int total = 0;
173     for (auto elem : list) {
174         total += elem;
175     }
176     return total;
177 }
178
179 void example_initializer_lists() {
180     std::cout << "\n== 8. INITIALIZER LISTS ==" << std::endl;
181
182     std::vector<int> vec = {1, 2, 3, 4, 5};
183     std::cout << "Vector initialized with {1, 2, 3, 4, 5}" << std::endl;
184     std::cout << "sum_list({10, 20, 30}) = " << sum_list({10, 20, 30}) << std
185         ::endl;
186 }
187
188 // =====
189 // 9. DECLTYPE
190 // =====
191 template <typename X, typename Y>
192 auto multiply(X x, Y y) -> decltype(x * y) {
193     return x * y;
194 }
195
196 void example_decltype() {
197     std::cout << "\n== 9. DECLTYPE ==" << std::endl;
198
199     int a = 5;
200     decltype(a) b = 10; // b is int
201
202     std::cout << "multiply(3, 4) = " << multiply(3, 4) << std::endl;
203     std::cout << "multiply(2.5, 4) = " << multiply(2.5, 4) << std::endl;
204 }
205
206 // =====
207 // 10. TYPE ALIASES
208 // =====
209 template <typename T>
```

```
209 using Vec = std::vector<T>;
210
211 using String = std::string;
212
213 void example_type_aliases() {
214     std::cout << "\n==> 10. TYPE ALIASES ==>" << std::endl;
215
216     Vec<int> numbers = {1, 2, 3};
217     String text = "Hello";
218
219     std::cout << "Vec<int> and String aliases work" << std::endl;
220 }
221
222 // =====
223 // 11. CONSTEXPR
224 // =====
225 constexpr int factorial(int n) {
226     return n <= 1 ? 1 : n * factorial(n - 1);
227 }
228
229 constexpr int square(int n) {
230     return n * n;
231 }
232
233 void example_constexpr() {
234     std::cout << "\n==> 11. CONSTEXPR ==>" << std::endl;
235
236     constexpr int fact5 = factorial(5);
237     constexpr int sq7 = square(7);
238
239     std::cout << "constexpr factorial(5) = " << fact5 << std::endl;
240     std::cout << "constexpr square(7) = " << sq7 << std::endl;
241 }
242
243 // =====
244 // 12. STATIC ASSERTIONS
245 // =====
246 void example_static_assert() {
247     std::cout << "\n==> 12. STATIC ASSERTIONS ==>" << std::endl;
248
249     static_assert(sizeof(int) >= 4, "int must be at least 4 bytes");
250     static_assert(sizeof(char) == 1, "char must be 1 byte");
251
252     std::cout << "Static assertions passed" << std::endl;
253 }
254
255 // =====
256 // 13. DELEGATING CONSTRUCTORS
257 // =====
258 class Rectangle {
259 private:
260     int width, height;
261 public:
262     Rectangle() : Rectangle(0, 0) {} // Delegate to another constructor
```

```
263     Rectangle(int w) : Rectangle(w, w) {} // Delegate
264     Rectangle(int w, int h) : width(w), height(h) {
265         std::cout << "Rectangle(" << width << ", " << height << ")" << std::endl;
266     }
267 };
268
269 void example_delegating_constructors() {
270     std::cout << "\n== 13. DELEGATING CONSTRUCTORS ==" << std::endl;
271
272     Rectangle r1;
273     Rectangle r2(10);
274     Rectangle r3(5, 8);
275 }
276
277 // =====
278 // 14. DEFAULT AND DELETE
279 // =====
280 class NonCopyable {
281 public:
282     NonCopyable() = default;
283     NonCopyable(const NonCopyable&) = delete;
284     NonCopyable& operator=(const NonCopyable&) = delete;
285 };
286
287 void example_default_delete() {
288     std::cout << "\n== 14. DEFAULT AND DELETE ==" << std::endl;
289
290     NonCopyable obj1;
291     // NonCopyable obj2 = obj1; // Error: copy constructor deleted
292
293     std::cout << "Non-copyable class works" << std::endl;
294 }
295
296 // =====
297 // 15. OVERRIDE AND FINAL
298 // =====
299 class Base {
300 public:
301     virtual void foo() { std::cout << "Base::foo()" << std::endl; }
302     virtual ~Base() = default;
303 };
304
305 class Derived final : public Base {
306 public:
307     void foo() override { std::cout << "Derived::foo()" << std::endl; }
308 };
309
310 void example_override_final() {
311     std::cout << "\n== 15. OVERRIDE AND FINAL ==" << std::endl;
312
313     std::unique_ptr<Base> ptr(new Derived());
314     ptr->foo();
315 }
```

```
316 // =====
317 // 16. SMART POINTERS
318 // =====
319 void example_smart_pointers() {
320     std::cout << "\n==== 16. SMART POINTERS ===" << std::endl;
321
322     // unique_ptr
323     std::unique_ptr<int> uptr(new int(42));
324     std::cout << "*uptr = " << *uptr << std::endl;
325
326     // shared_ptr
327     std::shared_ptr<int> sptr1 = std::make_shared<int>(100);
328     std::shared_ptr<int> sptr2 = sptr1;
329     std::cout << "shared_ptr count: " << sptr1.use_count() << std::endl;
330
331     // weak_ptr
332     std::weak_ptr<int> wptr = sptr1;
333     std::cout << "weak_ptr valid: " << !wptr.expired() << std::endl;
334 }
335
336 // =====
337 // 17. TUPLES
338 // =====
339 void example_tuples() {
340     std::cout << "\n==== 17. TUPLES ===" << std::endl;
341
342     std::tuple<int, std::string, double> tup{42, "hello", 3.14};
343
344     std::cout << "Tuple element 0: " << std::get<0>(tup) << std::endl;
345     std::cout << "Tuple element 1: " << std::get<1>(tup) << std::endl;
346     std::cout << "Tuple element 2: " << std::get<2>(tup) << std::endl;
347
348     int a;
349     std::string b;
350     double c;
351     std::tie(a, b, c) = tup;
352     std::cout << "Using tie: " << a << ", " << b << ", " << c << std::endl;
353 }
354
355 // =====
356 // 18. STD::ARRAY
357 // =====
358 void example_array() {
359     std::cout << "\n==== 18. STD::ARRAY ===" << std::endl;
360
361     std::array<int, 5> arr = {1, 2, 3, 4, 5};
362
363     std::cout << "Array size: " << arr.size() << std::endl;
364     std::cout << "Array elements: ";
365     for (const auto& elem : arr) {
366         std::cout << elem << " ";
367     }
368     std::cout << std::endl;
369 }
```

```
370 }
371
372 // =====
373 // 19. UNORDERED CONTAINERS
374 // =====
375 void example_unordered_containers() {
376     std::cout << "\n== 19. UNORDERED CONTAINERS ==" << std::endl;
377
378     std::unordered_map<std::string, int> map;
379     map["one"] = 1;
380     map["two"] = 2;
381     map["three"] = 3;
382
383     std::cout << "Unordered map: ";
384     for (const auto& pair : map) {
385         std::cout << pair.first << "=" << pair.second << " ";
386     }
387     std::cout << std::endl;
388 }
389
390 // =====
391 // 20. STD::THREAD
392 // =====
393 void thread_function(int n) {
394     std::cout << "Thread " << n << " running" << std::endl;
395 }
396
397 void example_threads() {
398     std::cout << "\n== 20. STD::THREAD ==" << std::endl;
399
400     std::thread t1(thread_function, 1);
401     std::thread t2(thread_function, 2);
402
403     t1.join();
404     t2.join();
405
406     std::cout << "Threads completed" << std::endl;
407 }
408
409 // =====
410 // 21. CHRONO
411 // =====
412 void example_chrono() {
413     std::cout << "\n== 21. STD::CHRONO ==" << std::endl;
414
415     auto start = std::chrono::high_resolution_clock::now();
416
417     // Do some work
418     std::this_thread::sleep_for(std::chrono::milliseconds(100));
419
420     auto end = std::chrono::high_resolution_clock::now();
421     auto duration = std::chrono::duration_cast<std::chrono::milliseconds>(end
422         - start);
```

```
423     std::cout << "Duration: " << duration.count() << " ms" << std::endl;
424 }
425
426 // =====
427 // 22. RAW STRING LITERALS
428 // =====
429 void example_raw_strings() {
430     std::cout << "\n==> 22. RAW STRING LITERALS ==>" << std::endl;
431
432     std::string normal = "Line 1\\nLine 2\\nLine 3";
433     std::string raw = R"(Line 1
434 Line 2
435 Line 3)";
436
437     std::cout << "Raw string with newlines preserved" << std::endl;
438 }
439
440 // =====
441 // 23. ATTRIBUTES
442 // =====
443 [[noreturn]] void terminate_program() {
444     std::exit(0);
445 }
446
447 void example_attributes() {
448     std::cout << "\n==> 23. ATTRIBUTES ==>" << std::endl;
449
450     std::cout << "[[noreturn]] attribute available" << std::endl;
451 }
452
453 // =====
454 // MAIN FUNCTION
455 // =====
456 int main() {
457     std::cout << "\n====="
458         << std::endl;
459     std::cout << "      C++11 FEATURES COMPREHENSIVE EXAMPLES" << std::endl;
460     std::cout << "====="
461         << std::endl;
462
463     example_auto();
464     example_nullptr();
465     example_range_for();
466     example_lambdas();
467     example_move_semantics();
468     example_variadic_templates();
469     example_strongly_typedEnums();
470     example_initializer_lists();
471     example_decltype();
472     example_type_aliases();
473     example_constexpr();
474     example_static_assert();
475     example_delegating_constructors();
476     example_default_delete();
```

```
475     example_override_final();
476     example_smart_pointers();
477     example_tuples();
478     example_array();
479     example_unordered_containers();
480     example_threads();
481     example_chrono();
482     example_raw_strings();
483     example_attributes();
484
485     std::cout << "\n======" << std::
486         endl;
487     std::cout << "      ALL C++11 EXAMPLES COMPLETED" << std::endl;
488     std::cout << "=====\\n" << std::
489         endl;
490
491     return 0;
492 }
```

12 Source Code: Cpp14Examples.cpp

File: src/Cpp14Examples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <memory>
5 #include <algorithm>
6 #include <utility>
7
8 // =====
9 // C++14 LANGUAGE FEATURES
10 // =====
11
12 // =====
13 // 1. BINARY LITERALS
14 // =====
15 void example_binary_literals() {
16     std::cout << "\n==== 1. BINARY LITERALS ===" << std::endl;
17
18     int a = 0b110;           // Binary literal
19     int b = 0b1111'1111;    // Binary with digit separator
20     int c = 0b1010'0101'1100; // Larger binary number
21
22     std::cout << "0b110 = " << a << std::endl;
23     std::cout << "0b1111'1111 = " << b << std::endl;
24     std::cout << "0b1010'0101'1100 = " << c << std::endl;
25 }
26
27 // =====
28 // 2. GENERIC LAMBDA EXPRESSIONS
29 // =====
30 void example_generic_lambdas() {
31     std::cout << "\n==== 2. GENERIC LAMBDA EXPRESSIONS ===" << std::endl;
32
33     auto identity = [] (auto x) { return x; };
34
35     int three = identity(3);
36     std::string foo = identity(std::string("foo"));
37     double pi = identity(3.14);
38
39     std::cout << "Identity(3) = " << three << std::endl;
40     std::cout << "Identity(\"foo\") = " << foo << std::endl;
41     std::cout << "Identity(3.14) = " << pi << std::endl;
42
43     // Generic lambda with multiple parameters
44     auto add = [] (auto a, auto b) { return a + b; };
45     std::cout << "add(10, 20) = " << add(10, 20) << std::endl;
46     std::cout << "add(1.5, 2.5) = " << add(1.5, 2.5) << std::endl;
47 }
48
49 // =====
```

```
50 // 3. LAMBDA CAPTURE INITIALIZERS
51 // =====
52 void example_lambda_capture_initializers() {
53     std::cout << "\n==== 3. LAMBDA CAPTURE INITIALIZERS ===" << std::endl;
54
55     // Initialize capture with expression
56     int factory_value = 2;
57     auto f = [x = factory_value * 10] { return x; };
58     std::cout << "Lambda with initialized capture: " << f() << std::endl;
59
60     // Generator with mutable capture
61     auto generator = [x = 0]() mutable {
62         return x++;
63     };
64     std::cout << "Generator call 1: " << generator() << std::endl;
65     std::cout << "Generator call 2: " << generator() << std::endl;
66     std::cout << "Generator call 3: " << generator() << std::endl;
67
68     // Move-only types in lambda
69     auto ptr = std::make_unique<int>(42);
70     auto task = [p = std::move(ptr)] {
71         std::cout << "Value in lambda: " << *p << std::endl;
72     };
73     task();
74     std::cout << "Original ptr is " << (ptr ? "valid" : "null") << std::endl;
75 }
76
77 // =====
78 // 4. RETURN TYPE DEDUCTION
79 // =====
80 auto multiply(int a, int b) {
81     return a * b; // Return type deduced as int
82 }
83
84 template <typename T>
85 auto add_values(T a, T b) {
86     return a + b; // Return type deduced from expression
87 }
88
89 void example_return_type_deduction() {
90     std::cout << "\n==== 4. RETURN TYPE DEDUCTION ===" << std::endl;
91
92     std::cout << "multiply(5, 6) = " << multiply(5, 6) << std::endl;
93     std::cout << "add_values(10, 20) = " << add_values(10, 20) << std::endl;
94     std::cout << "add_values(1.5, 2.5) = " << add_values(1.5, 2.5) << std::endl;
95
96     // Lambda with auto return type
97     auto square = [](auto x) { return x * x; };
98     std::cout << "square(7) = " << square(7) << std::endl;
99 }
100
101 // =====
102 // 5. DECLTYPE(AUTO)
```

```
103 // =====
104 template <typename Container>
105 decltype(auto) get_first(Container& c) {
106     return c[0]; // Returns reference if c[0] is a reference
107 }
108
109 void example decltype_auto() {
110     std::cout << "\n== 5. DECLTYPE(AUTO) ==" << std::endl;
111
112     const int x = 0;
113     auto x1 = x; // int
114     decltype(auto) x2 = x; // const int
115
116     std::cout << "auto strips const, decltype(auto) preserves it" << std::endl
117         ;
118
119     std::vector<int> vec = {1, 2, 3};
120     decltype(auto) first = get_first(vec);
121     first = 100; // Modifies vec[0]
122     std::cout << "Modified first element: " << vec[0] << std::endl;
123 }
124 // =====
125 // 6. RELAXED CONSTEXPR FUNCTIONS
126 // =====
127 constexpr int factorial(int n) {
128     // C++14 allows multiple statements in constexpr
129     int result = 1;
130     for (int i = 2; i <= n; ++i) {
131         result *= i;
132     }
133     return result;
134 }
135
136 constexpr int fibonacci(int n) {
137     if (n <= 1) return n;
138     int a = 0, b = 1;
139     for (int i = 2; i <= n; ++i) {
140         int temp = a + b;
141         a = b;
142         b = temp;
143     }
144     return b;
145 }
146
147 void example_relaxed_constexpr() {
148     std::cout << "\n== 6. RELAXED CONSTEXPR FUNCTIONS ==" << std::endl;
149
150     constexpr int fact5 = factorial(5);
151     constexpr int fib10 = fibonacci(10);
152
153     std::cout << "factorial(5) = " << fact5 << std::endl;
154     std::cout << "fibonacci(10) = " << fib10 << std::endl;
155 }
```

```
156 // =====
157 // 7. VARIABLE TEMPLATES
158 // =====
159 template <typename T>
160 constexpr T pi = T(3.1415926535897932385);
161
162 template <typename T>
163 constexpr T e = T(2.7182818284590452354);
164
165
166 void example_variable_templates() {
167     std::cout << "\n== 7. VARIABLE TEMPLATES ==" << std::endl;
168
169     std::cout << "pi<float> = " << pi<float> << std::endl;
170     std::cout << "pi<double> = " << pi<double> << std::endl;
171     std::cout << "e<float> = " << e<float> << std::endl;
172     std::cout << "e<double> = " << e<double> << std::endl;
173 }
174
175 // =====
176 // 8. [[DEPRECATED]] ATTRIBUTE
177 // =====
178 [[deprecated("Use new_function() instead")]]
179 void old_function() {
180     std::cout << "This is deprecated!" << std::endl;
181 }
182
183 void new_function() {
184     std::cout << "This is the new function!" << std::endl;
185 }
186
187 void example_deprecated_attribute() {
188     std::cout << "\n== 8. [[DEPRECATED]] ATTRIBUTE ==" << std::endl;
189
190     // old_function(); // Would generate compiler warning
191     new_function();
192     std::cout << "Using new function instead of deprecated one" << std::endl;
193 }
194
195 // =====
196 // C++14 LIBRARY FEATURES
197 // =====
198
199 // =====
200 // 9. USER-DEFINED LITERALS FOR STANDARD LIBRARY
201 // =====
202 void example_user_defined_literals() {
203     std::cout << "\n== 9. USER-DEFINED LITERALS ==" << std::endl;
204
205     using namespace std::string_literals;
206
207     auto str = "Hello"s; // std::string
208
209     std::cout << "String literal type: std::string" << std::endl;
```

```
210     std::cout << "User-defined string literals work in C++14" << std::endl;
211 }
212
213 // =====
214 // 10. STD::MAKE_UNIQUE
215 // =====
216 void example_make_unique() {
217     std::cout << "\n==> 10. STD::MAKE_UNIQUE ==>" << std::endl;
218
219     auto ptr1 = std::make_unique<int>(42);
220     auto ptr2 = std::make_unique<std::string>("Hello");
221     auto ptr3 = std::make_unique<std::vector<int>>(5, 10);
222
223     std::cout << "*ptr1 = " << *ptr1 << std::endl;
224     std::cout << "*ptr2 = " << *ptr2 << std::endl;
225     std::cout << "ptr3 size = " << ptr3->size() << std::endl;
226
227     // Array version
228     auto arr = std::make_unique<int []>(5);
229     for (int i = 0; i < 5; ++i) {
230         arr[i] = i * 10;
231     }
232     std::cout << "Array elements: ";
233     for (int i = 0; i < 5; ++i) {
234         std::cout << arr[i] << " ";
235     }
236     std::cout << std::endl;
237 }
238
239 // =====
240 // 11. COMPILE-TIME INTEGER SEQUENCES
241 // =====
242 template <typename T, T... Ints>
243 void print_sequence(std::integer_sequence<T, Ints...>) {
244     std::cout << "Sequence: ";
245     int dummy[] = {0, (std::cout << Ints << " ", 0)...};
246     (void)dummy;
247     std::cout << std::endl;
248 }
249
250 void example_integer_sequences() {
251     std::cout << "\n==> 11. COMPILE-TIME INTEGER SEQUENCES ==>" << std::endl;
252
253     using Seq = std::integer_sequence<int, 0, 1, 2, 3, 4>;
254     using IdxSeq = std::make_index_sequence<5>;
255
256     std::cout << "Integer sequence example (needs C++17 fold for printing)" <<
257             std::endl;
258     std::cout << "std::make_index_sequence<5> creates indices 0,1,2,3,4" <<
259             std::endl;
260 }
261
262 // =====
263 // 12. DIGIT SEPARATORS
```

```
262 // =====
263 void example_digit_separators() {
264     std::cout << "\n==== 12. DIGIT SEPARATORS ===" << std::endl;
265
266     int decimal = 1'000'000;
267     int hex = 0xDEAD'BEEF;
268     int binary = 0b1010'1010'1010;
269     double floating = 3.141'592'653'589;
270
271     std::cout << "1'000'000 = " << decimal << std::endl;
272     std::cout << "0xDEAD'BEEF = " << hex << std::endl;
273     std::cout << "0b1010'1010'1010 = " << binary << std::endl;
274     std::cout << "3.141'592'653'589 = " << floating << std::endl;
275 }
276
277 // =====
278 // MAIN FUNCTION
279 // =====
280 int main() {
281     std::cout << "\n===== C++14 FEATURES COMPREHENSIVE EXAMPLES =====" << std::endl;
282     std::cout << "===== ALL C++14 EXAMPLES COMPLETED =====\n" << std::endl;
283
284     // Language Features
285     example_binary_literals();
286     example_generic_lambdas();
287     example_lambda_capture_initializers();
288     example_return_type_deduction();
289     example_decltype_auto();
290     example_relaxed_constexpr();
291     example_variable_templates();
292     example_DEPRECATED_attribute();
293
294     // Library Features
295     example_user_defined_literals();
296     example_make_unique();
297     example_integer_sequences();
298     example_digit_separators();
299
300     std::cout << "\n===== ALL C++14 EXAMPLES COMPLETED =====\n" << std::endl;
301     std::cout << "===== ALL C++14 EXAMPLES COMPLETED =====\n" << std::endl;
302     std::cout << "===== ALL C++14 EXAMPLES COMPLETED =====\n" << std::endl;
303
304     return 0;
305 }
```

13 Source Code: Cpp17Concurrency.cpp

File: src/Cpp17Concurrency.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <future>
3 #include <thread>
4 #include <chrono>
5 #include <vector>
6 #include <numeric>
7 #include <algorithm>
8 #include <string>
9 #include <random>
10 #include <mutex>
11 #include <queue>
12 #include <condition_variable>
13 #include <atomic>
14 #include <type_traits>
15 #include <variant>
16 #include <optional>
17 #include <any>
18 #include <tuple>
19 #include <filesystem>
20 #include <sstream>
21 #include <fstream>
22 #include <map>
23 #include <array>
24 #include <functional>
25
26 using namespace std;
27 using namespace std::chrono;
28 using namespace std::chrono_literals;
29
30 // =====
31 // 1. BASIC FUTURE/PROMISE
32 // =====
33 void example_basic_future_promise() {
34     cout << "\n== 1. BASIC FUTURE/PROMISE ==" << endl;
35
36     promise<int> promise_obj;
37     future<int> future_obj = promise_obj.get_future();
38
39     thread t([&promise_obj]() {
40         cout << " Thread: Doing some computation..." << endl;
41         this_thread::sleep_for(1s);
42
43         int result = 42;
44         cout << " Thread: Setting promise value: " << result << endl;
45         promise_obj.set_value(result);
46     });
47
48     cout << "Main: Waiting for result..." << endl;
49     int result = future_obj.get();
```

```
50     cout << "Main: Got result: " << result << endl;
51
52     t.join();
53 }
54
55 // =====
56 // 2. FUTURE WITH EXCEPTION
57 // =====
58 void example_future_exception() {
59     cout << "\n== 2. FUTURE WITH EXCEPTION ==" << endl;
60
61     promise<int> promise_obj;
62     future<int> future_obj = promise_obj.get_future();
63
64     thread t([&promise_obj]() {
65         try {
66             cout << " Thread: Simulating error..." << endl;
67             throw runtime_error("Something went wrong!");
68         }
69         catch (...) {
70             promise_obj.set_exception(current_exception());
71         }
72     });
73
74     try {
75         cout << "Main: Waiting for result..." << endl;
76         int result = future_obj.get();
77         cout << "Main: Got result: " << result << endl;
78     }
79     catch (const exception& e) {
80         cout << "Main: Caught exception: " << e.what() << endl;
81     }
82
83     t.join();
84 }
85
86 // =====
87 // 3. ASYNC (HIGH-LEVEL FUTURE)
88 // =====
89 void example_async() {
90     cout << "\n== 3. ASYNC (HIGH-LEVEL FUTURE) ==" << endl;
91
92     auto future1 = async(launch::async, []() {
93         cout << " Async task 1 running..." << endl;
94         this_thread::sleep_for(500ms);
95         return 42;
96     });
97
98     auto future2 = async(launch::async, []() {
99         cout << " Async task 2 running..." << endl;
100        this_thread::sleep_for(300ms);
101        return 100;
102    });
103 }
```

```

104     auto future3 = async(launch::deferred, []() {
105         cout << "  Deferred task running..." << endl;
106         return 200;
107     });
108
109     cout << "Main: Doing other work..." << endl;
110     this_thread::sleep_for(100ms);
111
112     cout << "Result 1: " << future1.get() << endl;
113     cout << "Result 2: " << future2.get() << endl;
114     cout << "Result 3 (deferred): " << future3.get() << endl;
115 }
116
117 // =====
118 // 4. SHARED FUTURE (MULTIPLE WAITERS)
119 // =====
120 void example_shared_future() {
121     cout << "\n==== 4. SHARED FUTURE (MULTIPLE WAITERS) ===" << endl;
122
123     promise<int> promise_obj;
124     future<int> future_obj = promise_obj.get_future();
125     shared_future<int> shared_future_obj = future_obj.share();
126
127     vector<thread> threads;
128     for (int i = 0; i < 3; i++) {
129         threads.emplace_back([i, shared_future_obj]() {
130             cout << "  Thread " << i << ": Waiting for result..." << endl;
131             int result = shared_future_obj.get();
132             cout << "  Thread " << i << ": Got result: " << result << endl;
133         });
134     }
135
136     thread producer([&promise_obj]() {
137         this_thread::sleep_for(1s);
138         cout << "  Producer: Setting value to 999" << endl;
139         promise_obj.set_value(999);
140     });
141
142     for (auto& t : threads) t.join();
143     producer.join();
144 }
145
146 // =====
147 // 5. FUTURE WITH TIMEOUT
148 // =====
149 void example_future_timeout() {
150     cout << "\n==== 5. FUTURE WITH TIMEOUT ===" << endl;
151
152     promise<int> promise_obj;
153     future<int> future_obj = promise_obj.get_future();
154
155     thread slow_worker([&promise_obj]() {
156         cout << "  Slow worker: Starting (3 seconds)" << endl;
157         this_thread::sleep_for(3s);

```

```
158     promise_obj.set_value(42);
159     cout << " Slow worker: Finished" << endl;
160 };
161
162 cout << "Main: Waiting with timeout (2 seconds)..." << endl;
163
164 future_status status = future_obj.wait_for(2s);
165
166 if (status == future_status::ready) {
167     cout << "Main: Got result: " << future_obj.get() << endl;
168 }
169 else if (status == future_status::timeout) {
170     cout << "Main: Timeout! Task not ready yet" << endl;
171 }
172
173 this_thread::sleep_for(2s);
174 if (slow_worker.joinable()) {
175     if (future_obj.wait_for(0s) == future_status::ready) {
176         cout << "Main: Finally got result: " << future_obj.get() << endl;
177     }
178     slow_worker.join();
179 }
180
181 // =====
182 // 6. PACKAGED TASK
183 // =====
184
185 void example_packaged_task() {
186     cout << "\n== 6. PACKAGED TASK ==" << endl;
187
188     packaged_task<int(int, int)> task([](int a, int b) {
189         cout << " Task executing with " << a << " and " << b << endl;
190         this_thread::sleep_for(500ms);
191         return a + b;
192     });
193
194     future<int> result = task.get_future();
195
196     thread t(move(task), 10, 20);
197
198     cout << "Main: Waiting for packaged task result..." << endl;
199     cout << "Result: " << result.get() << endl;
200
201     t.join();
202 }
203
204 // =====
205 // 7. ASYNC PARALLEL COMPUTATION
206 // =====
207
208 void example_parallel_computation() {
209     cout << "\n== 7. ASYNC PARALLEL COMPUTATION ==" << endl;
210
211     auto compute_chunk = [](int start, int end) {
212         long long sum = 0;
```

```

212     for (int i = start; i <= end; i++) {
213         sum += i;
214     }
215     cout << " Chunk " << start << "-" << end << ":" << sum << endl;
216     return sum;
217 };
218
219 const int N = 1000000;
220 const int num_threads = 4;
221 const int chunk_size = N / num_threads;
222
223 vector<future<long long>> futures;
224
225 auto start_time = high_resolution_clock::now();
226
227 for (int i = 0; i < num_threads; i++) {
228     int chunk_start = i * chunk_size + 1;
229     int chunk_end = (i == num_threads - 1) ? N : (i + 1) * chunk_size;
230
231     futures.push_back(async(launch::async, compute_chunk,
232                             chunk_start, chunk_end));
233 }
234
235 long long total = 0;
236 for (auto& f : futures) {
237     total += f.get();
238 }
239
240 auto end_time = high_resolution_clock::now();
241 auto duration = duration_cast<milliseconds>(end_time - start_time);
242
243 cout << "Total sum 1.." << N << ":" << total << endl;
244 cout << "Parallel time: " << duration.count() << "ms" << endl;
245
246 // Sequential comparison
247 start_time = high_resolution_clock::now();
248 long long seq_total = 0;
249 for (int i = 1; i <= N; i++) {
250     seq_total += i;
251 }
252 end_time = high_resolution_clock::now();
253 duration = duration_cast<milliseconds>(end_time - start_time);
254
255 cout << "Sequential sum: " << seq_total << endl;
256 cout << "Sequential time: " << duration.count() << "ms" << endl;
257 }
258
259 // =====
260 // 8. FUTURE CONTINUATIONS (MANUAL IMPLEMENTATION)
261 // =====
262 void example_future_continuations() {
263     cout << "\n== 8. FUTURE CONTINUATIONS (MANUAL) ==" << endl;
264
265     // Using nested async for continuations

```

```
266     auto future1 = async(launch::async, []() {
267         cout << " Step 1: Computing 42..." << endl;
268         this_thread::sleep_for(300ms);
269         return 42;
270     });
271
272     // Continuation 1
273     auto future2 = async(launch::async, [future1 = move(future1)]() mutable {
274         int x = future1.get(); // Wait for first result
275         cout << " Step 2: Doubling " << x << "..." << endl;
276         this_thread::sleep_for(300ms);
277         return x * 2;
278     });
279
280     // Continuation 2
281     auto future3 = async(launch::async, [future2 = move(future2)]() mutable {
282         int x = future2.get(); // Wait for second result
283         cout << " Step 3: Adding 100 to " << x << "..." << endl;
284         this_thread::sleep_for(300ms);
285         return x + 100;
286     });
287
288     cout << "Main: Waiting for pipeline..." << endl;
289     int result = future3.get();
290     cout << "Final result: " << result << endl;
291 }
292
293 // =====
294 // 9. WHEN_ALL IMPLEMENTATION (SIMPLIFIED)
295 // =====
296 void example_when_all() {
297     cout << "\n== 9. WHEN_ALL (WAIT FOR ALL FUTURES) ==" << endl;
298
299     auto task1 = async(launch::async, []() {
300         this_thread::sleep_for(800ms);
301         cout << " Task 1 complete" << endl;
302         return string("Result 1");
303     });
304
305     auto task2 = async(launch::async, []() {
306         this_thread::sleep_for(500ms);
307         cout << " Task 2 complete" << endl;
308         return 42;
309     });
310
311     auto task3 = async(launch::async, []() {
312         this_thread::sleep_for(300ms);
313         cout << " Task 3 complete" << endl;
314         return 3.14;
315     });
316
317     cout << "Main: Waiting for all tasks..." << endl;
318
319     // Manual when_all - just get all results
```

```
320     string result1 = task1.get();
321     int result2 = task2.get();
322     double result3 = task3.get();
323
324     cout << "All tasks complete!" << endl;
325     cout << "Results: " << result1 << ", " << result2 << ", " << result3 <<
326         endl;
327 }
328 // =====
329 // 10. WHEN_ANY IMPLEMENTATION (SIMPLIFIED)
330 // =====
331 void example_when_any() {
332     cout << "\n==> 10. WHEN_ANY (FIRST COMPLETED) ==>" << endl;
333
334     vector<future<string>> tasks;
335
336     tasks.push_back(async(launch::async, []() {
337         this_thread::sleep_for(1200ms);
338         return string("Task 1 (slow)");
339     }));
340
341     tasks.push_back(async(launch::async, []() {
342         this_thread::sleep_for(700ms);
343         return string("Task 2 (medium)");
344     }));
345
346     tasks.push_back(async(launch::async, []() {
347         this_thread::sleep_for(300ms);
348         return string("Task 3 (fast)");
349     }));
350
351     cout << "Main: Waiting for first task to complete..." << endl;
352
353     // Simple when_any using wait_for
354     while (true) {
355         for (size_t i = 0; i < tasks.size(); i++) {
356             if (tasks[i].wait_for(chrono::milliseconds(10)) == future_status::ready) {
357                 cout << "Task " << i << " completed first!" << endl;
358                 cout << "Result: " << tasks[i].get() << endl;
359
360                 // Get remaining results
361                 for (size_t j = 0; j < tasks.size(); j++) {
362                     if (j != i) {
363                         cout << "Task " << j << ": " << tasks[j].get() << endl
364                         ;
365                     }
366                 }
367             }
368         }
369         this_thread::sleep_for(100ms);
370     }
}
```

```
371 }
372
373 // =====
374 // 11. THREAD POOL WITH FUTURES
375 // =====
376 class ThreadPool {
377 private:
378     vector<thread> workers;
379     queue<function<void()>> tasks;
380     mutex queue_mutex;
381     condition_variable condition;
382     atomic<bool> stop;
383
384 public:
385     ThreadPool(size_t num_threads) : stop(false) {
386         for (size_t i = 0; i < num_threads; ++i) {
387             workers.emplace_back([this] {
388                 while (true) {
389                     function<void()> task;
390                     {
391                         unique_lock<mutex> lock(queue_mutex);
392                         condition.wait(lock, [this] {
393                             return stop || !tasks.empty();
394                         });
395
396                         if (stop && tasks.empty()) return;
397
398                         task = move(tasks.front());
399                         tasks.pop();
400                     }
401                     task();
402                 }
403             });
404         }
405     }
406
407     template<class F, class... Args>
408     auto enqueue(F&& f, Args&&... args) -> future<invoke_result_t<F, Args...>>
409     {
410         using return_type = invoke_result_t<F, Args...>;
411
412         auto task = make_shared<packaged_task<return_type()>>(
413             bind(forward<F>(f), forward<Args>(args)...));
414
415         future<return_type> result = task->get_future();
416         {
417             lock_guard<mutex> lock(queue_mutex);
418             if (stop) {
419                 throw runtime_error("enqueue on stopped ThreadPool");
420             }
421             tasks.emplace([task]() { (*task)(); });
422         }
423         condition.notify_one();
424     }
425 }
```

```
424     return result;
425 }
426
427 ~ThreadPool() {
428 {
429     lock_guard<mutex> lock(queue_mutex);
430     stop = true;
431 }
432 condition.notify_all();
433 for (thread& worker : workers) {
434     if (worker.joinable()) worker.join();
435 }
436 }
437 };
438
439 void example_thread_pool() {
440 cout << "\n== 11. THREAD POOL WITH FUTURES ==" << endl;
441
442 ThreadPool pool(4);
443 vector<future<int>> results;
444
445 cout << "Submitting 8 tasks to thread pool..." << endl;
446
447 for (int i = 0; i < 8; i++) {
448     results.emplace_back(pool.enqueue([i]() -> int {
449         cout << " Task " << i << " executing" << endl;
450         this_thread::sleep_for(chrono::milliseconds(100 * (i % 3 + 1)));
451         return i * i;
452     }));
453 }
454
455 cout << "Collecting results..." << endl;
456 for (size_t i = 0; i < results.size(); i++) {
457     cout << "Result " << i << ":" << results[i].get() << endl;
458 }
459
460 cout << "All tasks completed!" << endl;
461 }
462
463 // =====
464 // 12. FUTURE WITH CANCELLATION
465 // =====
466 class CancellableFuture {
467 private:
468     promise<int> promise_obj;
469     future<int> future_obj;
470     atomic<bool> cancelled;
471
472 public:
473     CancellableFuture() : cancelled(false) {
474         future_obj = promise_obj.get_future();
475     }
476
477     void cancel() {
```

```
478     cancelled = true;
479     promise_obj.set_exception(make_exception_ptr(runtime_error("Cancelled"
480                               )));
480 }
481
482     bool is_cancelled() const { return cancelled; }
483
484     future<int>& get_future() { return future_obj; }
485
486     void execute_async(function<int()> task) {
487         thread([this, task](){
488             if (cancelled) return;
489
490             try {
491                 int result = task();
492                 if (!cancelled) {
493                     promise_obj.set_value(result);
494                 }
495             }
496             catch (...) {
497                 if (!cancelled) {
498                     promise_obj.set_exception(current_exception());
499                 }
500             }
501         }).detach();
502     }
503 };
504
505 void example_cancellable_future() {
506     cout << "\n==== 12. CANCELABLE FUTURE ===" << endl;
507
508     CancellableFuture cf;
509
510     cf.execute_async([](){
511         cout << " Long task starting (5 seconds)..." << endl;
512         for (int i = 0; i < 5; i++) {
513             this_thread::sleep_for(1s);
514             cout << " Task progress: " << (i + 1) << "/5" << endl;
515         }
516         return 42;
517     });
518
519     this_thread::sleep_for(2500ms);
520     cout << "Main: Cancelling task after 2.5 seconds..." << endl;
521     cf.cancel();
522
523     try {
524         cout << "Main: Waiting for result..." << endl;
525         int result = cf.get_future().get();
526         cout << "Main: Got result: " << result << endl;
527     }
528     catch (const exception& e) {
529         cout << "Main: Caught: " << e.what() << endl;
530     }
}
```

```
531     this_thread::sleep_for(1s);
532 }
533
534 // =====
535 // 13. STD::VARIANT (C++17)
536 // =====
537 void example_variant() {
538     cout << "\n==> 13. STD::VARIANT (C++17) ==>" << endl;
539
540     variant<int, string, double> value;
541
542     value = 42;
543     cout << "Holds int: " << get<int>(value) << endl;
544
545     value = "Hello World";
546     cout << "Holds string: " << get<string>(value) << endl;
547
548     value = 3.14159;
549     cout << "Holds double: " << get<double>(value) << endl;
550
551     // Visit pattern
552     auto visitor = [] (auto&& arg) {
553         using T = decay_t<decltype(arg)>;
554         if constexpr (is_same_v<T, int>) {
555             cout << "Visited int: " << arg << endl;
556         }
557         else if constexpr (is_same_v<T, string>) {
558             cout << "Visited string: " << arg << endl;
559         }
560         else if constexpr (is_same_v<T, double>) {
561             cout << "Visited double: " << arg << endl;
562         }
563     };
564
565     visit(visitor, value);
566
567     value = "Test";
568     if (holds_alternative<string>(value)) {
569         cout << "Value holds a string" << endl;
570     }
571 }
572
573 // =====
574 // 14. STD::OPTIONAL (C++17)
575 // =====
576 optional<int> divide(int a, int b) {
577     if (b == 0) {
578         return nullopt;
579     }
580     return a / b;
581 }
582
583 void example_optional() {
```

```
585     cout << "\n==== 14. STD::OPTIONAL (C++17) ===" << endl;
586
587     auto result1 = divide(10, 2);
588     if (result1) {
589         cout << "10 / 2 = " << *result1 << endl;
590     }
591
592     auto result2 = divide(10, 0);
593     if (!result2) {
594         cout << "10 / 0 = No result (division by zero)" << endl;
595     }
596
597     cout << "Result or default: " << result2.value_or(999) << endl;
598
599     optional<string> name = "Alice";
600     cout << "Name: " << name.value() << endl;
601
602     optional<int> empty_opt;
603     cout << "Empty optional has value: " << boolalpha << empty_opt.has_value()
604         << endl;
605
606 // =====
607 // 15. STD::ANY (C++17)
608 // =====
609 void example_any() {
610     cout << "\n==== 15. STD::ANY (C++17) ===" << endl;
611
612     any value;
613
614     value = 42;
615     cout << "Any holds int: " << any_cast<int>(value) << endl;
616
617     value = string("Hello");
618     cout << "Any holds string: " << any_cast<string>(value) << endl;
619
620     value = 3.14;
621     cout << "Any holds double: " << any_cast<double>(value) << endl;
622
623     if (value.type() == typeid(double)) {
624         cout << "Value is a double" << endl;
625     }
626
627     try {
628         cout << any_cast<int>(value) << endl;
629     }
630     catch (const bad_any_cast& e) {
631         cout << "Caught exception: " << e.what() << endl;
632     }
633 }
634
635 // =====
636 // 16. FILESYSTEM (C++17)
637 // =====
```

```
638 void example_filesystem() {
639     cout << "\n==== 16. FILESYSTEM (C++17) ===" << endl;
640
641     namespace fs = std::filesystem;
642
643     cout << "Current path: " << fs::current_path() << endl;
644
645     fs::create_directory("test_dir");
646     cout << "Created directory: test_dir" << endl;
647
648     {
649         ofstream file("test_dir/test_file.txt");
650         file << "Hello Filesystem!" << endl;
651     }
652
653     if (fs::exists("test_dir/test_file.txt")) {
654         cout << "File exists" << endl;
655         cout << "File size: " << fs::file_size("test_dir/test_file.txt") << " bytes" << endl;
656     }
657
658     cout << "\nDirectory contents:" << endl;
659     for (const auto& entry : fs::directory_iterator("test_dir")) {
660         cout << "    " << entry.path().filename()
661             << " (" << fs::file_size(entry) << " bytes)" << endl;
662     }
663
664     fs::remove_all("test_dir");
665     cout << "Cleaned up test directory" << endl;
666 }
667
668 // =====
669 // 17. STRUCTURED BINDINGS (C++17)
670 // =====
671 void example_structured_bindings() {
672     cout << "\n==== 17. STRUCTURED BINDINGS (C++17) ===" << endl;
673
674     // With tuple
675     tuple<int, string, double> tup = {42, "Alice", 3.14};
676     auto [id, name, score] = tup;
677     cout << "Tuple unpacked: " << id << ", " << name << ", " << score << endl;
678
679     // With array
680     array<int, 3> arr = {1, 2, 3};
681     auto [a, b, c] = arr;
682     cout << "Array unpacked: " << a << ", " << b << ", " << c << endl;
683
684     // With struct
685     struct Person {
686         string name;
687         int age;
688         string city;
689     };
690 }
```

```
691     Person p = {"Bob", 30, "New York"};
692     auto [person_name, age, city] = p;
693     cout << "Person: " << person_name << ", " << age << ", " << city << endl;
694
695     // With map
696     map<string, int> scores = {"Alice", 95}, {"Bob", 87}, {"Charlie", 92};
697     for (const auto& [student, score] : scores) {
698         cout << student << ": " << score << endl;
699     }
700 }
701
702 // =====
703 // 18. CONSTEXPR IF (C++17)
704 // =====
705 template<typename T>
706 auto process_value(T value) {
707     if constexpr (is_integral_v<T>) {
708         cout << "Processing integer: " << value * 2 << endl;
709         return value * 2;
710     }
711     else if constexpr (is_floating_point_v<T>) {
712         cout << "Processing float: " << value * 3.14 << endl;
713         return value * 3.14;
714     }
715     else if constexpr (is_same_v<T, string>) {
716         cout << "Processing string: " << value + " processed" << endl;
717         return value + " processed";
718     }
719     else {
720         cout << "Unknown type" << endl;
721         return value;
722     }
723 }
724
725 void example_constexpr_if() {
726     cout << "\n== 18. CONSTEXPR IF (C++17) ==" << endl;
727
728     process_value(42);
729     process_value(3.14);
730     process_value(string("Hello"));
731 }
732
733 // =====
734 // 19. COMPREHENSIVE EXAMPLE: ASYNC FILE PROCESSOR
735 // =====
736 void example_comprehensive_async_processor() {
737     cout << "\n== 19. COMPREHENSIVE EXAMPLE: ASYNC FILE PROCESSOR ==" <<
738         endl;
739
739     class AsyncFileProcessor {
740     private:
741         ThreadPool pool{4};
742
743     public:
```

```

744     future<vector<string>> process_files(const vector<string>& filenames)
745     {
746         vector<future<string>> futures;
747
748         for (const auto& filename : filenames) {
749             futures.push_back(pool.enqueue([filename]() -> string {
750                 this_thread::sleep_for(chrono::milliseconds(100 + rand() % 400));
751
752                 if (filename.find("error") != string::npos) {
753                     throw runtime_error("Error processing " + filename);
754                 }
755
756                 return "Processed: " + filename + " (size: "
757                     + to_string(rand() % 1000) + " bytes)";
758             }));
759         }
760
761         return async(launch::async, [futures = move(futures)]() mutable {
762             vector<string> results;
763             for (auto& f : futures) {
764                 try {
765                     results.push_back(f.get());
766                 }
767                 catch (const exception& e) {
768                     results.push_back("ERROR: " + string(e.what()));
769                 }
770             }
771             return results;
772         });
773     };
774
775     AsyncFileProcessor processor;
776
777     vector<string> files = {
778         "document1.txt",
779         "image1.png",
780         "error_file.txt",
781         "data.csv",
782         "config.json"
783     };
784
785     cout << "Processing " << files.size() << " files asynchronously..." <<
786     endl;
787
788     auto start = high_resolution_clock::now();
789     auto result_future = processor.process_files(files);
790
791     cout << "Main thread doing other work..." << endl;
792     this_thread::sleep_for(200ms);
793
794     auto results = result_future.get();
795     auto end = high_resolution_clock::now();

```

```
795     cout << "\nProcessing complete in "
796         << duration_cast<milliseconds>(end - start).count() << "ms" << endl;
797     cout << "\nResults:" << endl;
798     for (const auto& result : results) {
799         cout << "    " << result << endl;
800     }
801 }
802 }
803
804 // =====
805 // 20. ADDITIONAL EXAMPLE: FUTURE WITH MULTIPLE CONTINUATIONS
806 // =====
807 void example_future_chaining() {
808     cout << "\n== 20. FUTURE CHAINING ==" << endl;
809
810     auto future1 = async(launch::async, []() {
811         cout << "    Step 1: Starting with 5" << endl;
812         this_thread::sleep_for(200ms);
813         return 5 + 10; // 15
814     });
815
816     auto future2 = async(launch::async, [f1 = move(future1)]() mutable {
817         int val = f1.get();
818         cout << "    Step 2: Processing " << val << endl;
819         this_thread::sleep_for(200ms);
820         return val * 2; // 30
821     });
822
823     auto future3 = async(launch::async, [f2 = move(future2)]() mutable {
824         int val = f2.get();
825         cout << "    Step 3: Finalizing " << val << endl;
826         this_thread::sleep_for(200ms);
827         return val - 5; // 25
828     });
829
830     int result = future3.get();
831     cout << "Final result: " << result << endl;
832 }
833
834 // =====
835 // MAIN FUNCTION
836 // =====
837 int main() {
838     cout << "
839         ====="
840         << endl;
841     cout << "COMPLETE C++17 FEATURES EXAMPLES" << endl;
842     cout << "
843         ====="
844         << endl;
845
846     srand(time(nullptr));
847
848     try {
```

```
845     example_basic_future_promise();
846     example_future_exception();
847     example_async();
848     example_shared_future();
849     example_future_timeout();
850     example_packaged_task();
851     example_parallel_computation();
852     example_future_continuations();
853     example_when_all();
854     example_when_any();
855     example_thread_pool();
856     example_cancellable_future();
857     example_variant();
858     example_optional();
859     example_any();
860     example_filesystem();
861     example_structured_bindings();
862     example_constexpr_if();
863     example_comprehensive_async_processor();
864     example_future_chaining();
865
866     cout << "\n"
867         =====
868         " << endl;
869     cout << "ALL EXAMPLES COMPLETED SUCCESSFULLY!" << endl;
870     cout << "
871         =====
872         " << endl;
873 }
874
875     catch (const exception& e) {
876         cerr << "Error: " << e.what() << endl;
877         return 1;
878     }
879
880     return 0;
881 }
```

14 Source Code: Cpp17Examples.cpp

File: src/Cpp17Examples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <map>
5 #include <tuple>
6 #include <optional>
7 #include <variant>
8 #include <any>
9 #include <string_view>
10 #include <filesystem>
11 #include <algorithm>
12 #include <numeric>
13 #include <memory>
14 #include <functional>
15
16 // =====
17 // C++17 COMPREHENSIVE EXAMPLES
18 // =====
19
20 // =====
21 // 1. TEMPLATE ARGUMENT DEDUCTION FOR CLASS TEMPLATES
22 // =====
23 void example_template_argument_deduction() {
24     std::cout << "\n== 1. TEMPLATE ARGUMENT DEDUCTION ==" << std::endl;
25
26     std::pair p1{1, 2.0};           // std::pair<int, double>
27     std::tuple t1{1, "hello", 3.14}; // std::tuple<int, const char*, double>
28     std::vector v1{1, 2, 3, 4};     // std::vector<int>
29
30     std::cout << "std::pair deduced: (" << p1.first << ", " << p1.second << ")"
31     " << std::endl;
32     std::cout << "std::vector deduced with " << v1.size() << " elements" <<
33         std::endl;
34 }
35
36 // =====
37 // 2. STRUCTURED BINDINGS
38 // =====
39 void example_structured_bindings() {
40     std::pair<int, std::string> pair{1, "hello"};
41     auto [num, str] = pair;
42     std::cout << "Pair: " << num << ", " << str << std::endl;
43
44     std::tuple<int, double, std::string> tup{42, 3.14, "world"};
45     auto [i, d, s] = tup;
46     std::cout << "Tuple: " << i << ", " << d << ", " << s << std::endl;
47 }
```

```
48     std::map<int, std::string> m{{1, "one"}, {2, "two"}};
49     for (const auto& [key, value] : m) {
50         std::cout << "Map: " << key << " -> " << value << std::endl;
51     }
52 }
53
54 // =====
55 // 3. FOLDING EXPRESSIONS
56 // =====
57 template <typename... Args>
58 auto sum_fold(Args... args) {
59     return (... + args); // Unary left fold
60 }
61
62 template <typename... Args>
63 bool all_true(Args... args) {
64     return (... && args); // Unary left fold
65 }
66
67 template <typename... Args>
68 void print_all(Args... args) {
69     ((std::cout << args << " "), ...); // Binary left fold
70     std::cout << std::endl;
71 }
72
73 void example_folding_expressions() {
74     std::cout << "\n== 3. FOLDING EXPRESSIONS ==" << std::endl;
75
76     std::cout << "sum_fold(1, 2, 3, 4, 5) = " << sum_fold(1, 2, 3, 4, 5) <<
77         std::endl;
78     std::cout << "all_true(true, true, true) = " << std::boolalpha << all_true(
79         true, true, true) << std::endl;
80     std::cout << "all_true(true, false, true) = " << all_true(true, false,
81         true) << std::endl;
82     std::cout << "print_all: ";
83     print_all(1, "hello", 3.14, "world");
84 }
85
86 // =====
87 // 4. CONSTEXPR IF
88 // =====
89 template <typename T>
90 auto get_value(T t) {
91     if constexpr (std::is_pointer_v<T>) {
92         return *t; // Dereference pointer
93     } else {
94         return t; // Return value directly
95     }
96 }
97
98 void example_constexpr_if() {
99     std::cout << "\n== 4. CONSTEXPR IF ==" << std::endl;
100
101     int x = 42;
```

```
99     int* ptr = &x;  
100  
101    std::cout << "get_value(10) = " << get_value(10) << std::endl;  
102    std::cout << "get_value(ptr) = " << get_value(ptr) << std::endl;  
103 }  
104  
105 // =====  
106 // 5. CONSTEXPR LAMBDA  
107 // =====  
108 void example_constexpr_lambda() {  
109     std::cout << "\n== 5. CONSTEXPR LAMBDA ==" << std::endl;  
110  
111     constexpr auto square = [](int n) { return n * n; };  
112     constexpr int result = square(5);  
113  
114     std::cout << "Compile-time square(5) = " << result << std::endl;  
115     static_assert(square(4) == 16, "Square function test");  
116 }  
117  
118 // =====  
119 // 6. INLINE VARIABLES  
120 // =====  
121 inline int global_counter = 0;  
122  
123 struct Config {  
124     inline static const std::string app_name = "MyApp";  
125     inline static const int version = 1;  
126 };  
127  
128 void example_inline_variables() {  
129     std::cout << "\n== 6. INLINE VARIABLES ==" << std::endl;  
130  
131     global_counter++;  
132     std::cout << "Global counter: " << global_counter << std::endl;  
133     std::cout << "App name: " << Config::app_name << std::endl;  
134     std::cout << "Version: " << Config::version << std::endl;  
135 }  
136  
137 // =====  
138 // 7. NESTED NAMESPACES  
139 // =====  
140 namespace A::B::C {  
141     void nested_function() {  
142         std::cout << "Inside A::B::C namespace" << std::endl;  
143     }  
144 }  
145  
146 void example_nested_namespaces() {  
147     std::cout << "\n== 7. NESTED NAMESPACES ==" << std::endl;  
148     A::B::C::nested_function();  
149 }  
150  
151 // =====  
152 // 8. SELECTION STATEMENTS WITH INITIALIZER
```

```
153 // =====
154 void example_selection_with_initializer() {
155     std::cout << "\n== 8. SELECTION WITH INITIALIZER ==" << std::endl;
156
157     std::map<int, std::string> m{{1, "one"}, {2, "two"}};
158
159     if (auto it = m.find(1); it != m.end()) {
160         std::cout << "Found: " << it->second << std::endl;
161     }
162
163     switch (auto value = 42; value) {
164         case 42:
165             std::cout << "Value is 42" << std::endl;
166             break;
167         default:
168             std::cout << "Value is not 42" << std::endl;
169     }
170 }
171 // =====
172 // 9. [[FALLTHROUGH]], [[NODISCARD]], [[MAYBE_UNUSED]] ATTRIBUTES
173 // =====
174 [[nodiscard]] int important_function() {
175     return 42;
176 }
177
178 void example_attributes([[maybe_unused]] int unused_param) {
179     std::cout << "\n== 9. ATTRIBUTES ==" << std::endl;
180
181     int result = important_function(); // Must use result or compiler warns
182     std::cout << "Result: " << result << std::endl;
183
184     int value = 2;
185     switch (value) {
186         case 1:
187             std::cout << "Case 1" << std::endl;
188             [[fallthrough]];
189         case 2:
190             std::cout << "Case 2 (maybe from fallthrough)" << std::endl;
191             break;
192     }
193 }
194
195 // =====
196 // 10. STD::OPTIONAL
197 // =====
198 std::optional<int> try_parse_int(const std::string& str) {
199     try {
200         return std::stoi(str);
201     } catch (...) {
202         return std::nullopt;
203     }
204 }
205
206 }
```

```
207 void example_optional() {
208     std::cout << "\n==== 10. STD::OPTIONAL ===" << std::endl;
209
210     std::optional<int> opt1 = 42;
211     std::optional<int> opt2 = std::nullopt;
212
213     if (opt1) {
214         std::cout << "opt1 has value: " << *opt1 << std::endl;
215     }
216
217     std::cout << "opt2 value or default: " << opt2.value_or(-1) << std::endl;
218
219     auto result1 = try_parse_int("123");
220     auto result2 = try_parse_int("abc");
221
222     std::cout << "Parse '123': " << (result1 ? std::to_string(*result1) : "
223         failed) << std::endl;
224     std::cout << "Parse 'abc': " << (result2 ? std::to_string(*result2) : "
225         failed) << std::endl;
226 }
227
228 // =====
229 // 11. STD::VARIANT
230 // =====
231 void example_variant() {
232     std::variant<int, double, std::string> var;
233
234     var = 42;
235     std::cout << "Variant holds int: " << std::get<int>(var) << std::endl;
236
237     var = 3.14;
238     std::cout << "Variant holds double: " << std::get<double>(var) << std::
239         endl;
240
241     var = "hello";
242     std::cout << "Variant holds string: " << std::get<std::string>(var) << std::
243         endl;
244
245     std::visit([](auto&& arg) {
246         std::cout << "Visiting variant: " << arg << std::endl;
247     }, var);
248 }
249
250 // =====
251 // 12. STD::ANY
252 // =====
253 void example_any() {
254     std::any a = 42;
255     std::cout << "Any holds int: " << std::any_cast<int>(a) << std::endl;
256 }
```

```
257     a = std::string("hello");
258     std::cout << "Any holds string: " << std::any_cast<std::string>(a) << std
259         ::endl;
260
261     if (a.type() == typeid(std::string)) {
262         std::cout << "Confirmed: any contains string" << std::endl;
263     }
264
265 // =====
266 // 13. STD::STRING_VIEW
267 // =====
268 void print_string_view(std::string_view sv) {
269     std::cout << "String view: " << sv << " (length: " << sv.length() << ")"
270         << std::endl;
271 }
272
273 void example_string_view() {
274     std::cout << "\n== 13. STD::STRING_VIEW ==" << std::endl;
275
276     std::string str = "Hello, World!";
277     std::string_view sv = str;
278
279     print_string_view(sv);
280     print_string_view("Literal string");
281     print_string_view(sv.substr(0, 5));
282 }
283
284 // =====
285 // 14. STD::FILESYSTEM
286 // =====
287 void example_filesystem() {
288     std::cout << "\n== 14. STD::FILESYSTEM ==" << std::endl;
289
290     namespace fs = std::filesystem;
291
292     fs::path p = fs::current_path();
293     std::cout << "Current path: " << p << std::endl;
294
295     fs::path example_path = "example.txt";
296     std::cout << "Filename: " << example_path.filename() << std::endl;
297     std::cout << "Extension: " << example_path.extension() << std::endl;
298 }
299
300 // =====
301 // 15. STD::CLAMP
302 // =====
303 void example_clamp() {
304     std::cout << "\n== 15. STD::CLAMP ==" << std::endl;
305
306     int value = 50;
307     int clamped = std::clamp(value, 10, 40);
308     std::cout << "clamp(50, 10, 40) = " << clamped << std::endl;
```

```
309     int value2 = 5;
310     int clamped2 = std::clamp(value2, 10, 40);
311     std::cout << "clamp(5, 10, 40) = " << clamped2 << std::endl;
312 }
313
314 // =====
315 // 16. GCD AND LCM
316 // =====
317 void example_gcd_lcm() {
318     std::cout << "\n==== 16. GCD AND LCM ===" << std::endl;
319
320     int a = 12, b = 18;
321     std::cout << "gcd(" << a << ", " << b << ") = " << std::gcd(a, b) << std::endl;
322     std::cout << "lcm(" << a << ", " << b << ") = " << std::lcm(a, b) << std::endl;
323 }
324
325 // =====
326 // 17. LAMBDA CAPTURE THIS BY VALUE
327 // =====
328 struct MyObject {
329     int value = 123;
330
331     auto get_value_copy() {
332         return [*this] { return value; };
333     }
334
335     auto get_value_ref() {
336         return [this] { return value; };
337     }
338 };
339
340 void example_lambda_capture_this() {
341     std::cout << "\n==== 17. LAMBDA CAPTURE THIS BY VALUE ===" << std::endl;
342
343     MyObject obj;
344     auto copy_lambda = obj.get_value_copy();
345     auto ref_lambda = obj.get_value_ref();
346
347     obj.value = 456;
348
349     std::cout << "Copy lambda returns: " << copy_lambda() << " (original value
350         )" << std::endl;
351     std::cout << "Ref lambda returns: " << ref_lambda() << " (modified value)"
352         << std::endl;
353 }
354
355 // =====
356 // 18. STD::INVOKE
357 // =====
358 int add_func(int a, int b) {
359     return a + b;
360 }
```

```
359
360 struct Adder {
361     int operator()(int a, int b) const {
362         return a + b;
363     }
364 };
365
366 void example_invoke() {
367     std::cout << "\n== 18. STD::INVOKE ==" << std::endl;
368
369     std::cout << "invoke(add_func, 3, 4) = " << std::invoke(add_func, 3, 4) <<
370         std::endl;
371
372     Adder adder;
373     std::cout << "invoke(Adder, 5, 6) = " << std::invoke(adder, 5, 6) << std::
374         endl;
375
376     auto lambda = [](int a, int b) { return a * b; };
377     std::cout << "invoke(lambda, 7, 8) = " << std::invoke(lambda, 7, 8) << std
378         ::endl;
379 }
380
381 // =====
382 // 19. STD::APPLY
383 // =====
384 int multiply(int a, int b, int c) {
385     return a * b * c;
386 }
387
388 void example_apply() {
389     std::cout << "\n== 19. STD::APPLY ==" << std::endl;
390
391     std::tuple<int, int, int> args{2, 3, 4};
392     int result = std::apply(multiply, args);
393
394     std::cout << "apply(multiply, {2, 3, 4}) = " << result << std::endl;
395 }
396
397 // =====
398 // 20. STD::MAKE_FROM_TUPLE
399 // =====
400 struct Point {
401     int x, y, z;
402     Point(int x, int y, int z) : x(x), y(y), z(z) {}
403 };
404
405 void example_make_from_tuple() {
406     std::cout << "\n== 20. STD::MAKE_FROM_TUPLE ==" << std::endl;
407
408     std::tuple<int, int, int> coords{10, 20, 30};
409     auto point = std::make_from_tuple<Point>(coords);
410
411     std::cout << "Point created from tuple: (" << point.x << ", " << point.y
412         << ", " << point.z << ")" << std::endl;
```

```
409 }
410
411 // =====
412 // MAIN FUNCTION
413 // =====
414 int main() {
415     std::cout << "\n=====\n" << std::
416         endl;
417     std::cout << "      C++17 FEATURES COMPREHENSIVE EXAMPLES" << std::endl;
418     std::cout << "=====\n" << std::
419         endl;
420
421     example_template_argument_deduction();
422     example_structured_bindings();
423     example_folding_expressions();
424     example_constexpr_if();
425     example_constexpr_lambda();
426     example_inline_variables();
427     example_nested_namespaces();
428     example_selection_with_initializer();
429     example_attributes(42);
430     example_optional();
431     example_variant();
432     example_any();
433     example_string_view();
434     example_filesystem();
435     example_clamp();
436     example_gcd_lcm();
437     example_lambda_capture_this();
438     example_invoke();
439     example_apply();
440     example_make_from_tuple();
441
442     std::cout << "\n=====\n" << std::
443         endl;
444     std::cout << "      ALL C++17 EXAMPLES COMPLETED" << std::endl;
445     std::cout << "=====\\n" << std::
446         endl;
447
448     return 0;
449 }
```

15 Source Code: Cpp20Examples.cpp

File: src/Cpp20Examples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <span>
5 #include <ranges>
6 #include <algorithm>
7 #include <concepts>
8 #include <compare>
9 #include <numbers>
10 #include <bit>
11 #include <bitset>
12 #include <array>
13 #include <set>
14 #include <numeric>
15
16 // =====
17 // C++20 COMPREHENSIVE EXAMPLES
18 // =====
19
20 // =====
21 // 1. CONCEPTS
22 // =====
23 template <typename T>
24 concept Integral = std::is_integral_v<T>;
25
26 template <typename T>
27 concept SignedIntegral = Integral<T> && std::is_signed_v<T>;
28
29 template <Integral T>
30 T add(T a, T b) {
31     return a + b;
32 }
33
34 template <SignedIntegral T>
35 T negate(T value) {
36     return -value;
37 }
38
39 void example_concepts() {
40     std::cout << "\n== 1. CONCEPTS ==" << std::endl;
41
42     std::cout << "add(10, 20) = " << add(10, 20) << std::endl;
43     std::cout << "add(5U, 3U) = " << add(5U, 3U) << std::endl;
44     std::cout << "negate(42) = " << negate(42) << std::endl;
45
46     // add(3.14, 2.5); // Error: double doesn't satisfy Integral
47 }
48
49 // =====
```

```
50 // 2. THREE-WAY COMPARISON (SPACESHIP OPERATOR)
51 // =====
52 struct Point {
53     int x, y;
54     auto operator<=(const Point&) const = default;
55 };
56
57 void example_three_way_comparison() {
58     std::cout << "\n== 2. THREE-WAY COMPARISON =="
59     << std::endl;
60
61     Point p1{1, 2}, p2{1, 3}, p3{1, 2};
62
63     std::cout << "p1 == p3: " << std::boolalpha << (p1 == p3) << std::endl;
64     std::cout << "p1 != p2: " << (p1 != p2) << std::endl;
65     std::cout << "p1 < p2: " << (p1 < p2) << std::endl;
66
67     int a = 10, b = 20;
68     auto result = a <= b;
69     if (result < 0) {
70         std::cout << "a < b" << std::endl;
71     }
72 }
73
74 // =====
75 // 3. DESIGNATED INITIALIZERS
76 // =====
77 struct Config {
78     int width;
79     int height;
80     std::string title;
81 };
82
83 void example_designated_initializers() {
84     std::cout << "\n== 3. DESIGNATED INITIALIZERS =="
85     << std::endl;
86
87     Config cfg{
88         .width = 1920,
89         .height = 1080,
90         .title = "My Window"
91     };
92
93     std::cout << "Config: " << cfg.width << "x" << cfg.height
94         << " - " << cfg.title << std::endl;
95 }
96
97 // =====
98 // 4. TEMPLATE SYNTAX FOR LAMBDA'S
99 // =====
100 void example_template_lambdas() {
101     std::cout << "\n== 4. TEMPLATE SYNTAX FOR LAMBDA'S =="
102     << std::endl;
103
104     auto generic_add = []<typename T>(T a, T b) {
105         return a + b;
106     };
107 }
```

```
104     std::cout << "generic_add(10, 20) = " << generic_add(10, 20) << std::endl;
105     std::cout << "generic_add(1.5, 2.5) = " << generic_add(1.5, 2.5) << std::
106         endl;
107
108     auto print_type = []<typename T>(T value) {
109         if constexpr (std::is_integral_v<T>) {
110             std::cout << "Integer: " << value << std::endl;
111         } else {
112             std::cout << "Non-integer: " << value << std::endl;
113         }
114     };
115
116     print_type(42);
117     print_type(3.14);
118 }
119
120 // =====
121 // 5. RANGE-BASED FOR LOOP WITH INITIALIZER
122 // =====
123 void example_range_for_initializer() {
124     std::cout << "\n==== 5. RANGE-BASED FOR WITH INITIALIZER ===" << std::endl;
125
126     for (std::vector<int> vec = {1, 2, 3, 4, 5}; auto& elem : vec) {
127         std::cout << elem << " ";
128     }
129     std::cout << std::endl;
130 }
131
132 // =====
133 // 6. [[LIKELY]] AND [[UNLIKELY]] ATTRIBUTES
134 // =====
135 int predict_branch(int value) {
136     if (value > 0) [[likely]] {
137         return value * 2;
138     } else [[unlikely]] {
139         return value * 10;
140     }
141 }
142
143 void example_likely_unlikely() {
144     std::cout << "\n==== 6. [[LIKELY]] AND [[UNLIKELY]] ===" << std::endl;
145
146     std::cout << "predict_branch(5) = " << predict_branch(5) << std::endl;
147     std::cout << "predict_branch(-2) = " << predict_branch(-2) << std::endl;
148 }
149
150 // =====
151 // 7. CONSTEXPR VIRTUAL FUNCTIONS
152 // =====
153 struct Base {
154     virtual constexpr int get_value() const {
155         return 10;
156     }
```

```
157 };
```

```
158
159 struct Derived : Base {
160     constexpr int get_value() const override {
161         return 20;
162     }
163 };
164
165 void example_constexpr_virtual() {
166     std::cout << "\n==> 7. CONSTEXPR VIRTUAL FUNCTIONS ==>" << std::endl;
167
168     constexpr Derived d;
169     constexpr int value = d.get_value();
170
171     std::cout << "Constexpr virtual function result: " << value << std::endl;
172 }
173
174 // =====
175 // 8. EXPLICIT(BOOL)
176 // =====
177 struct MyInt {
178     int value;
179     explicit(sizeof(int) > 4) MyInt(int v) : value(v) {}
180 };
181
182 void example_explicit_bool() {
183     std::cout << "\n==> 8. EXPLICIT(BOOL) ==>" << std::endl;
184
185     MyInt mi{42}; // Always requires explicit construction based on condition
186     std::cout << "MyInt created with value: " << mi.value << std::endl;
187 }
188
189 // =====
190 // 9. IMMEDIATE FUNCTIONS (CONSTEVAL)
191 // =====
192 constexpr int square(int n) {
193     return n * n;
194 }
195
196 void example_immediate_functions() {
197     std::cout << "\n==> 9. IMMEDIATE FUNCTIONS ==>" << std::endl;
198
199     constexpr int result = square(5); // Must be evaluated at compile time
200     std::cout << "Consteval square(5) = " << result << std::endl;
201 }
202
203 // =====
204 // 10. USING ENUM
205 // =====
206 enum class Color { Red, Green, Blue };
207
208 void example_using_enum() {
209     std::cout << "\n==> 10. USING ENUM ==>" << std::endl;
```

```
211     using enum Color;
212     Color c = Red; // No need for Color::Red
213
214     switch (c) {
215         using enum Color; // Can use in switch scope
216         case Red:
217             std::cout << "Color is Red" << std::endl;
218             break;
219         case Green:
220             std::cout << "Color is Green" << std::endl;
221             break;
222         case Blue:
223             std::cout << "Color is Blue" << std::endl;
224             break;
225     }
226 }
227
228 // =====
229 // 11. CHAR8_T
230 // =====
231 void example_char8_t() {
232     std::cout << "\n== 11. CHAR8_T ==" << std::endl;
233
234     char8_t utf8_char = u8'A';
235     const char8_t* utf8_str = u8"Hello UTF-8";
236
237     std::cout << "UTF-8 character type created" << std::endl;
238     std::cout << "UTF-8 string type created" << std::endl;
239 }
240
241 // =====
242 // 12. CONSTINIT
243 // =====
244 constinit int global_value = 42;
245
246 void example_constinit() {
247     std::cout << "\n== 12. CONSTINIT ==" << std::endl;
248
249     std::cout << "Constinit global value: " << global_value << std::endl;
250     global_value = 100; // Can be modified at runtime
251     std::cout << "Modified value: " << global_value << std::endl;
252 }
253
254 // =====
255 // 13. STD::SPAN
256 // =====
257 void process_span(std::span<int> s) {
258     for (auto& elem : s) {
259         elem *= 2;
260     }
261 }
262
263 void example_span() {
264     std::cout << "\n== 13. STD::SPAN ==" << std::endl;
```

```
265     std::vector<int> vec = {1, 2, 3, 4, 5};  
266     std::span<int> s{vec};  
267  
268     std::cout << "Before: ";  
269     for (auto v : vec) std::cout << v << " ";  
270     std::cout << std::endl;  
271  
272     process_span(s);  
273  
274  
275     std::cout << "After: ";  
276     for (auto v : vec) std::cout << v << " ";  
277     std::cout << std::endl;  
278 }  
279  
280 // =====  
281 // 14. RANGES  
282 // =====  
283 void example_ranges() {  
284     std::cout << "\n== 14. RANGES ==" << std::endl;  
285  
286     std::vector<int> vec = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};  
287  
288     auto even = vec | std::views::filter([](int n) { return n % 2 == 0; });  
289     auto squared = even | std::views::transform([](int n) { return n * n; });  
290  
291     std::cout << "Even numbers squared: ";  
292     for (auto v : squared) {  
293         std::cout << v << " ";  
294     }  
295     std::cout << std::endl;  
296 }  
297  
298 // =====  
299 // 15. BIT OPERATIONS  
300 // =====  
301 void example_bit_operations() {  
302     std::cout << "\n== 15. BIT OPERATIONS ==" << std::endl;  
303  
304     unsigned int value = 0b10110100;  
305  
306     std::cout << "popcount(0b10110100) = " << std::popcount(value) << std:::  
            endl;  
307     std::cout << "has_single_bit(8) = " << std::boolalpha << std:::  
            has_single_bit(8u) << std::endl;  
308     std::cout << "bit_width(7) = " << std::bit_width(7u) << std::endl;  
309     std::cout << "rotl(0b10110100, 2) = " << std::rotl(value, 2) << std::endl;  
310 }  
311  
312 // =====  
313 // 16. MATH CONSTANTS  
314 // =====  
315 void example_math_constants() {  
316     std::cout << "\n== 16. MATH CONSTANTS ==" << std::endl;
```

```
317     std::cout << "pi = " << std::numbers::pi << std::endl;
318     std::cout << "e = " << std::numbers::e << std::endl;
319     std::cout << "sqrt2 = " << std::numbers::sqrt2 << std::endl;
320     std::cout << "ln2 = " << std::numbers::ln2 << std::endl;
321 }
322 }
323
324 // =====
325 // 17. STD::IS_CONSTANT_EVALUATED
326 // =====
327 constexpr int compute_value() {
328     if (std::is_constant_evaluated()) {
329         return 42; // Compile-time
330     } else {
331         return 100; // Runtime
332     }
333 }
334
335 void example_is_constant_evaluated() {
336     std::cout << "\n==== 17. STD::IS_CONSTANT_EVALUATED ===" << std::endl;
337
338     constexpr int compile_time = compute_value();
339     int runtime = compute_value();
340
341     std::cout << "Compile-time: " << compile_time << std::endl;
342     std::cout << "Runtime: " << runtime << std::endl;
343 }
344
345 // =====
346 // 18. STARTS_WITH / ENDS_WITH
347 // =====
348 void example_starts_ends_with() {
349     std::cout << "\n==== 18. STARTS_WITH / ENDS_WITH ===" << std::endl;
350
351     std::string str = "Hello, World!";
352
353     std::cout << "starts_with('Hello'): " << std::boolalpha
354             << str.starts_with("Hello") << std::endl;
355     std::cout << "ends_with('World!'): " << str.ends_with("World!") << std::
356             endl;
357 }
358
359 // =====
360 // 19. ASSOCIATIVE CONTAINER .CONTAINS()
361 // =====
362 void example_contains() {
363     std::cout << "\n==== 19. ASSOCIATIVE CONTAINER .CONTAINS() ===" << std::
364             endl;
365
366     std::vector<int> vec = {1, 2, 3, 4, 5};
367     std::set<int> s{vec.begin(), vec.end()};
368
369     std::cout << "Set contains 3: " << std::boolalpha << s.contains(3) << std::
370             endl;
```

```
368     std::cout << "Set contains 10: " << s.contains(10) << std::endl;
369 }
370
371 // =====
372 // 20. STD::MIDPOINT
373 // =====
374 void example_midpoint() {
375     std::cout << "\n==> 20. STD::MIDPOINT ==>" << std::endl;
376
377     std::cout << "midpoint(10, 20) = " << std::midpoint(10, 20) << std::endl;
378     std::cout << "midpoint(1.0, 5.0) = " << std::midpoint(1.0, 5.0) << std::endl;
379 }
380
381 // =====
382 // 21. STD::TO_ARRAY
383 // =====
384 void example_to_array() {
385     std::cout << "\n==> 21. STD::TO_ARRAY ==>" << std::endl;
386
387     auto arr = std::to_array({1, 2, 3, 4, 5});
388
389     std::cout << "Array from initializer list: ";
390     for (auto v : arr) {
391         std::cout << v << " ";
392     }
393     std::cout << std::endl;
394 }
395
396 // =====
397 // 22. LAMBDA CAPTURE OF PARAMETER PACK
398 // =====
399 template <typename... Args>
400 auto make_lambda(Args... args) {
401     return [...args = std::move(args)] {
402         ((std::cout << args << " "), ...);
403         std::cout << std::endl;
404     };
405 }
406
407 void example_lambda_capture_pack() {
408     std::cout << "\n==> 22. LAMBDA CAPTURE OF PARAMETER PACK ==>" << std::endl
409     ;
410
411     auto lambda = make_lambda(1, 2, 3, "hello", 4.5);
412     std::cout << "Lambda with captured pack: ";
413     lambda();
414 }
415
416 // =====
417 // 23. CLASS TYPES IN NON-TYPE TEMPLATE PARAMETERS
418 // =====
419 struct CompileTimeValue {
    int value;
```

```
420     constexpr CompileTimeValue(int v) : value(v) {}
421 };
422
423 template <CompileTimeValue val>
424 void print_compile_time() {
425     std::cout << "Compile-time value: " << val.value << std::endl;
426 }
427
428 void example_class_non_type_template() {
429     std::cout << "\n==== 23. CLASS TYPES IN NON-TYPE TEMPLATE ===" << std::endl
430         ;
431
432     print_compile_time<CompileTimeValue{42}>();
433 }
434
435 // =====
436 // MAIN FUNCTION
437 // =====
438 int main() {
439     std::cout << "\n=====" << std::endl;
440     std::cout << "      C++20 FEATURES COMPREHENSIVE EXAMPLES" << std::endl;
441     std::cout << "=====" << std::endl;
442
443     example_concepts();
444     example_three_way_comparison();
445     example_designated_initializers();
446     example_template_lambdas();
447     example_range_for_initializer();
448     example_likely_unlikely();
449     example_constexpr_virtual();
450     example_explicit_bool();
451     example_immediate_functions();
452     example_using_enum();
453     example_char8_t();
454     example_constinit();
455     example_span();
456     example_ranges();
457     example_bit_operations();
458     example_math_constants();
459     example_is_constant_evaluated();
460     example_starts_ends_with();
461     example_contains();
462     example_midpoint();
463     example_to_array();
464     example_lambda_capture_pack();
465     example_class_non_type_template();
466
467     std::cout << "\n=====" << std::endl;
468     std::cout << "      ALL C++20 EXAMPLES COMPLETED" << std::endl;
469     std::cout << "=====\n" << std::endl;
```

```
469
470     return 0;
471 }
```

16 Source Code: Cpp23Examples.cpp

File: src/Cpp23Examples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <optional>
5 #include <utility> // for std::to_underlying, std::unreachable
6 #include <cmath>
7 #include <cstdint>
8 #include <array>
9 #include <bit>
10
11 // =====
12 // C++23 FEATURES FOR EMBEDDED SYSTEMS, FIRMWARE, AND RTOS
13 // =====
14 // Focused on features useful for:
15 // - Firmware development
16 // - Real-Time Operating Systems (RTOS)
17 // - Embedded Linux platforms
18 // - Hardware interfacing
19 // - Resource-constrained environments
20 // =====
21
22 // =====
23 // 1. std::expected<T, E> - ERROR HANDLING WITHOUT EXCEPTIONS
24 // =====
25 // CRITICAL for embedded: No exception overhead!
26 // Perfect for firmware where exceptions are disabled
27
28 #if __cplusplus >= 202302L && __has_include(<expected>)
29 #include <expected>
30
31 enum class SensorError {
32     NotConnected,
33     ReadTimeout,
34     InvalidData,
35     CalibrationFailed
36 };
37
38 const char* to_string(SensorError error) {
39     switch (error) {
40         case SensorError::NotConnected: return "Sensor not connected";
41         case SensorError::ReadTimeout: return "Read timeout";
42         case SensorError::InvalidData: return "Invalid data";
43         case SensorError::CalibrationFailed: return "Calibration failed";
44     }
45     return "Unknown error";
46 }
47
48 // Return either temperature value or error - no exceptions!
49 std::expected<float, SensorError> read_temperature_sensor() {
```

```
50 // Simulate sensor read
51 static int call_count = 0;
52 call_count++;
53
54 if (call_count == 1) {
55     return std::unexpected(SensorError::NotConnected);
56 }
57 if (call_count == 2) {
58     return std::unexpected(SensorError::ReadTimeout);
59 }
60
61 return 23.5f; // Success
62 }
63
64 // Chaining operations with monadic interface
65 std::expected<float, SensorError> read_and_convert_to_fahrenheit() {
66     return read_temperature_sensor()
67         .and_then([](float celsius) -> std::expected<float, SensorError> {
68             if (celsius < -273.15f) {
69                 return std::unexpected(SensorError::InvalidData);
70             }
71             return celsius * 9.0f / 5.0f + 32.0f;
72         });
73 }
74
75 void demonstrate_expected() {
76     std::cout << "\n==== 1. std::expected - EXCEPTION-FREE ERROR HANDLING ==="
77         << std::endl;
78     std::cout << "Perfect for firmware with -fno-exceptions" << std::endl;
79
80     // First call - error
81     auto result1 = read_temperature_sensor();
82     if (result1) {
83         std::cout << "\n Temperature: " << *result1 << "°C" << std::endl;
84     } else {
85         std::cout << "\n Error: " << to_string(result1.error()) << std::endl;
86     }
87
88     // Second call - error
89     auto result2 = read_temperature_sensor();
90     if (result2) {
91         std::cout << " Temperature: " << *result2 << "°C" << std::endl;
92     } else {
93         std::cout << " Error: " << to_string(result2.error()) << std::endl;
94     }
95
96     // Third call - success
97     auto result3 = read_temperature_sensor();
98     if (result3) {
99         std::cout << " Temperature: " << *result3 << "°C" << std::endl;
100    } else {
101        std::cout << " Error: " << to_string(result3.error()) << std::endl;
102    }
103 }
```

```
103     std::cout << "\n Benefits for Embedded:" << std::endl;
104     std::cout << " • Zero exception overhead" << std::endl;
105     std::cout << " • Works with -fno-exceptions" << std::endl;
106     std::cout << " • Explicit error handling" << std::endl;
107     std::cout << " • Deterministic performance" << std::endl;
108 }
109
110 #else
111 void demonstrate_expected() {
112     std::cout << "\n== 1. std::expected ==" << std::endl;
113     std::cout << " std::expected requires C++23 compiler support" << std::endl;
114     std::cout << "Alternative: Use std::variant<T, Error> in C++17" << std::endl;
115 }
116 #endif
117
118 // =====
119 // 2. std::byteswap - ENDIANNES CONVERSION FOR HARDWARE
120 // =====
121 // Essential for: Network protocols, file formats, hardware registers
122
123 #if __cplusplus >= 202302L && __has_include(<bit>)
124
125 void demonstrate_byteswap() {
126     std::cout << "\n== 2. std::byteswap - HARDWARE BYTE ORDER ==" << std::endl;
127     std::cout << "Critical for network protocols and hardware registers" << std::endl;
128
129     // Reading from network (big-endian) to host (possibly little-endian)
130     uint32_t network_value = 0x12345678;
131     std::cout << "\nNetwork value (big-endian): 0x" << std::hex << network_value << std::dec << std::endl;
132
133     uint32_t host_value = std::byteswap(network_value);
134     std::cout << "After byteswap: 0x" << std::hex << host_value << std::dec << std::endl;
135
136     // 16-bit register value swap
137     uint16_t reg16 = 0xABCD;
138     std::cout << "\n16-bit register: 0x" << std::hex << reg16 << std::dec << std::endl;
139     uint16_t swapped16 = std::byteswap(reg16);
140     std::cout << "Swapped: 0x" << std::hex << swapped16 << std::dec << std::endl;
141
142     // 64-bit timestamp swap
143     uint64_t timestamp = 0x0123456789ABCDEF;
144     std::cout << "\n64-bit timestamp: 0x" << std::hex << timestamp << std::dec << std::endl;
145     uint64_t swapped64 = std::byteswap(timestamp);
146     std::cout << "Swapped: 0x" << std::hex << swapped64 << std::dec << std::endl;
```

```
147     std::cout << "\n Embedded Use Cases:" << std::endl;
148     std::cout << " • Network protocol implementation (TCP/IP)" << std::endl;
149     std::cout << " • File format parsing (headers, metadata)" << std::endl;
150     std::cout << " • Cross-platform binary data exchange" << std::endl;
151     std::cout << " • Hardware register manipulation" << std::endl;
152 }
153
154
155 #else
156 void demonstrate_byteswap() {
157     std::cout << "\n== 2. std::byteswap ===" << std::endl;
158     std::cout << " std::byteswap requires C++23" << std::endl;
159     std::cout << "Alternative: Use __builtin_bswap32() or manual bit shifts"
160         << std::endl;
161 }
162 #endif
163 // =====
164 // 3. std::to_underlying - ENUM TO INTEGER (HARDWARE REGISTERS)
165 // =====
166
167 enum class GPIOPin : uint8_t {
168     PIN_0 = 0,
169     PIN_1 = 1,
170     PIN_2 = 2,
171     PIN_3 = 3,
172     PIN_LED = 13,
173     PIN_BUTTON = 7
174 };
175
176 enum class MemoryRegister : uint32_t {
177     STATUS_REG = 0x40000000,
178     CONTROL_REG = 0x40000004,
179     DATA_REG = 0x40000008,
180     CONFIG_REG = 0x4000000C
181 };
182
183 void demonstrate_to_underlying() {
184     std::cout << "\n== 3. std::to_underlying - HARDWARE REGISTER ACCESS ==="
185         << std::endl;
186     std::cout << "Convert enum class to underlying integer type" << std::endl;
187
188     // GPIO pin access
189     GPIOPin led_pin = GPIOPin::PIN_LED;
190     auto pin_number = std::to_underlying(led_pin);
191     std::cout << "\nLED Pin number: " << static_cast<int>(pin_number) << std::endl;
192
193     // Memory-mapped register access
194     MemoryRegister status = MemoryRegister::STATUS_REG;
195     // Example: volatile uint32_t* status_ptr = reinterpret_cast<volatile
196     //           uint32_t*>(std::to_underlying(status));
197     std::cout << "Status register address: 0x" << std::hex << std::
198         to_underlying(status) << std::dec << std::endl;
```

```

196
197     // Array indexing with enum
198     std::array<const char*, 4> reg_names = {"STATUS", "CONTROL", "DATA", "
199         CONFIG"};
200     MemoryRegister reg = MemoryRegister::CONTROL_REG;
201     size_t index = (std::to_underlying(reg) - std::to_underlying(
202         MemoryRegister::STATUS_REG)) / 4;
203     std::cout << "Register name: " << reg_names[index] << std::endl;
204
205     std::cout << "\n Before C++23:" << std::endl;
206     std::cout << "    static_cast<std::underlying_type_t<GPIOPin>>(led_pin)" <<
207         std::endl;
208     std::cout << "\n C++23:" << std::endl;
209     std::cout << "    std::to_underlying(led_pin) // Much cleaner!" << std::
210         endl;
211 }
212
213 // =====
214 // 4. constexpr FOR <cmath> - COMPILE-TIME CALCULATIONS
215 // =====
216
217 // Lookup table generation at compile time
218 constexpr std::array<float, 256> generate_sine_lookup_table() {
219     std::array<float, 256> table{};
220     for (size_t i = 0; i < 256; ++i) {
221         // C++23: std::sin is now constexpr!
222         table[i] = std::sin(2.0 * 3.14159265358979323846 * i / 256.0);
223     }
224     return table;
225 }
226
227 // PWM duty cycle calculation at compile time
228 constexpr uint16_t calculate_pwm_value(float duty_percent) {
229     return static_cast<uint16_t>(duty_percent * 65535.0f / 100.0f);
230 }
231
232 void demonstrate_constexpr_cmath() {
233     std::cout << "\n==== 4. constexpr <cmath> - COMPILE-TIME CALCULATIONS ==="
234         << std::endl;
235     std::cout << "Generate lookup tables at compile time" << std::endl;
236
237     // Sine lookup table generated at compile time
238     constexpr auto sine_table = generate_sine_lookup_table();
239     std::cout << "\nSine lookup table (256 entries) generated at compile time"
240         << std::endl;
241     std::cout << "Sample values:" << std::endl;
242     std::cout << "    sin(0°)      " << sine_table[0] << std::endl;
243     std::cout << "    sin(90°)     " << sine_table[64] << std::endl;
244     std::cout << "    sin(180°)    " << sine_table[128] << std::endl;
245     std::cout << "    sin(270°)    " << sine_table[192] << std::endl;
246
247     // PWM values calculated at compile time
248     constexpr uint16_t pwm_25 = calculate_pwm_value(25.0f);
249     constexpr uint16_t pwm_50 = calculate_pwm_value(50.0f);

```

```

244 constexpr uint16_t pwm_75 = calculate_pwm_value(75.0f);
245
246 std::cout << "\nPWM duty cycle values (calculated at compile time):" <<
247     std::endl;
248 std::cout << " 25%: " << pwm_25 << std::endl;
249 std::cout << " 50%: " << pwm_50 << std::endl;
250 std::cout << " 75%: " << pwm_75 << std::endl;
251
252 std::cout << "\n Embedded Benefits:" << std::endl;
253 std::cout << " • Zero runtime cost for lookup tables" << std::endl;
254 std::cout << " • Stored in ROM/Flash, not RAM" << std::endl;
255 std::cout << " • Fast table lookups vs real-time calculations" << std::endl;
256 std::cout << " • Deterministic execution time" << std::endl;
257 }
258 // =====
259 // 5. if consteval - COMPILE-TIME VS RUNTIME PATHS
260 // =====
261
262 constexpr uint32_t crc32_compute(const char* data, size_t len) {
263     if (consteval) {
264         // Compile-time: Simple algorithm
265         uint32_t crc = 0xFFFFFFFF;
266         for (size_t i = 0; i < len; ++i) {
267             crc ^= static_cast<uint32_t>(data[i]);
268             for (int j = 0; j < 8; ++j) {
269                 crc = (crc >> 1) ^ (0xEDB88320 & -(crc & 1));
270             }
271         }
272         return ~crc;
273     } else {
274         // Runtime: Could use hardware CRC or optimized table lookup
275         std::cout << "[Using runtime CRC algorithm]" << std::endl;
276         uint32_t crc = 0xFFFFFFFF;
277         for (size_t i = 0; i < len; ++i) {
278             crc ^= static_cast<uint32_t>(data[i]);
279             for (int j = 0; j < 8; ++j) {
280                 crc = (crc >> 1) ^ (0xEDB88320 & -(crc & 1));
281             }
282         }
283         return ~crc;
284     }
285 }
286
287 void demonstrate_if_consteval() {
288     std::cout << "\n== 5. if consteval - COMPILE-TIME VS RUNTIME ==" << std::endl;
289     std::cout << "Different code paths for compile-time and runtime" << std::endl;
290
291     // Compile-time CRC calculation
292     constexpr const char* firmware_id = "FIRMWARE_V1.2.3";
293     constexpr uint32_t compile_time_crc = crc32_compute(firmware_id, 15);

```

```
294     std::cout << "\nFirmware ID: " << firmware_id << std::endl;
295     std::cout << "CRC32 (compile-time): 0x" << std::hex << compile_time_crc <<
296         std::dec << std::endl;
297
298     // Runtime CRC calculation
299     const char* runtime_data = "RUNTIME_DATA_PACKET";
300     uint32_t runtime_crc = crc32_compute(runtime_data, 19);
301     std::cout << "\nRuntime data: " << runtime_data << std::endl;
302     std::cout << "CRC32 (runtime): 0x" << std::hex << runtime_crc << std::dec
303         << std::endl;
304
305     std::cout << "\n Embedded Applications:" << std::endl;
306     std::cout << " • Compile-time: Simple, portable algorithm" << std::endl;
307     std::cout << " • Runtime: Hardware CRC accelerator" << std::endl;
308     std::cout << " • Firmware verification checksums" << std::endl;
309     std::cout << " • Protocol integrity checks" << std::endl;
310 }
311
312 // =====
313 // 6. std::unreachable - OPTIMIZATION HINTS FOR COMPILER
314 // =====
315
316 enum class DeviceState : uint8_t {
317     IDLE = 0,
318     RUNNING = 1,
319     STOPPED = 2,
320     ERROR = 3
321 };
322
323 [[nodiscard]] constexpr const char* device_state_name(DeviceState state) {
324     switch (state) {
325         case DeviceState::IDLE:    return "IDLE";
326         case DeviceState::RUNNING: return "RUNNING";
327         case DeviceState::STOPPED: return "STOPPED";
328         case DeviceState::ERROR:   return "ERROR";
329     }
330     std::unreachable(); // Tell compiler all cases covered
331 }
332
333 uint32_t process_command(uint8_t cmd) {
334     // Note: cmd >= 0 always true for unsigned type, kept for documentation
335     if (cmd <= 3) {
336         return cmd * 100; // Valid command processing
337     }
338
339     // Invalid command - should never happen with validated input
340     std::unreachable(); // Optimization hint
341 }
342
343 void demonstrate_unreachable() {
344     std::cout << "\n== 6. std::unreachable - COMPILER OPTIMIZATION ==" <<
345         std::endl;
346     std::cout << "Tell compiler certain code paths are impossible" << std::endl;
```

```

344     std::cout << "\nDevice states:" << std::endl;
345     std::cout << "    " << device_state_name(DeviceState::IDLE) << std::endl;
346     std::cout << "    " << device_state_name(DeviceState::RUNNING) << std::endl;
347     std::cout << "    " << device_state_name(DeviceState::STOPPED) << std::endl;
348     std::cout << "    " << device_state_name(DeviceState::ERROR) << std::endl;
349
350
351     std::cout << "\nCommand processing:" << std::endl;
352     std::cout << "    Command 0: " << process_command(0) << std::endl;
353     std::cout << "    Command 2: " << process_command(2) << std::endl;
354
355     std::cout << "\n Optimization Benefits:" << std::endl;
356     std::cout << "    • Eliminates dead code paths" << std::endl;
357     std::cout << "    • Better branch prediction" << std::endl;
358     std::cout << "    • Smaller code size" << std::endl;
359     std::cout << "    • Faster execution" << std::endl;
360
361     std::cout << "\n    WARNING: Reaching std::unreachable() is UB!" << std::endl;
362 }
363
364 // =====
365 // 7. SIZE_T LITERAL SUFFIX (uz/z) - TYPE-SAFE SIZES
366 // =====
367
368 void demonstrate_size_literals() {
369     std::cout << "\n== 7. SIZE_T LITERAL SUFFIX - TYPE SAFETY ==" << std::endl;
370     std::cout << "Avoid unsigned vs signed comparison warnings" << std::endl;
371
372     std::vector<uint32_t> buffer = {1, 2, 3, 4, 5};
373
374     // Old way - warning: comparison between signed and unsigned
375     // for (int i = 0; i < buffer.size(); ++i) { } // Warning!
376
377     // C++23 way - type-safe
378     constexpr size_t BUFFER_SIZE = 256uz; // uz suffix = size_t
379     std::array<uint8_t, BUFFER_SIZE> uart_buffer{};
380
381     std::cout << "\nBuffer allocations:" << std::endl;
382     std::cout << "    UART buffer: " << BUFFER_SIZE << " bytes" << std::endl;
383     std::cout << "    Vector size: " << buffer.size() << " elements" << std::endl;
384     std::cout << "    Array capacity: " << uart_buffer.size() << " bytes" << std::endl;
385
386     // No warning with uz suffix
387     if (buffer.size() > 3uz) {
388         std::cout << "    Buffer has more than 3 elements" << std::endl;
389     }
390
391     std::cout << "\n Before C++23:" << std::endl;
392     std::cout << "    if (buffer.size() > 3)      // May warn" << std::endl;
393     std::cout << "    if (buffer.size() > 3u)     // Wrong type (unsigned)" <<

```

```
        std::endl;
394     std::cout << "    if (buffer.size() > 3UL)    // Platform dependent" << std
            ::endl;
395     std::cout << "\n C++23:" << std::endl;
396     std::cout << "    if (buffer.size() > 3uz)    // Correct type!" << std::endl
            ;
397 }
398
399 // =====
400 // 8. MULTIDIMENSIONAL SUBSCRIPT OPERATOR
401 // =====
402
403 template<typename T, size_t Rows, size_t Cols>
404 class Matrix {
405 private:
406     std::array<T, Rows * Cols> data;
407
408 public:
409     // C++23: Multi-dimensional subscript operator
410     // Note: Requires GCC 14+, Clang 17+, or MSVC 2022 17.8+
411 #if defined(__cpp_multidimensional_subscript) &&
412     __cpp_multidimensional_subscript >= 202110L
413     constexpr T& operator[](size_t row, size_t col) {
414         return data[row * Cols + col];
415     }
416
417     constexpr const T& operator[](size_t row, size_t col) const {
418         return data[row * Cols + col];
419     }
420 #endif
421
422     // Fallback: Traditional at() function for older compilers
423     constexpr T& at(size_t row, size_t col) {
424         return data[row * Cols + col];
425     }
426
427     constexpr const T& at(size_t row, size_t col) const {
428         return data[row * Cols + col];
429     }
430
431     constexpr void fill(T value) {
432         data.fill(value);
433     }
434 };
435
436 void demonstrate_multidim_subscript() {
437     std::cout << "\n== 8. MULTIDIMENSIONAL SUBSCRIPT OPERATOR ==" << std::
            endl;
438
439 #if defined(__cpp_multidimensional_subscript) &&
440     __cpp_multidimensional_subscript >= 202110L
441     std::cout << " Multi-dimensional operator[] supported!" << std::endl;
442     std::cout << "Direct matrix[row, col] syntax" << std::endl;
443 }
```

```
442 Matrix<uint16_t, 3, 3> sensor_data;
443
444 // C++23: Clean syntax for 2D array access
445 sensor_data[0, 0] = 100;
446 sensor_data[0, 1] = 150;
447 sensor_data[0, 2] = 200;
448 sensor_data[1, 0] = 250;
449 sensor_data[1, 1] = 300;
450 sensor_data[1, 2] = 350;
451 sensor_data[2, 0] = 400;
452 sensor_data[2, 1] = 450;
453 sensor_data[2, 2] = 500;
454
455 std::cout << "\n3x3 Sensor data matrix:" << std::endl;
456 for (size_t row = 0; row < 3; ++row) {
457     std::cout << " ";
458     for (size_t col = 0; col < 3; ++col) {
459         std::cout << sensor_data[row, col] << "\t";
460     }
461     std::cout << std::endl;
462 }
463
464 std::cout << "\n C++23 syntax:" << std::endl;
465 std::cout << "    matrix[row, col]" // Direct syntax! << std::endl;
466
467 #else
468
469 std::cout << " Multi-dimensional operator[] requires GCC 14+, Clang 17+,
470           or MSVC 17.8+" << std::endl;
471 std::cout << "Using fallback at(row, col) method for demonstration" << std
472           ::endl;
473
474 Matrix<uint16_t, 3, 3> sensor_data;
475
476 // Fallback: Use at() method
477 sensor_data.at(0, 0) = 100;
478 sensor_data.at(0, 1) = 150;
479 sensor_data.at(0, 2) = 200;
480 sensor_data.at(1, 0) = 250;
481 sensor_data.at(1, 1) = 300;
482 sensor_data.at(1, 2) = 350;
483 sensor_data.at(2, 0) = 400;
484 sensor_data.at(2, 1) = 450;
485 sensor_data.at(2, 2) = 500;
486
487 std::cout << "\n3x3 Sensor data matrix (using at() method):" << std::endl;
488 for (size_t row = 0; row < 3; ++row) {
489     std::cout << " ";
490     for (size_t col = 0; col < 3; ++col) {
491         std::cout << sensor_data.at(row, col) << "\t";
492     }
493     std::cout << std::endl;
494 }
```

```
494     std::cout << "\n Before C++23:" << std::endl;
495     std::cout << "    matrix[row][col]      // Traditional double subscript" <<
496             std::endl;
496     std::cout << "    matrix.at(row, col)   // Member function" << std::endl;
497     std::cout << "\n C++23 (when compiler supports):" << std::endl;
498     std::cout << "    matrix[row, col]      // Direct multi-dimensional syntax!
498             " << std::endl;
499
500 #endif
501 }
502
503 // =====
504 // 9. PRACTICAL EMBEDDED EXAMPLE: FIRMWARE STATUS SYSTEM
505 // =====
506
507 #if __cplusplus >= 202302L && __has_include(<expected>)
508
509 enum class FirmwareError {
510     ConfigInvalid,
511     MemoryInsufficient,
512     HardwareNotResponding,
513     ChecksumMismatch
514 };
515
516 const char* firmware_error_name(FirmwareError err) {
517     switch (err) {
518         case FirmwareError::ConfigInvalid: return "Configuration invalid";
519         case FirmwareError::MemoryInsufficient: return "Insufficient memory";
520         case FirmwareError::HardwareNotResponding: return "Hardware not
520             responding";
521         case FirmwareError::ChecksumMismatch: return "Checksum mismatch";
522     }
523     std::unreachable();
524 }
525
526 class FirmwareStatus {
527 public:
528     std::expected<bool, FirmwareError> initialize() {
529         std::cout << " [1] Checking configuration..." << std::endl;
530         // Simulate config check
531
532         std::cout << " [2] Allocating memory..." << std::endl;
533         // Simulate memory allocation
534
535         std::cout << " [3] Initializing hardware..." << std::endl;
536         // Simulate hardware init
537
538         std::cout << " [4] Verifying checksums..." << std::endl;
539         constexpr uint32_t expected_crc = 0x12345678;
540         constexpr uint32_t actual_crc = 0x12345678;
541
542         if (expected_crc != actual_crc) {
543             return std::unexpected(FirmwareError::ChecksumMismatch);
544         }
545 }
```

```
545         return true;
546     }
547
548     std::expected<uint32_t, FirmwareError> get_hardware_id() {
549         // Simulate hardware ID read
550         return 0xABCD1234;
551     }
552 }
553 };
554
555 void demonstrate_practical_firmware() {
556     std::cout << "\n== 9. PRACTICAL EXAMPLE: FIRMWARE STATUS =="
557         << endl;
558     std::cout << "C++23 features in embedded firmware" << endl;
559
560     FirmwareStatus firmware;
561
562     std::cout << "\nInitializing firmware..." << endl;
563     auto init_result = firmware.initialize();
564
565     if (init_result) {
566         std::cout << " Firmware initialized successfully" << endl;
567
568         auto hw_id = firmware.get_hardware_id();
569         if (hw_id) {
570             std::cout << " Hardware ID: 0x" << std::hex << *hw_id << std::dec
571                         << std::endl;
572         }
573     } else {
574         std::cout << " Initialization failed: "
575             << firmware_error_name(init_result.error()) << endl;
576     }
577
578     std::cout << "\n This firmware code:" << endl;
579     std::cout << " • Uses std::expected (no exceptions)" << endl;
580     std::cout << " • Works with -fno-exceptions" << endl;
581     std::cout << " • Deterministic error handling" << endl;
582     std::cout << " • Suitable for safety-critical systems" << endl;
583 }
584
585 #else
586 void demonstrate_practical_firmware() {
587     std::cout << "\n== 9. PRACTICAL EXAMPLE: FIRMWARE STATUS =="
588         << endl;
589     std::cout << " Requires C++23 std::expected" << endl;
590 }
591 #endif
592
593 // =====
594 // MAIN FUNCTION
595 // =====
596
597 int main() {
598     std::cout << "\n
```

```
      =====" <<
596     std::endl;
std::cout << "  C++23 FEATURES FOR EMBEDDED SYSTEMS & FIRMWARE" << std::
      endl;
597     std::cout << "
      =====" <<
      std::endl;
598     std::cout << "Focused on: Firmware, RTOS, Embedded Linux" << std::endl;
599
600     demonstrate_expected();
601     demonstrate_byteswap();
602     demonstrate_to_underlying();
603     demonstrate_constexpr_cmath();
604     demonstrate_if_consteval();
605     demonstrate_unreachable();
606     demonstrate_size_literals();
607     demonstrate_multidim_subscript();
608     demonstrate_practical_firmware();
609
610     std::cout << "\n
      =====" <<
      std::endl;
611     std::cout << "  C++23 FEATURES SUMMARY FOR EMBEDDED" << std::endl;
612     std::cout << "
      =====" <<
      std::endl;
613
614     std::cout << "\n MUST-HAVE FOR FIRMWARE:" << std::endl;
615     std::cout << "\n1  std::expected<T, E>" << std::endl;
616     std::cout << "  •  No exception overhead" << std::endl;
617     std::cout << "  •  Works with -fno-exceptions" << std::endl;
618     std::cout << "  •  Explicit error handling" << std::endl;
619     std::cout << "  •  Perfect for RTOS and firmware" << std::endl;
620     std::cout << "  Use case: Sensor reads, hardware init, protocol parsing"
      << std::endl;
621
622     std::cout << "\n2  std::byteswap" << std::endl;
623     std::cout << "  •  Endianness conversion" << std::endl;
624     std::cout << "  •  Network protocol implementation" << std::endl;
625     std::cout << "  •  Binary file format parsing" << std::endl;
626     std::cout << "  •  Hardware register access" << std::endl;
627     std::cout << "  Use case: TCP/IP stack, file systems, cross-platform data
      " << std::endl;
628
629     std::cout << "\n3  std::to_underlying" << std::endl;
630     std::cout << "  •  Cleaner enum to integer conversion" << std::endl;
631     std::cout << "  •  Memory-mapped register access" << std::endl;
632     std::cout << "  •  GPIO pin manipulation" << std::endl;
633     std::cout << "  •  Hardware abstraction layers" << std::endl;
634     std::cout << "  Use case: Register maps, pin assignments, state machines"
      << std::endl;
635
636     std::cout << "\n4  constexpr <cmath>" << std::endl;
637     std::cout << "  •  Compile-time lookup table generation" << std::endl;
```

```

638     std::cout << " • Stored in ROM, not RAM" << std::endl;
639     std::cout << " • Zero runtime cost" << std::endl;
640     std::cout << " • Fast deterministic execution" << std::endl;
641     std::cout << " Use case: Sine/cosine tables, PWM values, calibration
642           data" << std::endl;

643     std::cout << "\n5 if consteval" << std::endl;
644     std::cout << " • Different paths for compile-time vs runtime" << std::
645           endl;
645     std::cout << " • Compile-time: simple algorithm" << std::endl;
646     std::cout << " • Runtime: hardware accelerator" << std::endl;
647     std::cout << " Use case: CRC calculation, crypto, compression" << std::
648           endl;

649     std::cout << "\n6 std::unreachable" << std::endl;
650     std::cout << " • Compiler optimization hints" << std::endl;
651     std::cout << " • Smaller code size" << std::endl;
652     std::cout << " • Better branch prediction" << std::endl;
653     std::cout << " Use case: State machines, validated inputs, switch
654           statements" << std::endl;

655     std::cout << "\n7 Size literal suffix (uz)" << std::endl;
656     std::cout << " • Type-safe size comparisons" << std::endl;
657     std::cout << " • No signed/unsigned warnings" << std::endl;
658     std::cout << " • Cleaner buffer management code" << std::endl;
659     std::cout << " Use case: Buffer sizes, array indexing, memory allocation
660           " << std::endl;

661     std::cout << "\n8 Multidimensional operator[]" << std::endl;
662     std::cout << " • Direct matrix[row, col] syntax" << std::endl;
663     std::cout << " • Cleaner multi-dimensional arrays" << std::endl;
664     std::cout << " • Natural matrix/tensor access" << std::endl;
665     std::cout << " Use case: Image buffers, sensor arrays, DSP data" << std
666           ::endl;

667     std::cout << "\n COMPILER SUPPORT (January 2026):" << std::endl;
668     std::cout << "\n   GCC 12+:" << std::endl;
669     std::cout << " • std::expected (use GCC 13+)" << std::endl;
670     std::cout << " • std::byteswap " << std::endl;
671     std::cout << " • std::to_underlying " << std::endl;
672     std::cout << " • if consteval " << std::endl;

673     std::cout << "\n   Clang 16+:" << std::endl;
674     std::cout << " • std::expected " << std::endl;
675     std::cout << " • Most C++23 features " << std::endl;

676     std::cout << "\n   MSVC 2022 (17.6+):" << std::endl;
677     std::cout << " • Excellent C++23 support " << std::endl;

678     std::cout << "\n   ARM Compiler 6:" << std::endl;
679     std::cout << " • Based on Clang, good C++23 support " << std::endl;

680     std::cout << "\n RECOMMENDED EMBEDDED COMPILER FLAGS:" << std::endl;
681     std::cout << " -std=c++23 # Enable C++23" << std::endl;

```

```
686     std::cout << " -fno-exceptions           # Disable exceptions" << std::endl
687     ;
688     std::cout << " -fno-rtti             # Disable RTTI" << std::endl;
689     std::cout << " -Os or -O2            # Optimize for size/speed" << std::
690     endl;
691     std::cout << " -flto                  # Link-time optimization" << std::
692     endl;
693     std::cout << " -ffunction-sections    # Dead code elimination" << std::
694     endl;
695
696     std::cout << "\n MIGRATION STRATEGY:" << std::endl;
697     std::cout << " 1. Start with std::to_underlying (easy win)" << std::endl;
698     std::cout << " 2. Add constexpr lookup tables (ROM savings)" << std::endl
699     ;
700     std::cout << " 3. Replace error codes with std::expected (safer)" << std
701     ::endl;
702     std::cout << " 4. Use std::byteswap for protocols (cleaner)" << std::endl
703     ;
704     std::cout << " 5. Add std::unreachable for optimizations" << std::endl;
705
706     std::cout << "\n
707     ======\n" << std::endl;
708
709     return 0;
710 }
```

17 Source Code: CppWrappingCLibrary.cpp

File: src/CppWrappingCLibrary.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // WRAPPING C LIBRARIES IN MODERN C++
3 // =====
4 // This example demonstrates best practices for wrapping C libraries
5 // (TCP/UDP sockets) in modern C++ with:
6 // - RAII for automatic resource management
7 // - noexcept for exception safety
8 // - [[nodiscard]] for preventing ignored errors
9 // - extern "C" for C library linkage
10 // - Strong types and error handling
11 //
12 // TOPICS COVERED:
13 // 1. C library integration (POSIX sockets)
14 // 2. RAII wrappers for C resources
15 // 3. noexcept specifications (safe and unsafe uses)
16 // 4. [[nodiscard]] attribute
17 // 5. std::optional and std::expected for error handling
18 // 6. Strong typing over raw C types
19 // =====
20
21 #include <iostream>
22 #include <string>
23 #include <string_view>
24 #include <optional>
25 #include <system_error>
26 #include <cstring>
27 #include <vector>
28 #include <memory>
29 #include <chrono>
30
31 // Platform-specific socket headers
32 #ifdef _WIN32
33     #include <winsock2.h>
34     #include <ws2tcpip.h>
35     #pragma comment(lib, "ws2_32.lib")
36     using socket_t = SOCKET;
37     constexpr socket_t INVALID_SOCKET_VALUE = INVALID_SOCKET;
38     #define CLOSE_SOCKET closesocket
39 #else
40     #include <sys/socket.h>
41     #include <netinet/in.h>
42     #include <arpa/inet.h>
43     #include <unistd.h>
44     #include <fcntl.h>
45     #include <netdb.h>
46     using socket_t = int;
47     constexpr socket_t INVALID_SOCKET_VALUE = -1;
48     #define CLOSE_SOCKET close
49 #endif
```

```
50 // =====
51 // SECTION 1: C LIBRARY FUNCTIONS (extern "C" linkage)
52 // =====
53 // These are C functions - they use C calling conventions and linkage
54 // extern "C" prevents C++ name mangling
55
56 extern "C" {
57     // Example: Custom C utility function we might have in a C library
58     int c_validate_port(int port) {
59         return (port > 0 && port <= 65535) ? 1 : 0;
60     }
61
62     // Note: socket(), bind(), listen(), etc. are already extern "C"
63     // from system headers, so we don't redeclare them
64 }
65
66 // =====
67 // SECTION 2: ERROR HANDLING TYPES
68 // =====
69
70 // Modern C++ error type using std::optional
71 enum class SocketError {
72     Success,
73     InvalidSocket,
74     BindFailed,
75     ListenFailed,
76     ConnectFailed,
77     SendFailed,
78     ReceiveFailed,
79     AcceptFailed,
80     SocketOptionFailed,
81     AddressResolutionFailed,
82     TimeoutExpired,
83     WouldBlock
84 };
85
86
87 // Convert error code to string
88 [[nodiscard]] constexpr std::string_view error_to_string(SocketError error)
89     noexcept {
90     switch (error) {
91         case SocketError::Success: return "Success";
92         case SocketError::InvalidSocket: return "Invalid socket";
93         case SocketError::BindFailed: return "Bind failed";
94         case SocketError::ListenFailed: return "Listen failed";
95         case SocketError::ConnectFailed: return "Connect failed";
96         case SocketError::SendFailed: return "Send failed";
97         case SocketError::ReceiveFailed: return "Receive failed";
98         case SocketError::AcceptFailed: return "Accept failed";
99         case SocketError::SocketOptionFailed: return "Socket option failed";
100        case SocketError::AddressResolutionFailed: return "Address resolution
101            failed";
102        case SocketError::TimeoutExpired: return "Timeout expired";
103        case SocketError::WouldBlock: return "Operation would block";
```

```
102     default: return "Unknown error";
103 }
104 }
105
106 // Result type for operations that can fail
107 template<typename T>
108 using Result = std::optional<T>;
109
110 // =====
111 // SECTION 3: RAII SOCKET WRAPPER
112 // =====
113 // Modern C++ wrapper that automatically manages socket lifecycle
114
115 class Socket {
116 private:
117     socket_t fd_;
118     bool is_valid_;
119
120 public:
121     // Constructor - creates socket
122     // noexcept(false) because it may throw
123     Socket(int domain = AF_INET, int type = SOCK_STREAM, int protocol = 0)
124         : fd_(::socket(domain, type, protocol)),
125           is_valid_(fd_ != INVALID_SOCKET_VALUE) {
126
127         if (!is_valid_) {
128             std::cerr << "Socket creation failed" << std::endl;
129         } else {
130             std::cout << " Socket created (fd=" << fd_ << ")" << std::endl;
131         }
132     }
133
134     // Tag type for from_fd constructor
135     struct from_fd_t {};
136     static constexpr from_fd_t from_fd{};
137
138     // Construct from existing socket (for accept())
139     Socket(from_fd_t, socket_t fd) noexcept
140         : fd_(fd), is_valid_(fd != INVALID_SOCKET_VALUE) {}
141
142     // Destructor - RAII automatically closes socket
143     // noexcept because destructors should not throw
144     ~Socket() noexcept {
145         if (is_valid_ && fd_ != INVALID_SOCKET_VALUE) {
146             std::cout << " Socket closing (fd=" << fd_ << ")" << std::endl;
147             CLOSE_SOCKET(fd_);
148         }
149     }
150
151     // Delete copy operations - sockets are unique resources
152     Socket(const Socket&) = delete;
153     Socket& operator=(const Socket&) = delete;
154
155     // Move operations - transfer ownership
```

```
156     Socket(Socket&& other) noexcept
157         : fd_(other.fd_), is_valid_(other.is_valid_) {
158             other.fd_ = INVALID_SOCKET_VALUE;
159             other.is_valid_ = false;
160         }
161
162     Socket& operator=(Socket&& other) noexcept {
163         if (this != &other) {
164             if (is_valid_) {
165                 CLOSE_SOCKET(fd_);
166             }
167             fd_ = other.fd_;
168             is_valid_ = other.is_valid_;
169             other.fd_ = INVALID_SOCKET_VALUE;
170             other.is_valid_ = false;
171         }
172         return *this;
173     }
174
175     // Check if socket is valid
176     // [[nodiscard]] - result should not be ignored!
177     [[nodiscard]] bool is_valid() const noexcept {
178         return is_valid_;
179     }
180
181     // Get raw socket descriptor
182     // [[nodiscard]] - caller needs this value!
183     [[nodiscard]] socket_t get() const noexcept {
184         return fd_;
185     }
186
187     // Bind to address
188     // [[nodiscard]] - error must be checked!
189     [[nodiscard]] SocketError bind(const std::string& address, uint16_t port)
190         noexcept {
191         if (!is_valid_) {
192             return SocketError::InvalidSocket;
193         }
194
195         sockaddr_in addr{};
196         addr.sin_family = AF_INET;
197         addr.sin_port = htons(port);
198
199         if (address.empty() || address == "0.0.0.0") {
200             addr.sin_addr.s_addr = INADDR_ANY;
201         } else {
202             addr.sin_addr.s_addr = inet_addr(address.c_str());
203         }
204
205         if (::bind(fd_, reinterpret_cast<sockaddr*>(&addr), sizeof(addr)) < 0)
206         {
207             return SocketError::BindFailed;
208         }
209     }
```

```
208     std::cout << " Socket bound to " << address << ":" << port << std::endl;
209     return SocketError::Success;
210 }
211
212 // Listen for connections
213 // [[nodiscard]] - error must be checked!
214 [[nodiscard]] SocketError listen(int backlog = 10) noexcept {
215     if (!is_valid_) {
216         return SocketError::InvalidSocket;
217     }
218
219     if (::listen(fd_, backlog) < 0) {
220         return SocketError::ListenFailed;
221     }
222
223     std::cout << " Socket listening (backlog=" << backlog << ")" << std::endl;
224     return SocketError::Success;
225 }
226
227 // Accept connection - returns new Socket
228 // [[nodiscard]] - must handle the result!
229 [[nodiscard]] Result<Socket> accept() noexcept {
230     if (!is_valid_) {
231         return std::nullopt;
232     }
233
234     sockaddr_in client_addr{};
235     socklen_t addr_len = sizeof(client_addr);
236
237     socket_t client_fd = ::accept(fd_, reinterpret_cast<sockaddr*>(&client_addr), &addr_len);
238
239     if (client_fd == INVALID_SOCKET_VALUE) {
240         return std::nullopt;
241     }
242
243     char client_ip[INET_ADDRSTRLEN];
244     inet_ntop(AF_INET, &client_addr.sin_addr, client_ip, INET_ADDRSTRLEN);
245     std::cout << " Connection accepted from " << client_ip
246             << ":" << ntohs(client_addr.sin_port) << std::endl;
247
248     return Socket(Socket::from_fd, client_fd);
249 }
250
251 // Connect to remote address
252 // [[nodiscard]] - error must be checked!
253 [[nodiscard]] SocketError connect(const std::string& address, uint16_t
254     port) noexcept {
255     if (!is_valid_) {
256         return SocketError::InvalidSocket;
257     }
```

```
258     sockaddr_in addr{};
259     addr.sin_family = AF_INET;
260     addr.sin_port = htons(port);
261     addr.sin_addr.s_addr = inet_addr(address.c_str());
262
263     if (::connect(fd_, reinterpret_cast<sockaddr*>(&addr), sizeof(addr)) <
264         0) {
265         return SocketError::ConnectFailed;
266     }
267
268     std::cout << " Connected to " << address << ":" << port << std::endl;
269     return SocketError::Success;
270 }
271
272 // [[nodiscard]] - must check if send succeeded!
273 [[nodiscard]] Result<size_t> send(const std::string& data) noexcept {
274     if (!is_valid_) {
275         return std::nullopt;
276     }
277
278     ssize_t sent = ::send(fd_, data.c_str(), data.length(), 0);
279
280     if (sent < 0) {
281         return std::nullopt;
282     }
283
284     std::cout << " Sent " << sent << " bytes" << std::endl;
285     return static_cast<size_t>(sent);
286 }
287
288 // Receive data
289 // [[nodiscard]] - must handle received data!
290 [[nodiscard]] Result<std::string> receive(size_t max_length = 4096)
291     noexcept {
292     if (!is_valid_) {
293         return std::nullopt;
294     }
295
296     std::vector<char> buffer(max_length);
297     ssize_t received = ::recv(fd_, buffer.data(), buffer.size(), 0);
298
299     if (received <= 0) {
300         return std::nullopt;
301     }
302
303     std::cout << " Received " << received << " bytes" << std::endl;
304     return std::string(buffer.data(), received);
305 }
306
307 // Set socket option
308 // [[nodiscard]] - error must be checked!
309 [[nodiscard]] SocketError set_reuse_address(bool enable) noexcept {
310     if (!is_valid_) {
```

```
310         return SocketError::InvalidSocket;
311     }
312
313     int opt = enable ? 1 : 0;
314     if (setsockopt(fd_, SOL_SOCKET, SO_REUSEADDR,
315                     reinterpret_cast<const char*>(&opt), sizeof(opt)) < 0) {
316         return SocketError::SocketOptionFailed;
317     }
318
319     std::cout << " SO_REUSEADDR set to " << (enable ? "true" : "false")
320             << std::endl;
321     return SocketError::Success;
322 }
323
324 // =====
325 // SECTION 4: HIGH-LEVEL TCP SERVER CLASS
326 // =====
327
328 class TcpServer {
329 private:
330     Socket listen_socket_;
331     uint16_t port_;
332     bool is_running_;
333
334 public:
335     // Constructor
336     // noexcept(false) - may throw if initialization fails critically
337     explicit TcpServer(uint16_t port)
338         : listen_socket_(AF_INET, SOCK_STREAM, 0),
339           port_(port),
340           is_running_(false) {
341
342     if (!listen_socket_.is_valid()) {
343         throw std::runtime_error("Failed to create listen socket");
344     }
345 }
346
347     // Start server
348     // [[nodiscard]] - must check if server started successfully!
349     [[nodiscard]] SocketError start() noexcept {
350         // Enable address reuse
351         auto err = listen_socket_.set_reuse_address(true);
352         if (err != SocketError::Success) {
353             return err;
354         }
355
356         // Bind to port
357         err = listen_socket_.bind("0.0.0.0", port_);
358         if (err != SocketError::Success) {
359             return err;
360         }
361
362         // Start listening
```

```
363     err = listen_socket_.listen();
364     if (err != SocketError::Success) {
365         return err;
366     }
367
368     is_running_ = true;
369     std::cout << " TCP Server started on port " << port_ << std::endl;
370     return SocketError::Success;
371 }
372
373 // Accept one client connection
374 // [[nodiscard]] - must handle the client socket!
375 [[nodiscard]] Result<Socket> accept_client() noexcept {
376     if (!is_running_) {
377         return std::nullopt;
378     }
379     return listen_socket_.accept();
380 }
381
382 // Check if server is running
383 [[nodiscard]] bool is_running() const noexcept {
384     return is_running_;
385 }
386
387 // Stop server
388 void stop() noexcept {
389     is_running_ = false;
390     std::cout << " TCP Server stopped" << std::endl;
391 }
392 };
393
394 // =====
395 // SECTION 5: HIGH-LEVEL TCP CLIENT CLASS
396 // =====
397
398 class TcpClient {
399 private:
400     Socket socket_;
401     bool is_connected_;
402
403 public:
404     // Constructor
405     TcpClient()
406         : socket_(AF_INET, SOCK_STREAM, 0),
407           is_connected_(false) {}
408
409     // Connect to server
410     // [[nodiscard]] - must check connection status!
411     [[nodiscard]] SocketError connect(const std::string& host, uint16_t port)
412         noexcept {
413         if (!socket_.is_valid()) {
414             return SocketError::InvalidSocket;
415         }
416     }
417 }
```

```
416     auto err = socket_.connect(host, port);
417     if (err == SocketError::Success) {
418         is_connected_ = true;
419     }
420     return err;
421 }
422
423 // Send message
424 // [[nodiscard]] - must check if send succeeded!
425 [[nodiscard]] Result<size_t> send(const std::string& message) noexcept {
426     if (!is_connected_) {
427         return std::nullopt;
428     }
429     return socket_.send(message);
430 }
431
432 // Receive message
433 // [[nodiscard]] - must handle received data!
434 [[nodiscard]] Result<std::string> receive() noexcept {
435     if (!is_connected_) {
436         return std::nullopt;
437     }
438     return socket_.receive();
439 }
440
441 // Check if connected
442 [[nodiscard]] bool is_connected() const noexcept {
443     return is_connected_;
444 }
445 };
446
447 // =====
448 // SECTION 6: DEMONSTRATION OF noexcept USAGE
449 // =====
450
451 void demonstrate_noexcept() {
452     std::cout << "\n== NOEXCEPT USAGE ==" << std::endl;
453
454     std::cout << "\n SAFE noexcept usage:" << std::endl;
455     std::cout << " • Getters that don't throw: is_valid() noexcept" << std::endl;
456     std::cout << " • Destructors: ~Socket() noexcept" << std::endl;
457     std::cout << " • Move operations: Socket(Socket&&) noexcept" << std::endl;
458     std::cout << " • Simple checks: error_to_string() noexcept" << std::endl
459     ;
460
461     std::cout << "\n Operations marked noexcept (but handle errors
462     internally):" << std::endl;
463     std::cout << " • bind() noexcept - returns error code instead of
464     throwing" << std::endl;
465     std::cout << " • send() noexcept - returns std::optional for errors" <<
466     std::endl;
467     std::cout << " • receive() noexcept - returns std::optional" << std::endl;
```

```
        endl;

464     std::cout << "\n NOT noexcept (may throw):" << std::endl;
465     std::cout << " • Constructor if critical initialization fails" << std::
466         endl;
467     std::cout << " • std::string operations (may throw std::bad_alloc)" <<
468         std::endl;

469     std::cout << "\n KEY PRINCIPLE:" << std::endl;
470     std::cout << "    Mark noexcept when you guarantee no exceptions will
471         escape" << std::endl;
472     std::cout << "    Use error codes/std::optional for expected failures" <<
473         std::endl;
474 }

475 // =====
476 // SECTION 7: DEMONSTRATION OF [[nodiscard]]
477 // =====

478 void demonstrate_nodiscard() {
479     std::cout << "\n== [nodiscard] ATTRIBUTE ==" << std::endl;
480
481     std::cout << "\n [[nodiscard]] forces checking return values:" << std::
482         endl;
483
484     Socket sock(AF_INET, SOCK_STREAM, 0);
485
486     // GOOD: Checking the return value
487     if (auto err = sock.bind("0.0.0.0", 8080); err != SocketError::Success) {
488         std::cout << "    Bind error checked: " << error_to_string(err) << std
489             ::endl;
490     }
491
492     // BAD: Would produce compiler warning (if we uncommented)
493     // sock.bind("0.0.0.0", 8080); // Warning: ignoring return value!
494
495     std::cout << "\n BENEFITS:" << std::endl;
496     std::cout << "    Prevents forgetting to check errors" << std::endl;
497     std::cout << "    Compiler warns about ignored return values" << std::
498         endl;
499     std::cout << "    Makes APIs safer to use" << std::endl;
500     std::cout << "    Self-documenting - shows value is important" << std::
501         endl;
502 }

503 // =====
504 // SECTION 8: RAII BENEFITS DEMONSTRATION
505 // =====

506 void demonstrate_raii() {
507     std::cout << "\n== RAI AUTOMATIC RESOURCE MANAGEMENT ==" << std::endl;
508
509     std::cout << "\nCreating socket in scope:" << std::endl;
510 }
```

```

509     Socket sock(AF_INET, SOCK_STREAM, 0);
510     auto err = sock.bind("0.0.0.0", 9999);
511     if (err == SocketError::Success) {
512         std::cout << "    Socket is active (fd=" << sock.get() << ")" <<
513                     std::endl;
514     }
515     // No need to manually close - destructor handles it!
516 }
517 std::cout << "    Socket automatically closed when out of scope!" << std
518     ::endl;
519
520 std::cout << "\n RAII GUARANTEES:" << std::endl;
521 std::cout << "    Resource acquired in constructor" << std::endl;
522 std::cout << "    Resource released in destructor" << std::endl;
523 std::cout << "    Exception-safe - cleanup always happens" << std::endl;
524 std::cout << "    No manual cleanup needed" << std::endl;
525 std::cout << "    No resource leaks possible" << std::endl;
526 }
527
528 // =====
529 // SECTION 9: EXTERN "C" USAGE
530 // =====
531
532 void demonstrate_extern_c() {
533     std::cout << "\n==== EXTERN \"C\" LINKAGE ===" << std::endl;
534
535     std::cout << "\n Purpose: Interface with C libraries" << std::endl;
536     std::cout << " • Prevents C++ name mangling" << std::endl;
537     std::cout << " • Allows C code to call C++ functions" << std::endl;
538     std::cout << " • Enables linking with C libraries" << std::endl;
539
540     // Call our C function
541     int port = 8080;
542     int is_valid = c_validate_port(port);
543     std::cout << "\n Called C function: c_validate_port(" << port << ") = "
544                 << (is_valid ? "valid" : "invalid") << std::endl;
545
546     std::cout << "\n USAGE PATTERNS:" << std::endl;
547     std::cout << "    extern \"C\" { ... }      - Wrap C declarations" << std::
548                     endl;
549     std::cout << "    #ifdef __cplusplus      - Conditional compilation" << std
550                     ::endl;
551     std::cout << "    System headers (socket.h) already use extern \"C\"" <<
552                     std::endl;
553 }
554
555 // =====
556 // SECTION 10: PRACTICAL EXAMPLES
557 // =====
558
559 void example_echo_server() {
560     std::cout << "\n==== EXAMPLE: SIMPLE ECHO SERVER ===" << std::endl;
561     std::cout << "Simulating echo server workflow...\n" << std::endl;
562 }
```

```
558     try {
559         TcpServer server(12345);
560
561         // Start server
562         if (auto err = server.start(); err != SocketError::Success) {
563             std::cout << "Failed to start server: " << error_to_string(err) <<
564             std::endl;
565             return;
566         }
567
568         std::cout << "Echo server would accept connections and echo messages
569             ..." << std::endl;
570         std::cout << "(Actual network operations skipped for demo)" << std::
571             endl;
572
573         server.stop();
574
575     } catch (const std::exception& e) {
576         std::cout << "Exception: " << e.what() << std::endl;
577     }
578
579 // =====
580 // MAIN FUNCTION
581 // =====
582
583 int main() {
584     std::cout << "\n";
585     std::cout << "                                         \n";
586     std::cout << "WRAPPING C LIBRARIES IN MODERN C++\n";
587     std::cout << "
588             \n";
589     std::cout << "    Demonstrates: RAI, noexcept, [[nodiscard]], extern \"C\""
590             \n";
591     std::cout << "    Example: TCP/UDP Socket Wrapper\n";
592     std::cout << "
593             \n";
594
595 #ifdef _WIN32
596     // Initialize Winsock on Windows
597     WSADATA wsaData;
598     if (WSAStartup(MAKEWORD(2, 2), &wsaData) != 0) {
599         std::cerr << "WSAStartup failed" << std::endl;
600         return 1;
601     }
602     std::cout << "\n Winsock initialized (Windows)" << std::endl;
603 #else
604     std::cout << "\n Using POSIX sockets (Linux/Unix)" << std::endl;
605 #endif
```

```
604 demonstrate_raii();
605 demonstrate_noexcept();
606 demonstrate_nodiscard();
607 demonstrate_extern_c();
608 example_echo_server();

609
610 std::cout << "\n" << std::string(70, '=') << std::endl;
611 std::cout << "BEST PRACTICES SUMMARY:\n";
612 std::cout << std::string(70, '=') << std::endl;

613
614 std::cout << "\n1. RAI (Resource Acquisition Is Initialization):" << std
       ::endl;
615 std::cout << "      Acquire resources in constructor" << std::endl;
616 std::cout << "      Release resources in destructor" << std::endl;
617 std::cout << "      Make classes non-copyable for unique resources" << std
       ::endl;
618 std::cout << "      Implement move semantics for transfer" << std::endl;
619
620 std::cout << "\n2. noexcept Usage:" << std::endl;
621 std::cout << "      Mark destructors noexcept (implicit in C++11+)" << std
       ::endl;
622 std::cout << "      Mark move operations noexcept (enables optimizations)" <<
       std::endl;
623 std::cout << "      Mark operations that handle errors via return codes" <<
       std::endl;
624 std::cout << "      DON'T mark operations that may allocate memory" << std
       ::endl;
625
626 std::cout << "\n3. [[nodiscard]] Usage:" << std::endl;
627 std::cout << "      Use for error codes that must be checked" << std::endl;
628 std::cout << "      Use for expensive operations (no wasted work)" << std::
       endl;
629 std::cout << "      Use for functions where ignoring result is likely a bug
       " << std::endl;
630 std::cout << "      Makes APIs self-documenting and safer" << std::endl;
631
632 std::cout << "\n4. extern \"C\" Linkage:" << std::endl;
633 std::cout << "      Wrap C library includes in extern \"C\" blocks" << std
       ::endl;
634 std::cout << "      Use #ifdef __cplusplus for C/C++ compatibility" << std
       ::endl;
635 std::cout << "      Only C-compatible functions can be extern \"C\"" << std
       ::endl;
636 std::cout << "      No overloading, no classes, no templates" << std::endl;
637
638 std::cout << "\n5. C/C++ Interop Patterns:" << std::endl;
639 std::cout << "      Create thin C++ wrapper classes (RAII)" << std::endl;
640 std::cout << "      Hide C types behind strong C++ types" << std::endl;
641 std::cout << "      Use std::optional for nullable results" << std::endl;
642 std::cout << "      Use error codes/exceptions instead of C error globals"
       << std::endl;
643 std::cout << "      Provide modern C++ interfaces (string_view, span, etc.)"
       << std::endl;
644
```

```
645     std::cout << "\n6. Modern C++ Features for C Wrappers:" << std::endl;
646     std::cout << "    std::optional<T> for operations that may fail" << std::
647         endl;
647     std::cout << "    std::string_view for non-owning string parameters" <<
648         std::endl;
648     std::cout << "    std::span<T> for array views (C++20)" << std::endl;
649     std::cout << "    std::unique_ptr with custom deleter" << std::endl;
650     std::cout << "    enum class for type-safe error codes" << std::endl;
651
652     std::cout << "\n All socket resources properly cleaned up by RAII!\n" <<
652         std::endl;
653
654 #ifdef _WIN32
655     WSACleanup();
656     std::cout << " Winsock cleaned up\n" << std::endl;
657 #endif
658
659     return 0;
660 }
```

18 Source Code: CreatingCApiFromCpp.cpp

File: src/CreatingCApiFromCpp.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // CREATING A C API FROM C++ CODE
3 // =====
4 // This example demonstrates how to expose C++ functionality through
5 // a C-compatible API. This is the REVERSE direction from the previous
6 // example - we're wrapping C++ in C, not C in C++.
7 //
8 // USE CASES:
9 // - Creating libraries usable from C code
10 // - Plugin systems with C interfaces
11 // - FFI (Foreign Function Interface) for Python, Rust, etc.
12 // - Legacy code integration
13 // - Stable ABI across compiler versions
14 //
15 // TOPICS COVERED:
16 // 1. Opaque pointers (pimpl idiom for C API)
17 // 2. extern "C" for C linkage
18 // 3. Exception handling across C boundary
19 // 4. C++ features hidden behind C API
20 // 5. Memory management strategies
21 // 6. Header guards and C/C++ compatibility
22 // =====
23
24 #include <iostream>
25 #include <string>
26 #include <vector>
27 #include <memory>
28 #include <cstring>
29 #include <stdexcept>
30 #include <algorithm>
31 #include <cstdint>
32
33 // =====
34 // SECTION 1: C++ IMPLEMENTATION (INTERNAL)
35 // =====
36 // This is the actual C++ code with modern features that we'll expose
37 // through a C API
38
39 namespace image_processing {
40
41 class Image {
42 private:
43     size_t width_;
44     size_t height_;
45     std::vector<uint8_t> pixels_;
46
47 public:
48     Image(size_t width, size_t height)
49         : width_(width), height_(height), pixels_(width * height, 0) {
```

```
50     std::cout << " C++ Image created (" << width_ << "x" << height_ << ")"
51         << std::endl;
52 }
53 ~Image() {
54     std::cout << " C++ Image destroyed" << std::endl;
55 }
56
57 // C++ features: const correctness, exceptions
58 size_t width() const noexcept { return width_; }
59 size_t height() const noexcept { return height_; }
60
61 uint8_t& at(size_t x, size_t y) {
62     if (x >= width_ || y >= height_) {
63         throw std::out_of_range("Pixel coordinates out of range");
64     }
65     return pixels_[y * width_ + x];
66 }
67
68 const uint8_t& at(size_t x, size_t y) const {
69     if (x >= width_ || y >= height_) {
70         throw std::out_of_range("Pixel coordinates out of range");
71     }
72     return pixels_[y * width_ + x];
73 }
74
75 // Modern C++ algorithm
76 void invert() {
77     std::transform(pixels_.begin(), pixels_.end(), pixels_.begin(),
78                   [] (uint8_t pixel) { return 255 - pixel; });
79     std::cout << " Image inverted (C++ algorithm)" << std::endl;
80 }
81
82 void fill(uint8_t value) {
83     std::fill(pixels_.begin(), pixels_.end(), value);
84     std::cout << " Image filled with value " << static_cast<int>(value)
85         << std::endl;
86 }
87
88 void apply_threshold(uint8_t threshold) {
89     for (auto& pixel : pixels_) {
90         pixel = (pixel >= threshold) ? 255 : 0;
91     }
92     std::cout << " Threshold applied at " << static_cast<int>(threshold)
93         << std::endl;
94 }
95
96 // Get raw data
97 const uint8_t* data() const noexcept { return pixels_.data(); }
98 size_t size() const noexcept { return pixels_.size(); }
99 };
100 } // namespace image_processing
```

```
101 // =====
102 // SECTION 2: C API HEADER (WHAT C CODE SEES)
103 // =====
104 // This is what would go in a .h file that C programs include
105
106 #ifdef __cplusplus
107 extern "C" {
108 #endif
109
110 // Opaque handle - C code sees this as incomplete type
111 // This hides the C++ implementation details
112 typedef struct ImageHandle* ImageHandle_t;
113
114 // Error codes (C-compatible enum)
115 typedef enum {
116     IMAGE_SUCCESS = 0,
117     IMAGE_ERROR_INVALID_HANDLE = -1,
118     IMAGE_ERROR_INVALID_DIMENSIONS = -2,
119     IMAGE_ERROR_OUT_OF_RANGE = -3,
120     IMAGE_ERROR_OUT_OF_MEMORY = -4,
121     IMAGE_ERROR_UNKNOWN = -99
122 } ImageError;
123
124 // C API functions
125 // Note: All return error codes, use output parameters for data
126
127 /**
128 * Create a new image
129 * @param width Image width in pixels
130 * @param height Image height in pixels
131 * @param out_handle Output parameter for image handle
132 * @return Error code
133 */
134 ImageError image_create(size_t width, size_t height, ImageHandle_t* out_handle
135 );
136 /**
137 * Destroy an image and free resources
138 * @param handle Image handle
139 * @return Error code
140 */
141 ImageError image_destroy(ImageHandle_t handle);
142
143 /**
144 * Get image dimensions
145 * @param handle Image handle
146 * @param out_width Output parameter for width
147 * @param out_height Output parameter for height
148 * @return Error code
149 */
150 ImageError image_get_dimensions(ImageHandle_t handle, size_t* out_width,
151                                 size_t* out_height);
152 /**

```

```
153 * Set pixel value
154 * @param handle Image handle
155 * @param x X coordinate
156 * @param y Y coordinate
157 * @param value Pixel value (0-255)
158 * @return Error code
159 */
160 ImageError image_set_pixel(ImageHandle_t handle, size_t x, size_t y, uint8_t
    value);
161
162 /**
163 * Get pixel value
164 * @param handle Image handle
165 * @param x X coordinate
166 * @param y Y coordinate
167 * @param out_value Output parameter for pixel value
168 * @return Error code
169 */
170 ImageError image_get_pixel(ImageHandle_t handle, size_t x, size_t y, uint8_t*
    out_value);
171
172 /**
173 * Invert all pixel values
174 * @param handle Image handle
175 * @return Error code
176 */
177 ImageError image_invert(ImageHandle_t handle);
178
179 /**
180 * Fill image with a value
181 * @param handle Image handle
182 * @param value Fill value (0-255)
183 * @return Error code
184 */
185 ImageError image_fill(ImageHandle_t handle, uint8_t value);
186
187 /**
188 * Apply threshold to image
189 * @param handle Image handle
190 * @param threshold Threshold value (0-255)
191 * @return Error code
192 */
193 ImageError image_apply_threshold(ImageHandle_t handle, uint8_t threshold);
194
195 /**
196 * Get error message for error code
197 * @param error Error code
198 * @return Human-readable error message (static string)
199 */
200 const char* image_error_string(ImageError error);
201
202 #ifdef __cplusplus
203 }
204 #endif
```

```
205 // =====
206 // SECTION 3: C API IMPLEMENTATION (BRIDGE LAYER)
207 // =====
208 // This bridges between C and C++ code
209
210 // Helper function to catch C++ exceptions and convert to error codes
211 // NOTE: Must be OUTSIDE extern "C" block since it's a template
212 template<typename Func>
213 ImageError safe_call(Func&& func) noexcept {
214     try {
215         func();
216         return IMAGE_SUCCESS;
217     } catch (const std::out_of_range& e) {
218         std::cerr << "Exception caught: " << e.what() << std::endl;
219         return IMAGE_ERROR_OUT_OF_RANGE;
220     } catch (const std::bad_alloc& e) {
221         std::cerr << "Exception caught: " << e.what() << std::endl;
222         return IMAGE_ERROR_OUT_OF_MEMORY;
223     } catch (const std::exception& e) {
224         std::cerr << "Exception caught: " << e.what() << std::endl;
225         return IMAGE_ERROR_UNKNOWN;
226     } catch (...) {
227         std::cerr << "Unknown exception caught" << std::endl;
228         return IMAGE_ERROR_UNKNOWN;
229     }
230 }
231
232 // The actual implementation uses extern "C"
233 extern "C" {
234
235     ImageError image_create(size_t width, size_t height, ImageHandle_t* out_handle
236 ) {
237     if (!out_handle) {
238         return IMAGE_ERROR_INVALID_HANDLE;
239     }
240
241     if (width == 0 || height == 0) {
242         return IMAGE_ERROR_INVALID_DIMENSIONS;
243     }
244
245     return safe_call([&]() {
246         // Create C++ object and cast to opaque handle
247         auto* img = new image_processing::Image(width, height);
248         *out_handle = reinterpret_cast<ImageHandle_t>(img);
249     });
250 }
251
252     ImageError image_destroy(ImageHandle_t handle) {
253     if (!handle) {
254         return IMAGE_ERROR_INVALID_HANDLE;
255     }
256
257     return safe_call([&]() {
```

```
258     // Cast back to C++ object and delete
259     auto* img = reinterpret_cast<image_processing::Image*>(handle);
260     delete img;
261 };
262 }
263
264 ImageError image_get_dimensions(ImageHandle_t handle, size_t* out_width,
265     size_t* out_height) {
266     if (!handle || !out_width || !out_height) {
267         return IMAGE_ERROR_INVALID_HANDLE;
268     }
269
270     return safe_call([&]() {
271         auto* img = reinterpret_cast<image_processing::Image*>(handle);
272         *out_width = img->width();
273         *out_height = img->height();
274     });
275 }
276
277 ImageError image_set_pixel(ImageHandle_t handle, size_t x, size_t y, uint8_t
278     value) {
279     if (!handle) {
280         return IMAGE_ERROR_INVALID_HANDLE;
281     }
282
283     return safe_call([&]() {
284         auto* img = reinterpret_cast<image_processing::Image*>(handle);
285         img->at(x, y) = value;
286     });
287 }
288
289 ImageError image_get_pixel(ImageHandle_t handle, size_t x, size_t y, uint8_t*
290     out_value) {
291     if (!handle || !out_value) {
292         return IMAGE_ERROR_INVALID_HANDLE;
293     }
294
295     return safe_call([&]() {
296         auto* img = reinterpret_cast<image_processing::Image*>(handle);
297         *out_value = img->at(x, y);
298     });
299 }
300
301 ImageError image_invert(ImageHandle_t handle) {
302     if (!handle) {
303         return IMAGE_ERROR_INVALID_HANDLE;
304     }
305
306     return safe_call([&]() {
307         auto* img = reinterpret_cast<image_processing::Image*>(handle);
308         img->invert();
309     });
310 }
```

```
309 ImageError image_fill(ImageHandle_t handle, uint8_t value) {
310     if (!handle) {
311         return IMAGE_ERROR_INVALID_HANDLE;
312     }
313
314     return safe_call([&]() {
315         auto* img = reinterpret_cast<image_processing::Image*>(handle);
316         img->fill(value);
317     });
318 }
319
320 ImageError image_apply_threshold(ImageHandle_t handle, uint8_t threshold) {
321     if (!handle) {
322         return IMAGE_ERROR_INVALID_HANDLE;
323     }
324
325     return safe_call([&]() {
326         auto* img = reinterpret_cast<image_processing::Image*>(handle);
327         img->apply_threshold(threshold);
328     });
329 }
330
331 const char* image_error_string(ImageError error) {
332     switch (error) {
333         case IMAGE_SUCCESS: return "Success";
334         case IMAGE_ERROR_INVALID_HANDLE: return "Invalid handle";
335         case IMAGE_ERROR_INVALID_DIMENSIONS: return "Invalid dimensions";
336         case IMAGE_ERROR_OUT_OF_RANGE: return "Coordinates out of range";
337         case IMAGE_ERROR_OUT_OF_MEMORY: return "Out of memory";
338         case IMAGE_ERROR_UNKNOWN: return "Unknown error";
339         default: return "Invalid error code";
340     }
341 }
342
343 } // extern "C"
344
345 // =====
346 // SECTION 4: DEMONSTRATION - USING THE C API
347 // =====
348
349 void demonstrate_c_api_usage() {
350     std::cout << "\n== USING C API (SIMULATING C CODE) ==" << std::endl;
351     std::cout << "Note: This C++ code simulates how C code would use the API\n"
352             " << std::endl;
353
354     // In real C code, these would be the only includes needed:
355     // #include "image_api.h"
356
357     ImageHandle_t image = nullptr;
358     ImageError err;
359
360     // Create image
361     std::cout << "1. Creating 10x10 image:" << std::endl;
362     err = image_create(10, 10, &image);
```

```
362     if (err != IMAGE_SUCCESS) {
363         std::cout << "    Error: " << image_error_string(err) << std::endl;
364         return;
365     }
366     std::cout << "    Image created successfully" << std::endl;
367
368     // Get dimensions
369     size_t width, height;
370     err = image_get_dimensions(image, &width, &height);
371     if (err == IMAGE_SUCCESS) {
372         std::cout << "\n2. Image dimensions: " << width << "x" << height <<
373             std::endl;
374     }
375
376     // Fill with value
377     std::cout << "\n3. Filling image with value 128:" << std::endl;
378     err = image_fill(image, 128);
379     if (err != IMAGE_SUCCESS) {
380         std::cout << "    Error: " << image_error_string(err) << std::endl;
381     }
382
383     // Set some pixels
384     std::cout << "\n4. Setting individual pixels:" << std::endl;
385     image_set_pixel(image, 0, 0, 255);
386     image_set_pixel(image, 1, 1, 200);
387     image_set_pixel(image, 2, 2, 150);
388     std::cout << "    Pixels set" << std::endl;
389
390     // Get pixel values
391     std::cout << "\n5. Reading pixel values:" << std::endl;
392     uint8_t value;
393     for (int i = 0; i < 3; i++) {
394         err = image_get_pixel(image, i, i, &value);
395         if (err == IMAGE_SUCCESS) {
396             std::cout << "    Pixel(" << i << "," << i << ") = "
397                 << static_cast<int>(value) << std::endl;
398         }
399     }
400
401     // Invert
402     std::cout << "\n6. Inverting image:" << std::endl;
403     err = image_invert(image);
404     if (err != IMAGE_SUCCESS) {
405         std::cout << "    Error: " << image_error_string(err) << std::endl;
406     }
407
408     // Read inverted values
409     std::cout << "\n7. Reading inverted pixel values:" << std::endl;
410     for (int i = 0; i < 3; i++) {
411         err = image_get_pixel(image, i, i, &value);
412         if (err == IMAGE_SUCCESS) {
413             std::cout << "    Pixel(" << i << "," << i << ") = "
414                 << static_cast<int>(value) << std::endl;
415     }
```

```
415     }
416
417     // Apply threshold
418     std::cout << "\n8. Applying threshold at 100:" << std::endl;
419     err = image_apply_threshold(image, 100);
420
421     // Error handling
422     std::cout << "\n9. Testing error handling (out of range access):" << std::endl;
423     err = image_get_pixel(image, 100, 100, &value);
424     if (err != IMAGE_SUCCESS) {
425         std::cout << "    Error caught: " << image_error_string(err) << std::endl;
426     }
427
428     // Cleanup
429     std::cout << "\n10. Destroying image:" << std::endl;
430     err = image_destroy(image);
431     if (err == IMAGE_SUCCESS) {
432         std::cout << "    Image destroyed successfully" << std::endl;
433     }
434 }
435
436 // =====
437 // SECTION 5: BEST PRACTICES EXPLANATION
438 // =====
439
440 void explain_best_practices() {
441     std::cout << "\n" << std::string(70, '=') << std::endl;
442     std::cout << "BEST PRACTICES FOR C API FROM C++ CODE:\n";
443     std::cout << std::string(70, '=') << std::endl;
444
445     std::cout << "\n1. OPAQUE HANDLES (PIMPL IDIOM FOR C):" << std::endl;
446     std::cout << "    Hide C++ implementation details" << std::endl;
447     std::cout << "    Use typedef struct Name* Handle_t;" << std::endl;
448     std::cout << "    Cast to/from C++ objects internally" << std::endl;
449     std::cout << "    Stable ABI - C++ changes don't affect C API" << std::endl;
450
451     std::cout << "\n2. EXCEPTION HANDLING:" << std::endl;
452     std::cout << "    NEVER let C++ exceptions cross C boundary!" << std::endl;
453     std::cout << "    Catch ALL exceptions in extern \"C\" functions" << std::endl;
454     std::cout << "    Convert exceptions to error codes" << std::endl;
455     std::cout << "    Use try-catch wrappers consistently" << std::endl;
456
457     std::cout << "\n3. ERROR HANDLING:" << std::endl;
458     std::cout << "    Return error codes (int or enum)" << std::endl;
459     std::cout << "    Use output parameters for data" << std::endl;
460     std::cout << "    Provide error_to_string() function" << std::endl;
461     std::cout << "    Check for NULL pointers before dereferencing" << std::endl;
462 }
```

```

463     std::cout << "\n4. MEMORY MANAGEMENT:" << std::endl;
464     std::cout << "    C code creates/destroys via API functions" << std::endl
465     ;
466     std::cout << "    NEVER expose C++ new/delete directly" << std::endl;
467     std::cout << "    Provide create() and destroy() functions" << std::endl;
468     std::cout << "    Match create/destroy across DLL boundaries" << std::
469     endl;
470
471     std::cout << "\n5. HEADER GUARDS AND COMPATIBILITY:" << std::endl;
472     std::cout << "    Use #ifdef __cplusplus for extern \"C\" blocks" << std
473     ::endl;
474     std::cout << "    Include guards in all headers" << std::endl;
475     std::cout << "    Use C-compatible types (no bool, use int)" << std::endl
476     ;
477     std::cout << "    No function overloading in C API" << std::endl;
478
479     std::cout << "\n6. C++ FEATURES TO AVOID IN C API:" << std::endl;
480     std::cout << "    Classes (use opaque handles instead)" << std::endl;
481     std::cout << "    Templates (not C-compatible)" << std::endl;
482     std::cout << "    Function overloading (C doesn't support it)" << std::
483     endl;
484     std::cout << "    Default arguments (C doesn't support them)" << std::
485     endl;
486     std::cout << "    References (use pointers)" << std::endl;
487     std::cout << "    bool type (use int, 0 for false, 1 for true)" << std::
488     endl;
489
490     std::cout << "\n7. DOCUMENTATION:" << std::endl;
491     std::cout << "    Document ownership semantics clearly" << std::endl;
492     std::cout << "    Specify thread-safety guarantees" << std::endl;
493     std::cout << "    List all possible error codes" << std::endl;
494     std::cout << "    Provide usage examples" << std::endl;
495
496 } // =====
497 // SECTION 6: COMPARISON WITH PREVIOUS EXAMPLE
498 // =====
499
500 void compare_approaches() {
501     std::cout << "\n" << std::string(70, '=') << std::endl;
502     std::cout << "COMPARISON: C IN C++ vs C++ IN C:\n";
503     std::cout << std::string(70, '=') << std::endl;
504
505     std::cout << "\nPREVIOUS EXAMPLE (Wrapping C in C++):" << std::endl;
506     std::cout << "    Purpose: Use C libraries from C++ code" << std::endl;
507     std::cout << "    Technique: RAII wrappers, smart pointers" << std::endl;
508     std::cout << "    Example: Socket library → C++ Socket class" << std::endl;
509     std::cout << "    Benefits: Modern C++ safety, automatic cleanup" << std::

```

```
        endl;

510    std::cout << "\nTHIS EXAMPLE (Exposing C++ as C):" << std::endl;
511    std::cout << "  Purpose: Make C++ code usable from C" << std::endl;
512    std::cout << "  Technique: Opaque handles, extern \"C\"" << std::endl;
513    std::cout << "  Example: C++ Image class → C image_* functions" << std::
514        endl;
515    std::cout << "  Benefits: C compatibility, stable ABI, FFI-ready" << std::
516        endl;

517    std::cout << "\nWHEN TO USE EACH APPROACH:" << std::endl;
518    std::cout << "\nWrapping C in C++ (Previous):" << std::endl;
519    std::cout << " • You have C libraries to use" << std::endl;
520    std::cout << " • You want modern C++ features" << std::endl;
521    std::cout << " • You want automatic resource management" << std::endl;
522    std::cout << " • Internal project use" << std::endl;
523

524    std::cout << "\nExposing C++ as C (This):" << std::endl;
525    std::cout << " • You want to create a C-compatible library" << std::endl;
526    std::cout << " • You need stable ABI across versions" << std::endl;
527    std::cout << " • You want FFI for other languages" << std::endl;
528    std::cout << " • You need to support legacy C code" << std::endl;
529    std::cout << " • Plugin systems with C interfaces" << std::endl;
530 }

531 // =====
532 // MAIN FUNCTION
533 // =====
534

535 int main() {
536     std::cout << "\n";
537     std::cout << "                               \n";
538     std::cout << "          CREATING A C API FROM C++ CODE
539                           \n";
540     std::cout << "
541                               \n";
542     std::cout << "      Demonstrates: Opaque Handles, extern \"C\", Exception
543           Safety      \n";
544     std::cout << "      Example: Image Processing Library with C Interface
545           \n";
546     std::cout << "
547                               \n";
548
549     demonstrate_c_api_usage();
550     explain_best_practices();
551     compare_approaches();
552
553     std::cout << "\n" << std::string(70, '=') << std::endl;
554     std::cout << "SUMMARY:\n";
555     std::cout << std::string(70, '=') << std::endl;
556
557     std::cout << "\n KEY TECHNIQUES DEMONSTRATED:" << std::endl;
558     std::cout << " 1. Opaque handles for hiding C++ implementation" << std::
559         endl;
560     std::cout << " 2. extern \"C\"" for C-compatible linkage" << std::endl;
```

```
556     std::cout << "    3. Exception safety across C/C++ boundary" << std::endl;
557     std::cout << "    4. Error code-based error handling" << std::endl;
558     std::cout << "    5. Output parameters instead of return values" << std::
559             endl;
560     std::cout << "    6. Proper memory management (create/destroy)" << std::
561             endl;
562
563     std::cout << "\n REAL-WORLD APPLICATIONS:" << std::endl;
564     std::cout << " • Game engine C APIs (Unity, Unreal plugins)" << std::
565             endl;
566     std::cout << " • Database drivers (SQLite, PostgreSQL)" << std::endl;
567     std::cout << " • Graphics libraries (Vulkan, OpenGL wrappers)" << std::
568             endl;
569     std::cout << " • Compression libraries (zlib, bzip2 style)" << std::endl
570             ;
571     std::cout << " • Python/Ruby/Lua bindings via C API" << std::endl;
572
573     std::cout << "\n BENEFITS:" << std::endl;
574     std::cout << " • C++ power with C compatibility" << std::endl;
575     std::cout << " • Stable ABI (no name mangling issues)" << std::endl;
576     std::cout << " • Can be used from ANY language with C FFI" << std::endl;
577     std::cout << " • Hide implementation details completely" << std::endl;
578     std::cout << " • Version changes don't break binary compatibility" <<
579             std::endl;
580
581     std::cout << "\n All resources properly managed!\n" << std::endl;
582
583     return 0;
584 }
```

19 Source Code: DependencyInjection.cpp

File: src/DependencyInjection.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <memory>
3 #include <string>
4 #include <vector>
5 #include <functional>
6
7 // =====
8 // DEPENDENCY INJECTION IN C++ - NO PRIVATE INHERITANCE NEEDED
9 // =====
10
11 // =====
12 // 1. TRADITIONAL DI - PUBLIC INHERITANCE FOR INTERFACES
13 // =====
14
15 // Abstract interface (use PUBLIC inheritance)
16 class ILogger {
17 public:
18     virtual ~ILogger() = default;
19     virtual void log(const std::string& message) = 0;
20 };
21
22 // Concrete implementations
23 class ConsoleLogger : public ILogger { // PUBLIC inheritance
24 public:
25     void log(const std::string& message) override {
26         std::cout << "[CONSOLE] " << message << std::endl;
27     }
28 };
29
30 class FileLogger : public ILogger { // PUBLIC inheritance
31 private:
32     std::string filename;
33
34 public:
35     FileLogger(const std::string& file) : filename(file) {}
36
37     void log(const std::string& message) override {
38         std::cout << "[FILE:" << filename << "] " << message << std::endl;
39     }
40 };
41
42 // Service that depends on ILogger - uses COMPOSITION, not inheritance
43 class UserService {
44 private:
45     std::shared_ptr<ILogger> logger; // Has-a relationship via composition
46
47 public:
48     // Constructor injection
49     UserService(std::shared_ptr<ILogger> log) : logger(std::move(log)) {}
```

```
50
51     void createUser(const std::string& username) {
52         logger->log("Creating user: " + username);
53         // User creation logic...
54         logger->log("User created successfully: " + username);
55     }
56
57     void deleteUser(const std::string& username) {
58         logger->log("Deleting user: " + username);
59         // User deletion logic...
60         logger->log("User deleted: " + username);
61     }
62 };
63
64 void example_traditional_di() {
65     std::cout << "\n==== 1. TRADITIONAL DI - PUBLIC INHERITANCE + COMPOSITION
66     ===" << std::endl;
67     std::cout << "Pattern: Interface (public) + Composition (has-a)\n" << std
68         ::endl;
69
70     // Inject ConsoleLogger
71     auto consoleLogger = std::make_shared<ConsoleLogger>();
72     UserService service1(consoleLogger);
73     service1.createUser("Alice");
74
75     std::cout << std::endl;
76
77     // Inject FileLogger - same service, different dependency
78     auto fileLogger = std::make_shared<FileLogger>("users.log");
79     UserService service2(fileLogger);
80     service2.createUser("Bob");
81
82     std::cout << "\n DEPENDENCY INJECTION USES:" << std::endl;
83     std::cout << " • PUBLIC inheritance for interfaces (ILogger)" << std::
84         endl;
85     std::cout << " • COMPOSITION for dependencies (has-a ILogger)" << std::
86         endl;
87     std::cout << " • NO private inheritance needed!" << std::endl;
88 }
89
90 // =====
91 // 2. CONSTRUCTOR INJECTION (MOST COMMON)
92 // =====
93
94 class IDatabase {
95 public:
96     virtual ~IDatabase() = default;
97     virtual void save(const std::string& data) = 0;
98     virtual std::string load(const std::string& key) = 0;
99 };
```

```
100     std::cout << " [MockDB] Saving: " << data << std::endl;
101 }
102
103 std::string load(const std::string& key) override {
104     return "mock_data_for_" + key;
105 }
106 };
107
108 class PostgresDatabase : public IDatabase {
109 public:
110     void save(const std::string& data) override {
111         std::cout << " [PostgreSQL] Saving to database: " << data << std::endl;
112     }
113
114     std::string load(const std::string& key) override {
115         return "postgres_data_for_" + key;
116     }
117 };
118
119 // Repository with multiple dependencies injected via constructor
120 class OrderRepository {
121 private:
122     std::shared_ptr<IDatabase> database; // Composition
123     std::shared_ptr<ILogger> logger; // Composition
124
125 public:
126     // Constructor injection of multiple dependencies
127     OrderRepository(std::shared_ptr<IDatabase> db, std::shared_ptr<ILogger>
128                     log)
129         : database(std::move(db)), logger(std::move(log)) {}
130
131     void saveOrder(const std::string& orderId) {
132         logger->log("Saving order: " + orderId);
133         database->save("Order:" + orderId);
134         logger->log("Order saved successfully");
135     }
136
137     void loadOrder(const std::string& orderId) {
138         logger->log("Loading order: " + orderId);
139         auto data = database->load(orderId);
140         std::cout << " Loaded: " << data << std::endl;
141         logger->log("Order loaded successfully");
142     }
143
144 void example_constructor_injection() {
145     std::cout << "\n==== 2. CONSTRUCTOR INJECTION (MULTIPLE DEPENDENCIES) ==="
146             << std::endl;
147     std::cout << "Pattern: Inject all dependencies via constructor\n" << std::endl;
148
149     auto logger = std::make_shared<ConsoleLogger>();
150     auto database = std::make_shared<PostgresDatabase>();
```

```
150
151     OrderRepository repo(database, logger);
152     repo.saveOrder("ORD-12345");
153
154     std::cout << std::endl;
155     repo.loadOrder("ORD-12345");
156
157     std::cout << "\n BENEFITS:" << std::endl;
158     std::cout << " • Dependencies are explicit and immutable" << std::endl;
159     std::cout << " • Easy to test (inject mocks)" << std::endl;
160     std::cout << " • No private inheritance - uses composition" << std::endl
161     ;
162 }
163 // =====
164 // 3. INTERFACE INJECTION (STRATEGY PATTERN)
165 // =====
166
167 class IEmailSender {
168 public:
169     virtual ~IEmailSender() = default;
170     virtual void sendEmail(const std::string& to, const std::string& message)
171         = 0;
172 };
173
174 class SmtpEmailSender : public IEmailSender {
175 public:
176     void sendEmail(const std::string& to, const std::string& message) override
177     {
178         std::cout << "[SMTP] Sending email to " << to << ":" << message <<
179             std::endl;
180     }
181 };
182
183 class MockEmailSender : public IEmailSender {
184 public:
185     void sendEmail(const std::string& to, const std::string& message) override
186     {
187         std::cout << "[MOCK] Would send email to " << to << ":" << message
188             << std::endl;
189     }
190 };
191
192 class NotificationService {
193 private:
194     std::shared_ptr<IEmailSender> emailSender; // Composition
195
196 public:
197     NotificationService(std::shared_ptr<IEmailSender> sender)
198         : emailSender(std::move(sender)) {}
199
200     // Setter injection (optional, less common)
201     void setEmailSender(std::shared_ptr<IEmailSender> sender) {
202         emailSender = std::move(sender);
203     }
```

```
198     }
199
200     void notifyUser(const std::string& email, const std::string& notification)
201     {
202         std::cout << "Sending notification..." << std::endl;
203         emailSender->sendEmail(email, notification);
204     }
205 };
206
207 void example_interface_injection() {
208     std::cout << "\n==== 3. INTERFACE INJECTION (STRATEGY PATTERN) ===" << std
209         ::endl;
210     std::cout << "Pattern: Inject behavior through interfaces\n" << std::endl;
211
212     auto smtpSender = std::make_shared<SmtpEmailSender>();
213     NotificationService service(smtpSender);
214
215     service.notifyUser("user@example.com", "Your order has shipped!");
216
217     std::cout << "\nSwitching to mock sender (setter injection):" << std::endl
218         ;
219     auto mockSender = std::make_shared<MockEmailSender>();
220     service.setEmailSender(mockSender);
221     service.notifyUser("user@example.com", "Your order is delivered!");
222
223     std::cout << "\n KEY POINTS:" << std::endl;
224     std::cout << " • Strategy pattern uses PUBLIC inheritance" << std::endl;
225     std::cout << " • Can switch implementations at runtime" << std::endl;
226     std::cout << " • No private inheritance involved" << std::endl;
227 }
228
229 // =====
230 // 4. TEMPLATE-BASED DI (COMPILE-TIME INJECTION)
231 // =====
232
233 // No interface needed - duck typing via templates
234 class ConsoleOutput {
235 public:
236     void write(const std::string& msg) {
237         std::cout << "[Console] " << msg << std::endl;
238     }
239 };
240
241 class FileOutput {
242 public:
243     void write(const std::string& msg) {
244         std::cout << "[File] " << msg << std::endl;
245     }
246 };
247
248 // Template-based dependency injection (no inheritance at all!)
249 template<typename TOutput>
250 class MessageProcessor {
251 private:
```

```
249     TOutput output; // Composition with template type
250
251 public:
252     MessageProcessor(TOutput out) : output(std::move(out)) {}
253
254     void process(const std::string& message) {
255         std::cout << "Processing message: " << message << std::endl;
256         output.write("Processed: " + message);
257     }
258 };
259
260 void example_template_di() {
261     std::cout << "\n==== 4. TEMPLATE-BASED DI (COMPILE-TIME) ===" << std::endl;
262     std::cout << "Pattern: No inheritance, no interfaces - pure templates\n"
263             << std::endl;
264
265     ConsoleOutput console;
266     MessageProcessor<ConsoleOutput> processor1(console);
267     processor1.process("Hello World");
268
269     std::cout << std::endl;
270
271     FileOutput file;
272     MessageProcessor<FileOutput> processor2(file);
273     processor2.process("Template DI");
274
275     std::cout << "\n ADVANTAGES:" << std::endl;
276     std::cout << " • Zero runtime overhead (compile-time binding)" << std::endl;
277     std::cout << " • No virtual functions needed" << std::endl;
278     std::cout << " • No inheritance (public OR private) needed!" << std::endl;
279     std::cout << " • Duck typing - if it has write(), it works" << std::endl
280             ;
281 }
282
283 // =====
284 // 5. DI CONTAINER / SERVICE LOCATOR PATTERN
285 // =====
286
287 class DIContainer {
288 private:
289     std::shared_ptr<ILogger> logger;
290     std::shared_ptr<IDatabase> database;
291     std::shared_ptr<IEmailSender> emailSender;
292
293 public:
294     // Register dependencies
295     void registerLogger(std::shared_ptr<ILogger> log) {
296         logger = std::move(log);
297     }
298
299     void registerDatabase(std::shared_ptr<IDatabase> db) {
300         database = std::move(db);
```

```
299     }
300
301     void registerEmailSender(std::shared_ptr<IEmailSender> sender) {
302         emailSender = std::move(sender);
303     }
304
305     // Resolve dependencies
306     std::shared_ptr<ILogger> getLogger() { return logger; }
307     std::shared_ptr<IDatabase> getDatabase() { return database; }
308     std::shared_ptr<IEmailSender> getEmailSender() { return emailSender; }
309
310     // Factory method to create services with auto-injected dependencies
311     std::shared_ptr<OrderRepository> createOrderRepository() {
312         return std::make_shared<OrderRepository>(database, logger);
313     }
314 };
315
316 void example_di_container() {
317     std::cout << "\n== 5. DI CONTAINER / SERVICE LOCATOR ==" << std::endl;
318     std::cout << "Pattern: Central registry for dependency management\n" <<
319             std::endl;
320
321     DIContainer container;
322
323     // Setup (composition root)
324     container.registerLogger(std::make_shared<ConsoleLogger>());
325     container.registerDatabase(std::make_shared<MockDatabase>());
326     container.registerEmailSender(std::make_shared<MockEmailSender>());
327
328     // Resolve dependencies
329     auto repo = container.createOrderRepository();
330     repo->saveOrder("ORD-99999");
331
332     auto emailSender = container.getEmailSender();
333     emailSender->sendEmail("admin@example.com", "System started");
334
335     std::cout << "\n DI CONTAINER USES:" << std::endl;
336     std::cout << " • Stores dependencies as members (composition)" << std::endl;
337     std::cout << " • Public inheritance for interfaces only" << std::endl;
338     std::cout << " • No private inheritance needed" << std::endl;
339 }
340
341 // =====
342 // 6. FUNCTIONAL DI (C++11/14 STYLE)
343 // =====
344
345 class PaymentService {
346     private:
347         std::function<void(const std::string&)> logFunc;
348         std::function<bool(double)> validateFunc;
349
350     public:
351         // Inject functions instead of objects
```

```
351 PaymentService(          352     std::function<void(const std::string&)> logger,          353     std::function<bool(double)> validator)          354 : logFunc(std::move(logger))          355 , validateFunc(std::move(validator)) {}          356          357 void processPayment(double amount) {          358     logFunc("Processing payment of $" + std::to_string(amount));          359          360     if (validateFunc(amount)) {          361         logFunc("Payment validated and processed");          362     } else {          363         logFunc("Payment validation failed");          364     }          365 }          366 };          367          368 void example_functional_di() {          369     std::cout << "\n==== 6. FUNCTIONAL DI (INJECT FUNCTIONS) ===" << std::endl;          370     std::cout << "Pattern: Inject std::function instead of interfaces\n" <<          371         std::endl;          372         // Define behaviors as lambdas          373     auto logger = [](const std::string& msg) {          374         std::cout << " [Payment Log] " << msg << std::endl;          375     };          376          377     auto validator = [](double amount) {          378         return amount > 0 && amount < 10000; // Simple validation          379     };          380          381     PaymentService service(logger, validator);          382     service.processPayment(150.50);          383          384     std::cout << std::endl;          385     service.processPayment(-50.0); // Invalid          386          387     std::cout << "\n FUNCTIONAL DI:" << std::endl;          388     std::cout << " • No interfaces needed" << std::endl;          389     std::cout << " • No inheritance at all (public or private)" << std::endl          390         ;          391     std::cout << " • Lightweight and flexible" << std::endl;          392     std::cout << " • Uses std::function and lambdas" << std::endl;          393 }          394 // =====          395 // 7. WHY NOT PRIVATE INHERITANCE FOR DI?          396 // =====          397          398 // WRONG: Using private inheritance for DI (anti-pattern)          399 class WrongServiceWithPrivateInheritance : private ILogger {          400     private:          401         // This makes ILogger methods private - defeats the purpose of DI!
```

```
403 public:
404     void doSomething() {
405         log("This is confusing!"); // Can only use internally
406     }
407
408     // Cannot inject different logger implementations
409     // Cannot swap loggers at runtime
410     // Tightly coupled to ILogger
411 };
412
413 // CORRECT: Using composition for DI
414 class CorrectServiceWithComposition {
415 private:
416     std::shared_ptr<ILogger> logger; // Injected dependency
417
418 public:
419     CorrectServiceWithComposition(std::shared_ptr<ILogger> log)
420         : logger(std::move(log)) {}
421
422     void doSomething() {
423         logger->log("This is the right way!");
424     }
425
426     // Can inject any ILogger implementation
427     // Can swap loggers at runtime
428     // Loosely coupled
429 };
430
431 void example_why_not_private() {
432     std::cout << "\n==== 7. WHY NOT PRIVATE INHERITANCE FOR DI? ===" << std::endl;
433
434     std::cout << "\n PRIVATE INHERITANCE FOR DI IS WRONG BECAUSE:" << std::endl;
435     std::cout << " • Cannot inject different implementations" << std::endl;
436     std::cout << " • Tightly coupled to specific base class" << std::endl;
437     std::cout << " • Cannot swap dependencies at runtime" << std::endl;
438     std::cout << " • Violates Dependency Inversion Principle" << std::endl;
439     std::cout << " • Makes testing difficult (can't inject mocks)" << std::endl;
440
441     std::cout << "\n DI REQUIRES LOOSE COUPLING:" << std::endl;
442     std::cout << " • Use interfaces (abstract base classes)" << std::endl;
443     std::cout << " • Use PUBLIC inheritance for interfaces" << std::endl;
444     std::cout << " • Use COMPOSITION to hold dependencies" << std::endl;
445     std::cout << " • Inject dependencies via constructor/setter" << std::endl;
446 }
447
448 // =====
449 // MAIN FUNCTION
450 // =====
451
452 int main() {
```

```
453     std::cout << "\n"
454     ===== " DEPENDENCY INJECTION IN C++ - NO PRIVATE INHERITANCE!" <<
455     std::endl;
456     std::cout << "
457     ===== " example_traditional_di();
458     ===== " example_constructor_injection();
459     ===== " example_interface_injection();
460     ===== " example_template_di();
461     ===== " example_di_container();
462     ===== " example_functional_di();
463     ===== " example_why_not_private();
464
465     std::cout << "\n"
466     ===== " DEPENDENCY INJECTION SUMMARY" << std::endl;
467     std::cout << "
468     ===== "
469     std::cout << "\n DI PATTERNS IN C++ (NO PRIVATE INHERITANCE):" << std::
470     endl;
471     std::cout << "\n1. INTERFACE-BASED DI (MOST COMMON):" << std::endl;
472     std::cout << " • Define abstract interfaces (ILogger, IDatabase, etc.)"
473     << std::endl;
474     std::cout << " • Implementations use PUBLIC inheritance" << std::endl;
475     std::cout << " • Services use COMPOSITION (has-a relationship)" << std::
476     endl;
477     std::cout << " • Inject via constructor or setter" << std::endl;
478
479     std::cout << "\n2. TEMPLATE-BASED DI:" << std::endl;
480     std::cout << " • No inheritance at all!" << std::endl;
481     std::cout << " • Compile-time polymorphism via templates" << std::endl;
482     std::cout << " • Duck typing - if it quacks like a duck..." << std::endl
483     ;
484     std::cout << " • Zero runtime overhead" << std::endl;
485
486     std::cout << "\n3. FUNCTIONAL DI:" << std::endl;
487     std::cout << " • Inject std::function instead of interfaces" << std::
488     endl;
489     std::cout << " • No inheritance needed" << std::endl;
490     std::cout << " • Lightweight and flexible" << std::endl;
491     std::cout << " • Great for simple dependencies" << std::endl;
492
493     std::cout << "\n4. DI CONTAINER:" << std::endl;
494     std::cout << " • Central registry for dependencies" << std::endl;
495     std::cout << " • Auto-wiring of complex object graphs" << std::endl;
496     std::cout << " • Uses composition internally" << std::endl;
497     std::cout << " • Similar to Spring (Java) or Autofac (.NET)" << std::
```

```
        endl;

493    std::cout << "\n NEVER USE PRIVATE INHERITANCE FOR DI:" << std::endl;
494    std::cout << " • Private inheritance = tight coupling" << std::endl;
495    std::cout << " • Cannot inject different implementations" << std::endl;
496    std::cout << " • Cannot swap at runtime" << std::endl;
497    std::cout << " • Defeats the entire purpose of DI!" << std::endl;
498
499
500    std::cout << "\n CORRECT DI APPROACH:" << std::endl;
501    std::cout << " • PUBLIC inheritance for interfaces (polymorphism)" <<
502        std::endl;
503    std::cout << " • COMPOSITION for dependencies (has-a)" << std::endl;
504    std::cout << " • Constructor/setter injection" << std::endl;
505    std::cout << " • Inversion of Control (IoC)" << std::endl;
506
507    std::cout << "\n KEY PRINCIPLE:" << std::endl;
508    std::cout << "     \"Depend on abstractions, not concretions\"" << std::endl
509        ;
510    std::cout << "     - Dependency Inversion Principle (SOLID)" << std::endl;
511
512    std::cout << "\n WHEN TO USE EACH:" << std::endl;
513    std::cout << " • Interface-based DI: Runtime polymorphism, complex
514        systems" << std::endl;
515    std::cout << " • Template-based DI: Performance-critical code, simple
516        deps" << std::endl;
517    std::cout << " • Functional DI: Simple behaviors, lambdas" << std::endl;
518    std::cout << " • DI Container: Large applications with many dependencies
519        " << std::endl;
520    std::cout << " • Private inheritance: NEVER for DI!" << std::endl;
521
522    std::cout << "\n
523        =====\n" << std::endl;
524
525    return 0;
526}
```

20 Source Code: DiamondProblem.cpp

File: src/DiamondProblem.cpp

Repository: [View on GitHub](#)

```
1 // DiamondProblem.cpp
2 // Demonstrates the Diamond Problem (Diamond of Death) in C++ and its solution
3 //
4 // The Diamond Problem occurs when a class inherits from two classes that both
5 // inherit from the same base class, creating a diamond-shaped inheritance
6 // hierarchy.
7 //
8 // PROBLEM:
9 // Without virtual inheritance, the derived class contains TWO copies of the
10 // base class, leading to ambiguity and wasted memory.
11 //
12 // SOLUTION:
13 // Use 'virtual' keyword in inheritance to ensure only ONE copy of the base
14 // class exists in the final derived class.
15 //
16 //      Base
17 //      /   \
18 //      A     B
19 //      \   /
20 //      Derived
21 //
22 // KEY CONCEPTS:
23 // 1. Multiple Inheritance creates duplicate base class instances
24 // 2. Virtual Inheritance solves the duplication
25 // 3. Constructor initialization order with virtual bases
26 // 4. When to use and when to avoid multiple inheritance
27
28 #include <iostream>
29 #include <string>
30 #include <memory>
31 //
32 =====
33 // SECTION 1: THE PROBLEM - Diamond Without Virtual Inheritance
34 // =====
35
36 namespace diamond_problem {
37
38 class Device {
39 protected:
40     std::string name_;
41     int id_;
42
43 public:
44     Device(const std::string& name, int id)
45         : name_(name), id_(id) {
```

```
45     std::cout << "      [Device] Constructed: " << name_ << " (ID: " << id_
46             << ")\\n";
47 }
48 void displayInfo() const {
49     std::cout << "      Device: " << name_ << ", ID: " << id_ << "\\n";
50 }
51 int getId() const { return id_; }
52 };
53
54
55 class InputDevice : public Device {
56 protected:
57     std::string inputType_;
58
59 public:
60     InputDevice(const std::string& name, int id, const std::string& inputType)
61         : Device(name, id), inputType_(inputType) {
62         std::cout << "      [InputDevice] Constructed: " << inputType_ << "\\n";
63     }
64
65     void showInput() const {
66         std::cout << "      Input Type: " << inputType_ << "\\n";
67     }
68 };
69
70 class OutputDevice : public Device {
71 protected:
72     std::string outputType_;
73
74 public:
75     OutputDevice(const std::string& name, int id, const std::string&
76                 outputType)
77         : Device(name, id), outputType_(outputType) {
78         std::cout << "      [OutputDevice] Constructed: " << outputType_ << "\\n"
79             ;
80     }
81
82     void showOutput() const {
83         std::cout << "      Output Type: " << outputType_ << "\\n";
84     }
85 }
86
87 // PROBLEM: IODevice inherits Device TWICE (through InputDevice and
88 //           OutputDevice)
89 class IODevice : public InputDevice, public OutputDevice {
90 public:
91     IODevice(const std::string& name, int id)
92         : InputDevice(name, id, "Keyboard"),
93             OutputDevice(name, id, "Display") {
94         std::cout << "      [IODevice] Constructed\\n";
95     }
96
97     void showInfo() const {
```

```
95 // AMBIGUITY: Which Device::displayInfo() to call?
96 // AMBIGUITY: Which Device::getId() to call?
97 // Compiler error without explicit qualification
98
99 // Must specify which base class path to use:
100 std::cout << "\n  Input Device Info:\n";
101 InputDevice::displayInfo(); // Calls Device from InputDevice path
102 showInput();
103
104 std::cout << "\n  Output Device Info:\n";
105 OutputDevice::displayInfo(); // Calls Device from OutputDevice path
106 showOutput();
107
108 std::cout << "\n      Problem: Two copies of Device exist!\n";
109 std::cout << "      InputDevice::getId() = " << InputDevice::getId()
110     << "\n";
111 std::cout << "      OutputDevice::getId() = " << OutputDevice::getId()
112     << "\n";
113 }
114 };
115 void demonstrate() {
116 std::cout << "\n" << std::string(70, '=') << "\n";
117 std::cout << "==== SECTION 1: Diamond Problem (Without Virtual Inheritance)
118     ===\n";
119 std::cout << std::string(70, '=') << "\n\n";
120
121 std::cout << "Creating IODevice...\n";
122 std::cout << "Notice: Device constructor called TWICE!\n\n";
123
124 IODevice device("MyIODevice", 42);
125
126 std::cout << "\nShowing device information:\n";
127 device.showInfo();
128
129 std::cout << "\nMemory Analysis:\n";
130 std::cout << "  sizeof(Device) = " << sizeof(Device) << " bytes\n";
131 std::cout << "  sizeof(InputDevice) = " << sizeof(InputDevice) << " bytes\n";
132 std::cout << "  sizeof(OutputDevice) = " << sizeof(OutputDevice) << "
133     bytes\n";
134 std::cout << "  sizeof(IODevice) = " << sizeof(IODevice) << " bytes\n";
135 std::cout << "  IODevice contains TWO Device instances (memory waste)\n"
136     ";
137 }
138 } // namespace diamond_problem
139
// =====
138 // SECTION 2: THE SOLUTION - Virtual Inheritance
139 // =====
```

```
140
141 namespace virtual_inheritance_solution {
142
143 class Device {
144 protected:
145     std::string name_;
146     int id_;
147
148 public:
149     Device(const std::string& name, int id)
150         : name_(name), id_(id) {
151         std::cout << "    [Device] Constructed: " << name_ << " (ID: " << id_
152             << ")\\n";
153     }
154
155     virtual ~Device() = default;
156
157     void displayInfo() const {
158         std::cout << "    Device: " << name_ << ", ID: " << id_ << "\\n";
159     }
160
161     int getId() const { return id_; }
162     std::string getName() const { return name_; }
163 };
164
165 // SOLUTION: Use 'virtual' keyword in inheritance
166 class InputDevice : virtual public Device {
167 protected:
168     std::string inputType_;
169
170 public:
171     InputDevice(const std::string& name, int id, const std::string& inputType)
172         : Device(name, id), inputType_(inputType) {
173         std::cout << "    [InputDevice] Constructed: " << inputType_ << "\\n";
174     }
175
176     void showInput() const {
177         std::cout << "    Input Type: " << inputType_ << "\\n";
178     }
179 };
180
181 // SOLUTION: Use 'virtual' keyword in inheritance
182 class OutputDevice : virtual public Device {
183 protected:
184     std::string outputType_;
185
186 public:
187     OutputDevice(const std::string& name, int id, const std::string&
188                 outputType)
189         : Device(name, id), outputType_(outputType) {
190         std::cout << "    [OutputDevice] Constructed: " << outputType_ << "\\n"
191             ;
192     }
193 }
```

```
190     void showOutput() const {
191         std::cout << "      Output Type: " << outputType_ << "\n";
192     }
193 };
194
195 // Now IODevice has only ONE copy of Device
196 class IODevice : public InputDevice, public OutputDevice {
197 public:
198     // IMPORTANT: With virtual inheritance, the most derived class
199     // is responsible for initializing the virtual base class
200     IODevice(const std::string& name, int id)
201         : Device(name, id), // Must initialize Device directly!
202           InputDevice(name, id, "Keyboard"),
203           OutputDevice(name, id, "Display") {
204         std::cout << "      [IODevice] Constructed\n";
205     }
206
207     void showInfo() const {
208         // No ambiguity now - only one Device exists
209         std::cout << "\n  Device Info:\n";
210         displayInfo(); // Unambiguous!
211
212         std::cout << "\n  Input/Output Details:\n";
213         showInput();
214         showOutput();
215
216         std::cout << "\n      Solution: Only ONE copy of Device exists!\n";
217         std::cout << "      getId() = " << getId() << " (no ambiguity)\n";
218     }
219 };
220
221 void demonstrate() {
222     std::cout << "\n" << std::string(70, '=') << "\n";
223     std::cout << "==== SECTION 2: Solution - Virtual Inheritance ===\n";
224     std::cout << std::string(70, '=') << "\n\n";
225
226     std::cout << "Creating IODevice with virtual inheritance...\n";
227     std::cout << "Notice: Device constructor called ONCE!\n\n";
228
229     IODevice device("MyIODevice", 42);
230
231     std::cout << "\nShowing device information:\n";
232     device.showInfo();
233
234
235     std::cout << "\nMemory Analysis:\n";
236     std::cout << "      sizeof(Device) = " << sizeof(Device) << " bytes\n";
237     std::cout << "      sizeof(InputDevice) = " << sizeof(InputDevice) << " bytes\n";
238     std::cout << "      sizeof(OutputDevice) = " << sizeof(OutputDevice) << " bytes\n";
239     std::cout << "      sizeof(IODevice) = " << sizeof(IODevice) << " bytes\n";
240     std::cout << "      IODevice contains only ONE Device instance (no
241         duplication)\n";
```

```
241 }
242
243 } // namespace virtual_inheritance_solution
244
245 // =====
246 // SECTION 3: Real-World Example - File System
247 //
248 // =====
249
250 namespace filesystem_example {
251
252 class File {
253 protected:
254     std::string path_;
255     size_t size_;
256
257 public:
258     File(const std::string& path, size_t size)
259         : path_(path), size_(size) {
260         std::cout << "    [File] Created: " << path_ << "(" << size_ << "
261             bytes)\n";
262     }
263
264     virtual ~File() = default;
265
266     std::string getPath() const { return path_; }
267     size_t getSize() const { return size_; }
268
269     void displayInfo() const {
270         std::cout << "    File: " << path_ << "(" << size_ << " bytes)\n";
271     }
272 };
273
274 // Readable file
275 class ReadableFile : virtual public File {
276 public:
277     ReadableFile(const std::string& path, size_t size)
278         : File(path, size) {
279         std::cout << "    [ReadableFile] Readable permissions added\n";
280     }
281
282     void read() const {
283         std::cout << "    Reading from: " << path_ << "\n";
284     }
285 };
286
287 // Writable file
288 class WritableFile : virtual public File {
289 public:
290     WritableFile(const std::string& path, size_t size)
291         : File(path, size) {
```

```
290         std::cout << "      [WritableFile] Writable permissions added\n";
291     }
292
293     void write(const std::string& data) {
294         std::cout << "      Writing to: " << path_ << " - Data: " << data << "
295             \"\n";
296         size_ += data.length();
297     }
298
299 // Read-Write file - inherits from both
300 class ReadWriteFile : public ReadableFile, public WritableFile {
301 public:
302     ReadWriteFile(const std::string& path, size_t size)
303         : File(path, size), // Initialize virtual base
304           ReadableFile(path, size),
305           WritableFile(path, size) {
306         std::cout << "      [ReadWriteFile] Read-Write file created\n";
307     }
308
309     void showInfo() const {
310         displayInfo(); // No ambiguity
311         std::cout << "      Permissions: Read + Write\n";
312     }
313 };
314
315 void demonstrate() {
316     std::cout << "\n" << std::string(70, '=') << "\n";
317     std::cout << "==== SECTION 3: Real-World Example - File System ===\n";
318     std::cout << std::string(70, '=') << "\n\n";
319
320     std::cout << "Creating ReadWriteFile with virtual inheritance:\n\n";
321     ReadWriteFile file("document.txt", 1024);
322
323     std::cout << "\nUsing the file:\n";
324     file.showInfo();
325     file.read();
326     file.write("Hello, World!");
327
328     std::cout << "\nFinal state:\n";
329     file.displayInfo();
330 }
331
332 } // namespace filesystem_example
333
334 /**
335 // SECTION 4: Constructor Initialization Order
336 /**
337 =====
338 namespace initialization_order {
```

```
339
340 class Base {
341 public:
342     Base(int value) {
343         std::cout << "[Base] Constructed with value: " << value << "\n";
344     }
345 };
346
347 class A : virtual public Base {
348 public:
349     A(int value) : Base(value) {
350         std::cout << "[A] Constructed\n";
351     }
352 };
353
354 class B : virtual public Base {
355 public:
356     B(int value) : Base(value) {
357         std::cout << "[B] Constructed\n";
358     }
359 };
360
361 class Derived : public A, public B {
362 public:
363     // CRITICAL: Derived class must initialize virtual base class directly!
364     // The Base(value) calls in A and B are IGNORED
365     Derived(int value)
366         : Base(value), // This is the one that matters!
367             A(value),
368             B(value) {
369         std::cout << "[Derived] Constructed\n";
370     }
371 };
372
373 void demonstrate() {
374     std::cout << "\n" << std::string(70, '=') << "\n";
375     std::cout << "==== SECTION 4: Constructor Initialization Order ====\n";
376     std::cout << std::string(70, '=') << "\n\n";
377
378     std::cout << "Important: Virtual base classes are initialized first,\n";
379     std::cout << "                    by the MOST DERIVED class.\n\n";
380
381     std::cout << "Creating Derived object:\n";
382     Derived d(42);
383
384     std::cout << "\nInitialization order:\n";
385     std::cout << " 1. Base (initialized by Derived, not A or B)\n";
386     std::cout << " 2. A\n";
387     std::cout << " 3. B\n";
388     std::cout << " 4. Derived\n";
389 }
390
391 } // namespace initialization_order
```

```
393 // =====
394 // SECTION 5: When to Avoid Multiple Inheritance
395 //
396 =====
397
398 namespace alternative_designs {
399
400 // Instead of multiple inheritance, use composition
401 class Device {
402 protected:
403     std::string name_;
404     int id_;
405
406 public:
407     Device(const std::string& name, int id)
408         : name_(name), id_(id) {}
409
410     std::string getName() const { return name_; }
411     int getId() const { return id_; }
412 };
413
414 class InputCapability {
415     std::string inputType_;
416
417 public:
418     explicit InputCapability(const std::string& type) : inputType_(type) {}
419
420     void handleInput() const {
421         std::cout << "    Handling input: " << inputType_ << "\n";
422     }
423 };
424
425 class OutputCapability {
426     std::string outputType_;
427
428 public:
429     explicit OutputCapability(const std::string& type) : outputType_(type) {}
430
431     void handleOutput() const {
432         std::cout << "    Handling output: " << outputType_ << "\n";
433     }
434
435 // Composition-based design - cleaner and more flexible
436 class IODevice {
437     Device device_;
438     InputCapability input_;
439     OutputCapability output_;
440
441 public:
442     IODevice(const std::string& name, int id)
```

```
443     : device_(name, id),
444     input_("Keyboard"),
445     output_("Display") {
446     std::cout << "    [IODevice] Constructed using composition\n";
447 }
448
449 void showInfo() const {
450     std::cout << "    Device: " << device_.getName()
451             << " (ID: " << device_.getId() << ")\n";
452     input_.handleInput();
453     output_.handleOutput();
454 }
455 };
456
457 void demonstrate() {
458     std::cout << "\n" << std::string(70, '=') << "\n";
459     std::cout << "==== SECTION 5: Alternative - Composition Over Inheritance
460             ===\n";
461     std::cout << std::string(70, '=') << "\n\n";
462
463     std::cout << "Creating IODevice with composition:\n";
464     IODevice device("MyIODevice", 42);
465
466     std::cout << "\nUsing the device:\n";
467     device.showInfo();
468
469     std::cout << "\nBenefits:\n";
470     std::cout << "    No diamond problem\n";
471     std::cout << "    More flexible\n";
472     std::cout << "    Easier to understand\n";
473     std::cout << "    Simpler construction\n";
474 }
475 } // namespace alternative_designs
476
477 /**
478 // SECTION 6: Best Practices
479 /**
480 =====
481
482 void show_best_practices() {
483     std::cout << "\n" << std::string(70, '=') << "\n";
484     std::cout << "==== Best Practices for Diamond Problem ===\n";
485     std::cout << std::string(70, '=') << "\n\n";
486
487     std::cout << "1. UNDERSTAND THE PROBLEM\n";
488     std::cout << "    • Multiple inheritance creates duplicate base class
489                 instances\n";
490     std::cout << "    • Causes ambiguity and memory waste\n";
491     std::cout << "    • Creates the \"diamond\" inheritance shape\n\n";
```

```
491     std::cout << "2. USE VIRTUAL INHERITANCE WHEN NEEDED\n";
492     std::cout << " • Add 'virtual' keyword: class Derived : virtual public
493         Base\n";
494     std::cout << " • Ensures only ONE base class instance exists\n";
495     std::cout << " • Most derived class initializes the virtual base\n\n";
496
497     std::cout << "3. INITIALIZATION ORDER RULES\n";
498     std::cout << " • Virtual base classes initialized FIRST\n";
499     std::cout << " • Most derived class is responsible for initialization\n"
500         ;
501     std::cout << " • Base class constructors in intermediate classes are
502         ignored\n\n";
503
504     std::cout << "4. PERFORMANCE CONSIDERATIONS\n";
505     std::cout << " • Virtual inheritance has small runtime overhead (vtable
506         pointer)\n";
507     std::cout << " • Slightly larger object size\n";
508     std::cout << " • Usually worth it to avoid duplication\n\n";
509
510     std::cout << "5. PREFER COMPOSITION OVER MULTIPLE INHERITANCE\n";
511     std::cout << " • Composition is often clearer and more flexible\n";
512     std::cout << " • No diamond problem at all\n";
513     std::cout << " • Easier to test and maintain\n\n";
514
515     std::cout << "6. WHEN TO USE MULTIPLE INHERITANCE\n";
516     std::cout << "     Inheriting multiple pure interfaces (abstract classes)\n
517         ";
518     std::cout << "     Mixins (adding orthogonal functionality)\n";
519     std::cout << "     Inheriting implementation from multiple classes\n\n";
520
521     std::cout << "7. INTERFACE SEGREGATION\n";
522     std::cout << " • Use multiple pure abstract classes (interfaces)\n";
523     std::cout << " • No diamond problem with pure interfaces\n";
524     std::cout << " • Clear contracts without implementation conflicts\n\n";
525
526     std::cout << "REMEMBER:\n";
527     std::cout << "     \"Prefer composition over inheritance\" - Gang of Four\n";
528     std::cout << "     \"Virtual inheritance solves the diamond problem\" -
529         Bjarne Stroustrup\n";
530 }
531 // =====
532 // MAIN FUNCTION
533 // =====
534
535 int main() {
536     std::cout << "\n";
537     std::cout << "                                         \n";
538     std::cout << "             Diamond Problem (Diamond of Death) in C++\n";
539 }
```

```
534     std::cout << "           Solution: Virtual Inheritance
535                     \n";
536     std::cout << "           \n";
537 // Demonstrate the problem
538 diamond_problem::demonstrate();
539
540 // Show the solution
541 virtual_inheritance_solution::demonstrate();
542
543 // Real-world example
544 filesystem_example::demonstrate();
545
546 // Initialization order
547 initialization_order::demonstrate();
548
549 // Alternative designs
550 alternative_designs::demonstrate();
551
552 // Best practices
553 show_best_practices();
554
555 std::cout << "\n" << std::string(70, '=') << "\n";
556 std::cout << "All demonstrations completed!\n";
557 std::cout << std::string(70, '=') << "\n\n";
558
559 return 0;
560 }
```

21 Source Code: EigenSensorFusion.cpp

File: src/EigenSensorFusion.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // EIGEN LIBRARY: SENSOR FUSION AND PARTICLE FILTER
3 // =====
4 // This example demonstrates advanced robotics and embedded systems
5 // applications using the Eigen library for linear algebra and tensors.
6 //
7 // TOPICS COVERED:
8 // 1. Eigen Tensors - Multi-dimensional arrays for sensor data
9 // 2. Kalman Filter - Optimal sensor fusion (IMU + GPS)
10 // 3. Complementary Filter - Lightweight sensor fusion (Accel + Gyro)
11 // 4. Extended Kalman Filter (EKF) - Nonlinear sensor fusion
12 // 5. Particle Filter - Monte Carlo localization and tracking
13 // 6. Sensor Fusion Pipeline - Real-time data processing
14 //
15 // INSTALL EIGEN:
16 // =====
17 // Ubuntu/Debian: sudo apt-get install libeigen3-dev
18 // macOS: brew install eigen
19 // Windows: vcpkg install eigen3
20 // Manual: Download from https://eigen.tuxfamily.org/
21 //
22 // BUILD INSTRUCTIONS:
23 // =====
24 // g++ -std=c++17 -O3 -I/usr/include/eigen3 EigenSensorFusion.cpp -o
25 // EigenSensorFusion
26 //
27 // For CMake:
28 // find_package(Eigen3 REQUIRED)
29 // target_link_libraries(EigenSensorFusion Eigen3::Eigen)
30 //
31 // APPLICATIONS:
32 // =====
33 // - Drone attitude estimation (IMU fusion)
34 // - Robot localization (particle filter)
35 // - Autonomous vehicles (multi-sensor fusion)
36 // - Indoor navigation (dead reckoning + WiFi)
37 // - Wearable devices (activity recognition)
38 // =====
39 #include <iostream>
40 #include <vector>
41 #include <random>
42 #include <cmath>
43 #include <iomanip>
44 #include <Eigen/Dense>
45 #include <Eigen/Core>
46
47 using namespace Eigen;
48
```

```
49 // =====
50 // 1. SENSOR DATA STRUCTURES
51 // =====
52
53 struct IMUData {
54     Vector3d accel;        // Accelerometer (m/s2)
55     Vector3d gyro;         // Gyroscope (rad/s)
56     double timestamp;
57
58     IMUData(const Vector3d& a, const Vector3d& g, double t)
59         : accel(a), gyro(g), timestamp(t) {}
60 };
61
62 struct GPSData {
63     Vector2d position;    // Latitude, Longitude (or x, y in meters)
64     double accuracy;      // GPS accuracy (meters)
65     double timestamp;
66
67     GPSData(const Vector2d& pos, double acc, double t)
68         : position(pos), accuracy(acc), timestamp(t) {}
69 };
70
71 struct State {
72     Vector3d position;    // x, y, z
73     Vector3d velocity;    // vx, vy, vz
74     Vector3d orientation; // roll, pitch, yaw (Euler angles)
75
76     State() : position(Vector3d::Zero()),
77                velocity(Vector3d::Zero()),
78                orientation(Vector3d::Zero()) {}
79 };
80
81 // =====
82 // 2. KALMAN FILTER FOR SENSOR FUSION
83 // =====
84
85 class KalmanFilter {
86 private:
87     // State: [x, y, vx, vy] - position and velocity in 2D
88     VectorXd x;           // State vector (4x1)
89     MatrixXd P;          // State covariance (4x4)
90     MatrixXd F;          // State transition (4x4)
91     MatrixXd H;          // Measurement matrix (2x4)
92     MatrixXd Q;          // Process noise (4x4)
93     MatrixXd R;          // Measurement noise (2x2)
94
95 public:
96     KalmanFilter() {
97         // Initialize state: [x, y, vx, vy]
98         x = VectorXd::Zero(4);
99
100        // Initialize covariance
101        P = MatrixXd::Identity(4, 4) * 1000.0;
102    }
```

```
103     // State transition matrix (constant velocity model)
104     F = MatrixXd::Identity(4, 4);
105     // F will be updated with dt in predict()
106
107     // Measurement matrix (we measure position only)
108     H = MatrixXd::Zero(2, 4);
109     H(0, 0) = 1.0; // Measure x
110     H(1, 1) = 1.0; // Measure y
111
112     // Process noise (model uncertainty)
113     Q = MatrixXd::Identity(4, 4) * 0.1;
114
115     // Measurement noise (GPS uncertainty)
116     R = MatrixXd::Identity(2, 2) * 5.0; // 5m GPS accuracy
117 }
118
119 // Prediction step (using IMU or motion model)
120 void predict(double dt) {
121     // Update state transition matrix with dt
122     F(0, 2) = dt; // x = x + vx * dt
123     F(1, 3) = dt; // y = y + vy * dt
124
125     // Predict state
126     x = F * x;
127
128     // Predict covariance
129     P = F * P * F.transpose() + Q;
130 }
131
132 // Update step (using GPS measurement)
133 void update(const Vector2d& measurement, double measurement_noise) {
134     // Update measurement noise with actual GPS accuracy
135     R = MatrixXd::Identity(2, 2) * (measurement_noise * measurement_noise)
136         ;
137
138     // Innovation (measurement residual)
139     VectorXd z = VectorXd(2);
140     z << measurement(0), measurement(1);
141     VectorXd y = z - H * x;
142
143     // Innovation covariance
144     MatrixXd S = H * P * H.transpose() + R;
145
146     // Kalman gain
147     MatrixXd K = P * H.transpose() * S.inverse();
148
149     // Update state
150     x = x + K * y;
151
152     // Update covariance
153     MatrixXd I = MatrixXd::Identity(4, 4);
154     P = (I - K * H) * P;
155 }
```

```
156     Vector2d getPosition() const {
157         return Vector2d(x(0), x(1));
158     }
159
160     Vector2d getVelocity() const {
161         return Vector2d(x(2), x(3));
162     }
163
164     VectorXd getState() const { return x; }
165     MatrixXd getCovariance() const { return P; }
166 };
167
168 // =====
169 // 3. COMPLEMENTARY FILTER (Lightweight Sensor Fusion)
170 // =====
171
172 class ComplementaryFilter {
173 private:
174     Vector3d orientation; // Roll, Pitch, Yaw
175     double alpha; // Filter coefficient (0-1)
176
177 public:
178     ComplementaryFilter(double filter_alpha = 0.98)
179         : orientation(Vector3d::Zero()), alpha(filter_alpha) {}
180
181     // Fuse accelerometer and gyroscope data
182     void update(const Vector3d& accel, const Vector3d& gyro, double dt) {
183         // Calculate angles from accelerometer (for roll and pitch only)
184         double accel_roll = std::atan2(accel.y(), accel.z());
185         double accel_pitch = std::atan2(-accel.x(),
186                                         std::sqrt(accel.y()*accel.y() + accel.z()
187                                                 ()*accel.z())));
188
189         // Integrate gyroscope (rate) to get angle
190         Vector3d gyro_angle = orientation + gyro * dt;
191
192         // Complementary filter: trust gyro for short-term, accel for long-
193         // term
194         orientation(0) = alpha * gyro_angle(0) + (1.0 - alpha) * accel_roll;
195             // Roll
196         orientation(1) = alpha * gyro_angle(1) + (1.0 - alpha) * accel_pitch;
197             // Pitch
198         orientation(2) = gyro_angle(2); // Yaw (no accel reference, use gyro
199             only)
200     }
201
202     Vector3d getOrientation() const { return orientation; }
203
204     // Convert to degrees for readability
205     Vector3d getOrientationDegrees() const {
206         return orientation * 180.0 / M_PI;
207     }
208 };
209
```

```
205 // =====
206 // 4. PARTICLE FILTER (Monte Carlo Localization)
207 // =====
208
209 struct Particle {
210     Vector2d position;    // x, y
211     double weight;        // Importance weight
212
213     Particle() : position(Vector2d::Zero()), weight(1.0) {}
214     Particle(const Vector2d& pos, double w) : position(pos), weight(w) {}
215 };
216
217 class ParticleFilter {
218 private:
219     std::vector<Particle> particles;
220     int num_particles;
221     std::mt19937 rng;
222
223 public:
224     ParticleFilter(int n_particles = 1000)
225         : num_particles(n_particles), rng(std::random_device{}()) {
226
227         // Initialize particles with random positions
228         std::normal_distribution<double> dist(0.0, 10.0);
229         particles.reserve(num_particles);
230
231         for (int i = 0; i < num_particles; ++i) {
232             Vector2d pos(dist(rng), dist(rng));
233             particles.emplace_back(pos, 1.0 / num_particles);
234         }
235     }
236
237     // Prediction step: move particles based on motion model
238     void predict(const Vector2d& control_input, double dt, double motion_noise)
239     {
240         std::normal_distribution<double> noise(0.0, motion_noise);
241
242         for (auto& particle : particles) {
243             // Move particle according to motion model + noise
244             particle.position += control_input * dt;
245             particle.position(0) += noise(rng);
246             particle.position(1) += noise(rng);
247         }
248     }
249
250     // Update step: weight particles based on measurement likelihood
251     void update(const Vector2d& measurement, double measurement_noise) {
252         double weight_sum = 0.0;
253
254         for (auto& particle : particles) {
255             // Calculate distance from particle to measurement
256             double distance = (particle.position - measurement).norm();
257
258             // Gaussian likelihood (closer = higher weight)
```

```
258     double likelihood = std::exp(-0.5 * (distance * distance) /
259                                     (measurement_noise * measurement_noise
260                                      ));
261
262     particle.weight *= likelihood;
263     weight_sum += particle.weight;
264 }
265
266 // Normalize weights
267 if (weight_sum > 0.0) {
268     for (auto& particle : particles) {
269         particle.weight /= weight_sum;
270     }
271 }
272
273 // Resample particles based on weights (importance resampling)
274 void resample() {
275     std::vector<Particle> new_particles;
276     new_particles.reserve(num_particles);
277
278     // Cumulative sum of weights
279     std::vector<double> cumsum(num_particles);
280     cumsum[0] = particles[0].weight;
281     for (int i = 1; i < num_particles; ++i) {
282         cumsum[i] = cumsum[i-1] + particles[i].weight;
283     }
284
285     // Systematic resampling
286     std::uniform_real_distribution<double> uniform(0.0, 1.0 /
287                                                 num_particles);
288     double r = uniform(rng);
289
290     int idx = 0;
291     for (int i = 0; i < num_particles; ++i) {
292         double u = r + (double)i / num_particles;
293
294         while (idx < num_particles - 1 && u > cumsum[idx]) {
295             idx++;
296         }
297
298         new_particles.emplace_back(particles[idx].position,
299                                   1.0 / num_particles);
300     }
301
302     particles = std::move(new_particles);
303 }
304
305 // Estimate position (weighted average)
306 Vector2d getEstimate() const {
307     Vector2d estimate = Vector2d::Zero();
308
309     for (const auto& particle : particles) {
310         estimate += particle.position * particle.weight;
311     }
312 }
```

```
310     }
311
312     return estimate;
313 }
314
315 // Get effective number of particles (measure of degeneracy)
316 double getEffectiveParticles() const {
317     double weight_sum_sq = 0.0;
318     for (const auto& particle : particles) {
319         weight_sum_sq += particle.weight * particle.weight;
320     }
321     return 1.0 / weight_sum_sq;
322 }
323
324 const std::vector<Particle>& getParticles() const { return particles; }
325 };
326
327 // =====
328 // 5. EXTENDED KALMAN FILTER (EKF) FOR NONLINEAR SYSTEMS
329 // =====
330
331 class ExtendedKalmanFilter {
332 private:
333     VectorXd x;      // State: [x, y, theta, v]
334     MatrixXd P;      // Covariance
335     MatrixXd Q;      // Process noise
336     MatrixXd R;      // Measurement noise
337
338 public:
339     ExtendedKalmanFilter() {
340         // State: [x, y, theta, v] - position, heading, velocity
341         x = VectorXd::Zero(4);
342         P = MatrixXd::Identity(4, 4) * 100.0;
343         Q = MatrixXd::Identity(4, 4) * 0.1;
344         R = MatrixXd::Identity(2, 2) * 5.0;
345     }
346
347     // Predict with nonlinear motion model
348     void predict(double v, double omega, double dt) {
349         // Nonlinear motion model for differential drive robot
350         double theta = x(2);
351
352         // Predict state
353         x(0) += v * std::cos(theta) * dt;    // x
354         x(1) += v * std::sin(theta) * dt;    // y
355         x(2) += omega * dt;                 // theta
356         x(3) = v;                         // velocity
357
358         // Jacobian of motion model
359         MatrixXd F = MatrixXd::Identity(4, 4);
360         F(0, 2) = -v * std::sin(theta) * dt;
361         F(1, 2) = v * std::cos(theta) * dt;
362
363         // Predict covariance
```

```
364     P = F * P * F.transpose() + Q;
365 }
366
367 // Update with GPS measurement [x, y]
368 void update(const Vector2d& measurement) {
369     // Measurement model (linear: measure x, y directly)
370     MatrixXd H = MatrixXd::Zero(2, 4);
371     H(0, 0) = 1.0;
372     H(1, 1) = 1.0;
373
374     // Innovation
375     VectorXd z(2);
376     z << measurement(0), measurement(1);
377     VectorXd y = z - H * x;
378
379     // Innovation covariance
380     MatrixXd S = H * P * H.transpose() + R;
381
382     // Kalman gain
383     MatrixXd K = P * H.transpose() * S.inverse();
384
385     // Update
386     x = x + K * y;
387     P = (MatrixXd::Identity(4, 4) - K * H) * P;
388 }
389
390 Vector2d getPosition() const { return Vector2d(x(0), x(1)); }
391 double getHeading() const { return x(2); }
392 double getVelocity() const { return x(3); }
393 };
394
395 // =====
396 // 6. SENSOR FUSION PIPELINE (Multi-Sensor Integration)
397 // =====
398
399 class SensorFusionPipeline {
400 private:
401     KalmanFilter kf;
402     ComplementaryFilter cf;
403     ParticleFilter pf;
404
405     std::vector<IMUData> imu_buffer;
406     std::vector<GPSData> gps_buffer;
407
408     Vector2d last_position;
409     double last_timestamp;
410
411 public:
412     SensorFusionPipeline()
413         : pf(500), last_position(Vector2d::Zero()), last_timestamp(0.0) {}
414
415     void addIMUData(const IMUData& imu) {
416         imu_buffer.push_back(imu);
```

```
418     // Update complementary filter for orientation
419     if (!imu_buffer.empty()) {
420         double dt = 0.01; // Assume 100 Hz IMU
421         if (imu_buffer.size() > 1) {
422             dt = imu.timestamp - imu_buffer[imu_buffer.size() - 2].timestamp
423                 ;
424         }
425     }
426 }
427
428 void addGPSData(const GPSData& gps) {
429     gps_buffer.push_back(gps);
430
431     // Update Kalman filter
432     if (last_timestamp > 0.0) {
433         double dt = gps.timestamp - last_timestamp;
434         kf.predict(dt);
435     }
436     kf.update(gps.position, gps.accuracy);
437
438     // Update particle filter
439     Vector2d velocity = kf.getVelocity();
440     double dt = gps.timestamp - last_timestamp;
441     if (dt > 0.0) {
442         pf.predict(velocity, dt, 1.0);
443         pf.update(gps.position, gps.accuracy);
444
445         // Resample if particles degenerate
446         if (pf.getEffectiveParticles() < 100) {
447             pf.resample();
448         }
449     }
450
451     last_position = gps.position;
452     last_timestamp = gps.timestamp;
453 }
454
455 Vector2d getKalmanPosition() const { return kf.getPosition(); }
456 Vector2d getParticlePosition() const { return pf.getEstimate(); }
457 Vector3d getOrientation() const { return cf.getOrientationDegrees(); }
458
459 void printStatus() const {
460     std::cout << "\nSensor Fusion Status:\n";
461     std::cout << "-----\n";
462
463     auto kf_pos = kf.getPosition();
464     std::cout << "Kalman Filter: (" << std::fixed << std::setprecision
465         (2)
466             << kf_pos(0) << ", " << kf_pos(1) << ")\n";
467
468     auto pf_pos = pf.getEstimate();
469     std::cout << "Particle Filter: (" << std::fixed << std::setprecision
470         (2)
```

```
469         << pf_pos(0) << ", " << pf_pos(1) << ")\\n";
470
471     auto orient = cf.getOrientationDegrees();
472     std::cout << "Orientation: Roll=" << std::fixed << std::;
473             setprecision(1)
474             << orient(0) << "\u00b0 Pitch=" << orient(1)
475             << "\u00b0 Yaw=" << orient(2) << "\u00b0\\n";
476
477     std::cout << "Effective Particles: " << (int)pf.getEffectiveParticles
478             () << "\\n";
479 }
480
481 // =====
482 // DEMONSTRATION FUNCTIONS
483 // =====
484 void demonstrate_kalman_filter() {
485     std::cout << "=====\\n"
486             ;
487     std::cout << "1. KALMAN FILTER - GPS/IMU FUSION\\n";
488     std::cout << "=====\\n"
489             ;
490     std::cout << "Scenario: Robot moving in a circle, fusing GPS measurements\\
491             n\\n";
492
493     KalmanFilter kf;
494     std::mt19937 rng(42);
495     std::normal_distribution<double> gps_noise(0.0, 3.0); // 3m GPS noise
496
497     // Simulate circular motion
498     double dt = 0.1; // 10 Hz
499     double radius = 50.0;
500     double angular_vel = 0.1; // rad/s
501
502     std::cout << std::fixed << std::setprecision(2);
503     std::cout << "Time True Position GPS Measurement Kalman Estimate
504             Error\\n";
505     std::cout << "---- ----- ----- -----\\n";
506
507     for (int i = 0; i < 20; ++i) {
508         double t = i * dt;
509
510         // True position (circular motion)
511         Vector2d true_pos(radius * std::cos(angular_vel * t),
512                           radius * std::sin(angular_vel * t));
513
514         // Noisy GPS measurement
515         Vector2d gps_measurement = true_pos + Vector2d(gps_noise(rng),
516                                                       gps_noise(rng));
517
518         // Kalman filter predict and update
519         kf.predict(dt);
```

```

515     kf.update(gps_measurement, 3.0);
516
517     Vector2d kf_estimate = kf.getPosition();
518     double error = (kf_estimate - true_pos).norm();
519
520     std::cout << std::setw(4) << t << " "
521             << "(" << std::setw(6) << true_pos(0) << ", "
522             << std::setw(6) << true_pos(1) << ")"
523             << "(" << std::setw(6) << gps_measurement(0) << ", "
524             << std::setw(6) << gps_measurement(1) << ")"
525             << "(" << std::setw(6) << kf_estimate(0) << ", "
526             << std::setw(6) << kf_estimate(1) << ")"
527             << std::setw(5) << error << "m\n";
528 }
529
530 std::cout << "\n Kalman filter smooths noisy GPS and predicts motion!\n";
531 }
532
533 void demonstrate_complementary_filter() {
534     std::cout << "\n=====\\n";
535     std::cout << "2. COMPLEMENTARY FILTER - ACCELEROMETER/GYROSCOPE FUSION\\n";
536     std::cout << "=====\\n";
537     std::cout << "Scenario: IMU measuring tilt angles (roll, pitch)\\n\\n";
538
539     ComplementaryFilter cf(0.98);
540     std::mt19937 rng(42);
541     std::normal_distribution<double> accel_noise(0.0, 0.5);
542     std::normal_distribution<double> gyro_noise(0.0, 0.01);
543
544     double dt = 0.01; // 100 Hz IMU
545     double true_roll = 0.0;
546     double true_pitch = 0.0;
547
548     std::cout << std::fixed << std::setprecision(2);
549     std::cout << "Time    True Angles        Accel Angles      Filtered Angles\\n"
550             << "-----  -----  -----  -----\\n";
551     std::cout << "----  -----  -----  -----\\n";
552
553     for (int i = 0; i < 15; ++i) {
554         double t = i * 0.1;
555
556         // Simulate sinusoidal motion
557         true_roll = 30.0 * std::sin(2 * M_PI * 0.5 * t) * M_PI / 180.0; // ±30°
558         true_pitch = 20.0 * std::cos(2 * M_PI * 0.3 * t) * M_PI / 180.0; // ±20°
559
560         // Simulate accelerometer (measures gravity vector)
561         double g = 9.81;
562         Vector3d true_accel(-g * std::sin(true_pitch),
563                             g * std::sin(true_roll) * std::cos(true_pitch),

```

```

563                     g * std::cos(true_roll) * std::cos(true_pitch));
564
565     Vector3d accel = true_accel + Vector3d(accel_noise(rng),
566                                              accel_noise(rng),
567                                              accel_noise(rng));
568
569     // Simulate gyroscope (measures angular rates)
570     double roll_rate = 30.0 * 2 * M_PI * 0.5 * std::cos(2 * M_PI * 0.5 * t
571     ) * M_PI / 180.0;
572     double pitch_rate = -20.0 * 2 * M_PI * 0.3 * std::sin(2 * M_PI * 0.3 * t
573     ) * M_PI / 180.0;
574
575     Vector3d gyro(roll_rate + gyro_noise(rng),
576                   pitch_rate + gyro_noise(rng),
577                   gyro_noise(rng));
578
579     // Update filter 10 times (simulating 100 Hz between prints)
580     for (int j = 0; j < 10; ++j) {
581         cf.update(accel, gyro, dt);
582     }
583
584     // Calculate angles from accelerometer only (for comparison)
585     double accel_roll = std::atan2(accel.y(), accel.z()) * 180.0 / M_PI;
586     double accel_pitch = std::atan2(-accel.x(),
587                                     std::sqrt(accel.y()*accel.y() + accel.z()
588                                     ()*accel.z())))
589     * 180.0 / M_PI;
590
591     auto filtered = cf.getOrientationDegrees();
592
593     std::cout << std::setw(4) << t << " "
594     << "R=" << std::setw(6) << (true_roll * 180.0 / M_PI)
595     << "° P=" << std::setw(6) << (true_pitch * 180.0 / M_PI) <<
596     "° "
597     << "R=" << std::setw(6) << accel_roll
598     << "° P=" << std::setw(6) << accel_pitch << "° "
599     << "R=" << std::setw(6) << filtered(0)
600     << "° P=" << std::setw(6) << filtered(1) << "°\n";
601 }
602
603 void demonstrate_particle_filter() {
604     std::cout << "\n=====\n";
605     std::cout << "3. PARTICLE FILTER - ROBOT LOCALIZATION\n";
606     std::cout << "=====\n";
607     ;
608     std::cout << "Scenario: Robot with odometry and GPS, 500 particles\n\n";
609     ParticleFilter pf(500);
610     std::mt19937 rng(42);

```

```

610     std::normal_distribution<double> gps_noise(0.0, 5.0);
611
612     // Robot starts at origin, moves in square path
613     Vector2d true_pos(0.0, 0.0);
614     Vector2d velocity(2.0, 0.0);    // 2 m/s
615     double dt = 1.0;
616
617     std::cout << std::fixed << std::setprecision(2);
618     std::cout << "Time      True Position      GPS Measurement      Particle
619             Estimate      Error      N_eff\n";
620     std::cout << "----      -----      -----      -----";
621     std::cout << "\n";
622
623     for (int i = 0; i < 20; ++i) {
624         // Move robot (square path)
625         if (i % 5 == 0 && i > 0) {
626             // Turn 90 degrees
627             double temp = velocity(0);
628             velocity(0) = -velocity(1);
629             velocity(1) = temp;
630         }
631
632         true_pos += velocity * dt;
633
634         // Particle filter prediction
635         pf.predict(velocity, dt, 0.5);
636
637         // GPS measurement (every 2 seconds)
638         if (i % 2 == 0) {
639             Vector2d gps = true_pos + Vector2d(gps_noise(rng), gps_noise(rng));
640             ;
641             pf.update(gps, 5.0);
642
643             // Resample if needed
644             if (pf.getEffectiveParticles() < 100) {
645                 pf.resample();
646             }
647
648             std::cout << std::setw(4) << (i * dt) << "      "
649                         << "(" << std::setw(6) << true_pos(0) << ", "
650                         << std::setw(6) << true_pos(1) << ")      "
651                         << "(" << std::setw(6) << gps(0) << ", "
652                         << std::setw(6) << gps(1) << ")";
653
654         } else {
655             std::cout << std::setw(4) << (i * dt) << "      "
656                         << "(" << std::setw(6) << true_pos(0) << ", "
657                         << std::setw(6) << true_pos(1) << ")      "
658                         << "      No GPS      ";
659
660         }
661
662         Vector2d estimate = pf.getEstimate();
663         double error = (estimate - true_pos).norm();
664
665         std::cout << "(" << std::setw(6) << estimate(0) << ", "
666

```

```
661         << std::setw(6) << estimate(1) << ")      "
662         << std::setw(5) << error << "m   "
663         << std::setw(5) << (int)pf.getEffectiveParticles() << "\n";
664     }
665
666     std::cout << "\n Particle filter handles multimodal distributions and
667     nonlinearity!\n";
668 }
669
670 void demonstrate_sensor_fusion_pipeline() {
671     std::cout << "\n=====\
672     n";
673     std::cout << "4. COMPLETE SENSOR FUSION PIPELINE\n";
674     std::cout << "=====\
675     n";
676     std::cout << "Scenario: Drone with IMU (100 Hz) and GPS (1 Hz)\n\n";
677
678 SensorFusionPipeline pipeline;
679 std::mt19937 rng(42);
680 std::normal_distribution<double> accel_noise(0.0, 0.3);
681 std::normal_distribution<double> gyro_noise(0.0, 0.01);
682 std::normal_distribution<double> gps_noise(0.0, 3.0);
683
684 double t = 0.0;
685 double dt_imu = 0.01;    // 100 Hz
686 double dt_gps = 1.0;    // 1 Hz
687
688 Vector2d position(0.0, 0.0);
689 Vector2d velocity(5.0, 3.0); // 5 m/s east, 3 m/s north
690
691 std::cout << "Fusing IMU (100 Hz) with GPS (1 Hz)... \n\n";
692
693 for (int i = 0; i < 10; ++i) {
694     // Simulate 100 IMU samples between GPS updates
695     for (int j = 0; j < 100; ++j) {
696         t += dt_imu;
697
698         // Simulate IMU data
699         Vector3d accel(accel_noise(rng), accel_noise(rng),
700                         9.81 + accel_noise(rng));
701         Vector3d gyro(gyro_noise(rng), gyro_noise(rng),
702                         0.1 + gyro_noise(rng)); // 0.1 rad/s yaw rate
703
704         IMUData imu(accel, gyro, t);
705         pipeline.addIMUData(imu);
706     }
707
708     // GPS update (1 Hz)
709     position += velocity * dt_gps;
710     Vector2d gps_pos = position + Vector2d(gps_noise(rng), gps_noise(rng))
711     ;
712     GPSData gps(gps_pos, 3.0, t);
713     pipeline.addGPSData(gps);
714 }
```

```
711     // Print status
712     std::cout << "t = " << std::fixed << std::setprecision(1)
713         << t << "s:\n";
714     pipeline.printStatus();
715     std::cout << "\n";
716 }
717
718 std::cout << " Complete sensor fusion combines all algorithms!\n";
719 }
720
721 // =====
722 // MAIN FUNCTION
723 // =====
724
725 int main() {
726     std::cout << "\n";
727     std::cout << "
728         =====\n"
729         ;
730     std::cout << "EIGEN LIBRARY: SENSOR FUSION AND PARTICLE FILTER\n";
731     std::cout << "
732         =====\n"
733         ;
734     std::cout << "Advanced robotics and embedded systems examples\n";
735     std::cout << "
736         =====\n"
737         ;
738
739     try {
740         demonstrate_kalman_filter();
741         demonstrate_complementary_filter();
742         demonstrate_particle_filter();
743         demonstrate_sensor_fusion_pipeline();
744
745         std::cout << "\n
746             =====\n";
747         std::cout << "SUMMARY\n";
748         std::cout << "
749             =====\n";
750         std::cout << "\n";
751         std::cout << "Algorithms Demonstrated:\n";
752         std::cout << " 1. Kalman Filter      - Optimal linear sensor
753             fusion\n";
754         std::cout << " 2. Complementary Filter - Lightweight IMU fusion\n";
755         std::cout << " 3. Particle Filter    - Nonlinear localization\n";
756         std::cout << " 4. Complete Pipeline   - Multi-sensor integration\n";
757         ;
758         std::cout << "\n";
759         std::cout << "Applications:\n";
760         std::cout << " • Drone attitude estimation (IMU)\n";
761         std::cout << " • Robot localization (GPS + odometry)\n";
762         std::cout << " • Autonomous vehicles (multi-sensor fusion)\n";
```

```

753     std::cout << " • Indoor navigation (WiFi + dead reckoning)\n";
754     std::cout << " • Wearable devices (activity recognition)\n";
755     std::cout << "\n";
756     std::cout << "Eigen Library Benefits:\n";
757     std::cout << "    Fast matrix operations (vectorized)\n";
758     std::cout << "    Header-only (easy integration)\n";
759     std::cout << "    Industry standard (used in ROS, OpenCV)\n";
760     std::cout << "    Compile-time optimization\n";
761     std::cout << "    Suitable for embedded systems\n";
762     std::cout << "\n";
763     std::cout << "
764     =====\n";
765     std::cout << "ALL EXAMPLES COMPLETED SUCCESSFULLY!\n";
766     std::cout << "
767     =====\n";
768 } catch (const std::exception& e) {
769     std::cerr << "Error: " << e.what() << std::endl;
770     return 1;
771 }
772
773 }
774
775 /*
776 EXPECTED OUTPUT:
777 =====
778 =====
779 1. KALMAN FILTER - GPS/IMU FUSION
780 =====
781 Scenario: Robot moving in a circle, fusing GPS measurements
782
783 Time      True Position          GPS Measurement        Kalman Estimate       Error
784 -----  -----
785 0.0      ( 50.00,    0.00)      ( 50.42,   -1.83)      ( 50.21,   -0.91)      1.06m
786 0.1      ( 49.95,    4.99)      ( 52.45,    7.12)      ( 51.33,    3.11)      2.41m
787 0.2      ( 49.80,    9.98)      ( 48.73,   12.89)      ( 50.03,   11.44)      2.02m
788 ...
789
790 Kalman filter smooths noisy GPS and predicts motion!
791
792 =====
793 2. COMPLEMENTARY FILTER - ACCELEROMETER/GYROSCOPE FUSION
794 =====
795 Scenario: IMU measuring tilt angles (roll, pitch)
796
797 Time      True Angles          Accel Angles        Filtered Angles
798 -----  -----
799 0.0      R= 0.00° P= 20.00°    R= -0.53° P= 20.41°    R= -0.05° P= 20.04°
800 0.1      R= 14.63° P= 19.40°    R= 14.98° P= 19.78°    R= 14.68° P= 19.45°
801 ...

```

```
803
804     Complementary filter combines fast gyro and stable accel!
805
806 =====
807 3. PARTICLE FILTER - ROBOT LOCALIZATION
808 =====
809 Scenario: Robot with odometry and GPS, 500 particles
810
811 Time    True Position        GPS Measurement      Particle Estimate   Error   N_eff
812 ----  -----  -----  -----  -----  -----
813 0.0    ( 2.00,    0.00)  ( 4.42,   -3.57)  ( 3.21,   -1.79)  2.49m  500
814 2.0    ( 4.00,    0.00)  ( 5.73,   -1.08)  ( 4.86,   -0.54)  1.23m  487
815 ...
816
817     Particle filter handles multimodal distributions and nonlinearity!
818
819 =====
820 4. COMPLETE SENSOR FUSION PIPELINE
821 =====
822 Scenario: Drone with IMU (100 Hz) and GPS (1 Hz)
823
824 Fusing IMU (100 Hz) with GPS (1 Hz)...
825
826 t = 1.0s:
827
828 Sensor Fusion Status:
829 -----
830 Kalman Filter: (5.00, 3.00)
831 Particle Filter: (5.00, 3.00)
832 Orientation: Roll=0.0° Pitch=0.0° Yaw=5.7°
833 Effective Particles: 500
834 ...
835
836 Complete sensor fusion combines all algorithms!
837
838 APPLICATIONS IN EMBEDDED SYSTEMS:
839 =====
840
841 1. DRONE FLIGHT CONTROLLER
842     - Complementary filter for attitude (roll, pitch, yaw)
843     - Kalman filter for position/velocity estimation
844     - Runs at 500 Hz on STM32F4 (168 MHz ARM Cortex-M4)
845
846 2. AUTONOMOUS ROBOT
847     - Particle filter for localization
848     - EKF for sensor fusion (LIDAR + wheel encoders)
849     - Real-time operation on Raspberry Pi
850
851 3. WEARABLE FITNESS TRACKER
852     - Complementary filter for step detection
853     - Lightweight sensor fusion (accelerometer + gyroscope)
854     - Low power consumption (<1 mW)
855
856 4. INDOOR POSITIONING SYSTEM
```

```
857     - Particle filter with WiFi RSSI measurements
858     - Dead reckoning with IMU between updates
859     - Accuracy: 2-5 meters
860
861 PERFORMANCE CHARACTERISTICS:
862 =====
863
864 Algorithm          Computational Cost      Memory Usage      Accuracy
865 -----          -----      -----
866 Kalman Filter      O(n2) per update      O(n2)          Optimal (linear)
867 Complementary Filter  O(1) per sample      O(1)            Good (simple)
868 Particle Filter    O(N) per update      O(N)            Excellent (
869           nonlinear)
870 EKF                O(n2) per update      O(n2)          Good (linearized)
871 Where: n = state dimension, N = number of particles
872
873 EIGEN LIBRARY ADVANTAGES:
874 =====
875
876 1. PERFORMANCE
877     - Vectorization (SSE, AVX)
878     - Loop unrolling
879     - Cache optimization
880     - Compile-time size optimization
881
882 2. EASE OF USE
883     - Intuitive matrix syntax
884     - Automatic memory management
885     - Expression templates
886
887 3. PORTABILITY
888     - Header-only (no linking)
889     - Cross-platform
890     - ARM NEON support for embedded
891
892 4. INDUSTRY ADOPTION
893     - ROS (Robot Operating System)
894     - OpenCV (Computer Vision)
895     - TensorFlow (Machine Learning)
896     - Many robotics companies
897
898 BUILD INSTRUCTIONS:
899 =====
900
901 # Install Eigen
902 sudo apt-get install libeigen3-dev  # Ubuntu/Debian
903 brew install eigen                  # macOS
904 vcpkg install eigen3               # Windows
905
906 # Compile
907 g++ -std=c++17 -O3 -march=native -I/usr/include/eigen3 \
908   EigenSensorFusion.cpp -o EigenSensorFusion
909
```

```
910 # For embedded (ARM Cortex-M4 with NEON)
911 arm-none-eabi-g++ -std=c++17 -O3 -mfpu=neon -mthumb -mcpu=cortex-m4 \
912     -I/path/to/eigen EigenSensorFusion.cpp
913
914 # CMake
915 find_package(Eigen3 REQUIRED)
916 target_link_libraries(EigenSensorFusion Eigen3::Eigen)
917
918 FURTHER READING:
919 =====
920
921 1. Kalman Filter:
922     - "Kalman and Bayesian Filters in Python" by Roger Labbe
923     - http://doi.org/10.1109/PROC.1976.10155
924
925 2. Particle Filter:
926     - "Probabilistic Robotics" by Thrun, Burgard, Fox
927     - Monte Carlo Localization (MCL)
928
929 3. Sensor Fusion:
930     - "State Estimation for Robotics" by Timothy Barfoot
931     - "Optimal State Estimation" by Dan Simon
932
933 4. Eigen Library:
934     - https://eigen.tuxfamily.org/
935     - Eigen documentation and tutorials
936 */
```

22 Source Code: EmbeddedSystemsAvoid.cpp

File: src/EmbeddedSystemsAvoid.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <vector>
3 #include <string>
4 #include <memory>
5 #include <cstdint>
6 #include <array>
7 #include <cstring>
8
9 // =====
10 // WHY AVOID THESE IN EMBEDDED SYSTEMS - DETAILED EXPLANATIONS
11 // =====
12 // Target System Specification (Typical Microcontroller):
13 // - MCU: ARM Cortex-M4 @ 80MHz
14 // - Flash: 256KB (code storage)
15 // - RAM: 64KB (data, stack, heap)
16 // - Stack: 4KB (limited call depth)
17 // - Heap: 8KB (if enabled, often disabled)
18 // - No MMU (no virtual memory, no memory protection)
19 // - Real-time constraints: 1ms task deadlines
20 // =====
21
22 // =====
23 // 1. PROBLEM: new/delete AND HEAP ALLOCATION
24 // =====
25
26 void demonstrate_heap_fragmentation() {
27     std::cout << "\n== 1. PROBLEM: new/delete (HEAP FRAGMENTATION) =="
28         << std::endl;
29
30     std::cout << "\n TARGET SYSTEM CONSTRAINTS:" << std::endl;
31     std::cout << " • Heap size: 8KB (8192 bytes)" << std::endl;
32     std::cout << " • No MMU, no memory defragmentation" << std::endl;
33     std::cout << " • Fragmentation = permanent until reboot" << std::endl;
34
35     std::cout << "\n BAD CODE (Using new/delete):" << std::endl;
36     std::cout << R"(

37     // Allocate various sizes over time
38     void* ptr1 = new char[100];    // 100 bytes
39     void* ptr2 = new char[200];    // 200 bytes
40     void* ptr3 = new char[100];    // 100 bytes

41     delete[] ptr2;   // Free middle block

42
43     // Now heap looks like: [100 used] [200 FREE] [100 used]
44     // Try to allocate 250 bytes - FAILS!
45     // Even though 200 bytes are free, they're not contiguous
46     void* ptr4 = new char[250];   // Out of memory!
47 )" << std::endl;
```

```
49     std::cout << " PROBLEMS:" << std::endl;
50     std::cout << " 1. Fragmentation: Free memory becomes unusable" << std::
51         endl;
52     std::cout << " 2. Non-deterministic: Allocation time varies (0.1μs to 10
53         ms)" << std::endl;
54     std::cout << " 3. Leaks: One forgotten delete = permanent memory loss" <<
55         std::endl;
56     std::cout << " 4. Overhead: 8-16 bytes per allocation for bookkeeping" <<
57         std::endl;
58     std::cout << " 5. System failure: malloc() returns nullptr, hard to
59         recover" << std::endl;
60
61
62     std::cout << "\n SOLUTION: Memory Pools" << std::endl;
63     std::cout << " • Pre-allocated fixed-size blocks" << std::endl;
64     std::cout << " • O(1) allocation time: always <1μs" << std::endl;
65     std::cout << " • No fragmentation" << std::endl;
66     std::cout << " • Deterministic behavior" << std::endl;
67
68 }
69
70 // =====
71 // 2. PROBLEM: std::vector (DYNAMIC REALLOCATION)
72 // =====
73
74 void demonstrate_vector_problems() {
75     std::cout << "\n==== 2. PROBLEM: std::vector (DYNAMIC REALLOCATION) ===" <<
76         std::endl;
77
78     std::cout << "\n SCENARIO: Sensor data collection" << std::endl;
79     std::cout << " • Need to store 100 sensor readings" << std::endl;
80     std::cout << " • Each reading: 4 bytes (float)" << std::endl;
81     std::cout << " • Expected memory: 400 bytes" << std::endl;
82
83     std::cout << "\n BAD CODE (Using std::vector):" << std::endl;
84     std::cout << R"(

85         std::vector<float> sensor_data;

86         for (int i = 0; i < 100; ++i) {
87             sensor_data.push_back(read_sensor()); // Unpredictable!
88         }
89     )" << std::endl;
90
91     std::cout << " WHAT ACTUALLY HAPPENS:" << std::endl;
92     std::cout << " Iteration 1: Allocate 4 bytes (capacity=1)" << std::endl;
93     std::cout << " Iteration 2: Reallocate to 8 bytes, copy 1 element" << std::
94         endl;
95     std::cout << " Iteration 3: Reallocate to 16 bytes, copy 2 elements" <<
96         std::endl;
97     std::cout << " Iteration 5: Reallocate to 32 bytes, copy 4 elements" <<
```

```
        std::endl;
94     std::cout << "    Iteration 9: Reallocate to 64 bytes, copy 8 elements" <<
95         std::endl;
96     std::cout << "    ... (continues with exponential growth)" << std::endl;
97
98     std::cout << "\n PROBLEMS:" << std::endl;
99     std::cout << "    1. Multiple allocations: ~7 allocations for 100 elements"
100        << std::endl;
101    std::cout << "    2. Memory copies: ~100 element copies total" << std::endl;
102    std::cout << "    3. Peak memory: Needs 2x during reallocation" << std::endl;
103        ;
104    std::cout << "    (800 bytes instead of 400 bytes!)" << std::endl;
105    std::cout << "    4. Heap fragmentation: Old blocks left behind" << std::
106        endl;
107    std::cout << "    5. Timing: Each push_back() takes different time" << std::
108        endl;
109    std::cout << "        - Normal: 0.1µs" << std::endl;
110    std::cout << "        - Reallocation: 50µs (500x slower!)" << std::endl;
111
112    std::cout << "\n SOLUTION: std::array or fixed buffer" << std::endl;
113    std::cout << R"(

114     std::array<float, 100> sensor_data; // Fixed size, stack allocated
115     size_t count = 0;

116     for (int i = 0; i < 100; ++i) {
117         sensor_data[count++] = read_sensor(); // Constant time!
118     }
119 )" << std::endl;
120 }

121
122 // =====
123 // 3. PROBLEM: std::string (DYNAMIC ALLOCATION)
124 // =====
125
126 void demonstrate_string_problems() {
127     std::cout << "\n==== 3. PROBLEM: std::string (DYNAMIC ALLOCATION) ===" <<
128         std::endl;
129
130     std::cout << "\n SCENARIO: UART message building" << std::endl;
131     std::cout << " • Need message: \"TEMP:25.5C\r\n\" " << std::endl;
132     std::cout << " • Length: 13 characters" << std::endl;
133
134     std::cout << "\n BAD CODE (Using std::string):" << std::endl;
135     std::cout << R"(

136     std::string msg = "TEMP:";           // Allocation 1
137     msg += std::to_string(25.5);        // Allocation 2 + reallocation
138     msg += "C\r\n";                   // Possible reallocation 3
139
140 )"
```

```
139     send_uart(msg.c_str());
140 )" << std::endl;
141
142     std::cout << " PROBLEMS:" << std::endl;
143     std::cout << " 1. Multiple allocations: 2-3 heap allocations" << std::
144         endl;
145     std::cout << " 2. SSO ambiguity: Small String Optimization" << std::endl;
146     std::cout << " - Strings <16 chars: stored inline (good)" << std::endl
147         ;
148     std::cout << " - Strings >=16 chars: heap allocation (bad)" << std::
149         endl;
150     std::cout << " - Behavior changes at runtime!" << std::endl;
151     std::cout << " 3. Hidden cost: std::to_string() always allocates" << std
152         ::endl;
153     std::cout << " 4. Exception throwing: Can throw std::bad_alloc" << std::
154         endl;
155
156     std::cout << "\n MEMORY COST:" << std::endl;
157     std::cout << " • std::string object: 24-32 bytes" << std::endl;
158     std::cout << " • String data: 13 bytes" << std::endl;
159     std::cout << " • Heap overhead: 8-16 bytes" << std::endl;
160     std::cout << " • Total: ~45-60 bytes for 13-char string!" << std::endl;
161
162     std::cout << "\n SOLUTION: Fixed-size buffer" << std::endl;
163     std::cout << R"(

164     char msg[32];
165     snprintf(msg, sizeof(msg), "TEMP:%.1fC\r\n", 25.5f);
166     send_uart(msg);

167     // Total stack usage: 32 bytes, zero heap allocations
168 )" << std::endl;
169 }
170
171 // =====
172 // 4. PROBLEM: VIRTUAL FUNCTIONS (VTABLE OVERHEAD)
173 // =====
174
175 class BaseSensor {
176 public:
177     virtual ~BaseSensor() = default;
178     virtual float read() = 0;
179     virtual const char* name() = 0;
180 };
181
182 class TempSensor : public BaseSensor {
183 public:
184     float read() override { return 25.5f; }
185     const char* name() override { return "Temperature"; }
186 };
```

```
187
188 void demonstrate_virtual_function_overhead() {
189     std::cout << "\n==== 4. PROBLEM: VIRTUAL FUNCTIONS (VTABLE) ===" << std::endl;
190
191     std::cout << "\n MEMORY OVERHEAD PER OBJECT:" << std::endl;
192     std::cout << " • vtable pointer (vptr): 4 bytes (32-bit) or 8 bytes (64-
193         bit)" << std::endl;
194     std::cout << " • vtable itself: 8 bytes per virtual function" << std::endl;
195     std::cout << " • Small objects become bloated!" << std::endl;
196
197     std::cout << "\nExample object sizes:" << std::endl;
198     std::cout << "    sizeof(BaseSensor) = " << sizeof(BaseSensor) << " bytes"
199         << std::endl;
200     std::cout << "    sizeof(TempSensor) = " << sizeof(TempSensor) << " bytes"
201         << std::endl;
202
203     std::cout << "\n PROBLEMS:" << std::endl;
204     std::cout << " 1. RAM overhead: Every object has vptr (4-8 bytes)" << std::endl;
205     std::cout << "      - With 100 sensors: 400-800 bytes wasted!" << std::endl;
206     std::cout << " 2. Flash overhead: vtable stored in Flash" << std::endl;
207     std::cout << "      - 3 virtual functions = 24 bytes Flash per class" <<
208         std::endl;
209     std::cout << " 3. Indirection: Function call requires:" << std::endl;
210     std::cout << "      a. Load vptr from object (1 memory access)" << std::endl;
211     std::cout << "      b. Load function pointer from vtable (2nd memory access
212         )" << std::endl;
213     std::cout << "      c. Indirect jump (breaks CPU pipeline)" << std::endl;
214     std::cout << " 4. Not inlineable: Compiler can't optimize" << std::endl;
215     std::cout << " 5. Cache misses: Vtable and code in different locations"
216         << std::endl;
217
218     std::cout << "\n PERFORMANCE IMPACT:" << std::endl;
219     std::cout << "  Direct call: 1-2 CPU cycles" << std::endl;
220     std::cout << "  Virtual call: 10-20 CPU cycles (10x slower!)" << std::endl;
221
222     std::cout << " • At 80MHz: Virtual call = 125-250ns overhead" << std::endl;
223     std::cout << " • In 1ms task: Can fit 4000 direct calls or 400 virtual
224         calls" << std::endl;
225
226     std::cout << "\n SOLUTION: Static polymorphism (CRTP or templates)" <<
227         std::endl;
228     std::cout << R"(  

229     template<typename Derived>  

230     class SensorBase {  

231         float read() { return static_cast<Derived*>(this)->read_impl(); }  

232     };  

233
234 // Zero overhead, fully inlineable, no vtable!
```

```
226     )" << std::endl;
227 }
228
229 // =====
230 // 5. PROBLEM: RTTI (Runtime Type Information)
231 // =====
232
233 void demonstrate_rtti_overhead() {
234     std::cout << "\n==== 5. PROBLEM: RTTI (typeid, dynamic_cast) ===" << std::endl;
235
236     std::cout << "\n OVERHEAD:" << std::endl;
237     std::cout << " • Type info in Flash: 20-50 bytes per polymorphic class"
238         << std::endl;
239     std::cout << " • Name strings: Variable length (stored in Flash)" << std::endl;
240
241     std::cout << " • Dynamic_cast: String comparison overhead" << std::endl;
242
243     std::cout << "\n BAD CODE:" << std::endl;
244     std::cout << R"(

245         BaseSensor* sensor = get_sensor();

246         // dynamic_cast requires RTTI
247         if (TempSensor* temp = dynamic_cast<TempSensor*>(sensor)) {
248             // Process temperature sensor
249         }
250     )" << std::endl;

251     std::cout << "\n PROBLEMS:" << std::endl;
252     std::cout << " 1. Flash overhead: RTTI adds 5-10KB to binary size" << std::endl;
253         << std::endl;
254     std::cout << "      - On 256KB Flash: 2-4% wasted!" << std::endl;
255     std::cout << " 2. RAM overhead: Type info structures in RAM" << std::endl;
256         ;
257     std::cout << " 3. CPU overhead: String comparisons for casts" << std::endl;
258         << std::endl;
259     std::cout << " 4. Complexity: Name mangling, RTTI tables" << std::endl;
260
261     std::cout << "\n TIMING:" << std::endl;
262     std::cout << " static_cast<>: 0 cycles (compile-time)" << std::endl;
263     std::cout << " dynamic_cast<>: 100-500 cycles (runtime check!)" << std::endl;
264         << std::endl;
265
266     std::cout << "\n SOLUTION: std::variant or manual type tags" << std::endl;
267         ;
268     std::cout << R"(

269         enum class SensorType { Temperature, Humidity };

270
271         struct Sensor {
272             SensorType type;
273             float value;
274         };
275
276         // Check type with simple enum comparison (1 cycle)
```

```

272     if (sensor.type == SensorType::Temperature) { ... }
273     )" << std::endl;
274
275     std::cout << "\n GCC FLAG:" << std::endl;
276     std::cout << " -fno-rtti (disables RTTI, saves 5-10KB)" << std::endl;
277 }
278
279 // =====
280 // 6. PROBLEM: EXCEPTIONS
281 // =====
282
283 void demonstrate_exception_overhead() {
284     std::cout << "\n== 6. PROBLEM: EXCEPTIONS ==" << std::endl;
285
286     std::cout << "\n OVERHEAD:" << std::endl;
287     std::cout << " • Exception tables in Flash: 10-30KB" << std::endl;
288     std::cout << " • Unwinding code: 5-10KB" << std::endl;
289     std::cout << " • Per-function overhead: Extra instructions for cleanup"
290         << std::endl;
291     std::cout << " • Total: 15-40KB on 256KB Flash (6-15%!)" << std::endl;
292
293     std::cout << "\n BAD CODE:" << std::endl;
294     std::cout << R"(

295         try {
296             sensor_data.push_back(value); // May throw std::bad_alloc
297             config.parse(json_string); // May throw parse_error
298             send_network(data); // May throw network_error
299         } catch (const std::exception& e) {
300             log_error(e.what());
301         }
302     )" << std::endl;
303
304     std::cout << "\n PROBLEMS:" << std::endl;
305     std::cout << " 1. Code bloat: Exception tables for every function" << std::endl;
306     std::cout << " 2. Unpredictable: Stack unwinding takes unknown time" << std::endl;
307     std::cout << "      - Normal: 0ns (no exception)" << std::endl;
308     std::cout << "      - Exception: 10-1000µs (milliseconds!)" << std::endl;
309     std::cout << " 3. RAM for stack: Need extra stack for unwinding" << std::endl;
310     std::cout << " 4. Real-time unsafe: Can't use in ISRs" << std::endl;
311     std::cout << " 5. Hidden control flow: Function can exit anywhere" << std::endl;
312
313     std::cout << "\n REAL-TIME VIOLATION:" << std::endl;
314     std::cout << " Task deadline: 1ms" << std::endl;
315     std::cout << " Exception thrown: 500µs to unwind" << std::endl;
316     std::cout << " Result: DEADLINE MISSED! System fails!" << std::endl;
317
318     std::cout << "\n SOLUTION: Error codes or std::optional" << std::endl;
319     std::cout << R"(

320         enum class Error { None, OutOfMemory, ParseError, NetworkError };

```

```
321     Error result = sensor_data.add(value);
322     if (result != Error::None) {
323         handle_error(result); // Explicit, predictable
324     }
325
326     // Or use std::optional (C++17)
327     std::optional<float> maybe_value = read_sensor();
328     if (maybe_value) {
329         process(*maybe_value);
330     }
331 )" << std::endl;
332
333     std::cout << "\n GCC FLAG:" << std::endl;
334     std::cout << " -fno-exceptions (disables exceptions, saves 15-40KB)" <<
335         std::endl;
336 }
337 // =====
338 // 7. PROBLEM: iostream (CODE BLOAT)
339 // =====
340
341 void demonstrate_iostream_bloat() {
342     std::cout << "\n==== 7. PROBLEM: iostream (CODE BLOAT) ===" << std::endl;
343
344     std::cout << "\n BINARY SIZE IMPACT:" << std::endl;
345
346     std::cout << "\n BAD CODE:" << std::endl;
347     std::cout << R"(#include <iostream>
348
349     int main() {
350         std::cout << "Temperature: " << 25.5 << "C" << std::endl;
351         return 0;
352     }
353 )" << std::endl;
354
355     std::cout << "\n BINARY SIZE:" << std::endl;
356     std::cout << " Without iostream: 2-5KB" << std::endl;
357     std::cout << " With iostream: 60-150KB (!)" << std::endl;
358     std::cout << " Increase: 30-60x larger!" << std::endl;
359
360     std::cout << "\n WHAT'S INCLUDED:" << std::endl;
361     std::cout << " • Locale support: 20-40KB" << std::endl;
362     std::cout << " • Formatting code: 15-30KB" << std::endl;
363     std::cout << " • Stream state management: 10-20KB" << std::endl;
364     std::cout << " • Virtual functions (std::ios_base): vtables" << std::endl;
365         ;
366     std::cout << " • Static initialization: Global constructors" << std::endl;
367         ;
368
369     std::cout << "\n SOLUTION: printf/snprintf" << std::endl;
370     std::cout << R"(#include <stdio.h>
```

```
372 int main() {
373     printf("Temperature: %.1fC\n", 25.5);
374     return 0;
375 }
376
377 // Binary size: 5-10KB (10x smaller!)
378 )" << std::endl;
379
380 std::cout << "\n COMPARISON (ARM Cortex-M4):" << std::endl;
381 std::cout << "    iostream: 80KB Flash + 2KB RAM" << std::endl;
382 std::cout << "    printf:    8KB Flash + 512 bytes RAM" << std::endl;
383 std::cout << "    sprintf:   6KB Flash + 0 bytes heap" << std::endl;
384
385 std::cout << "\n ON 256KB FLASH:" << std::endl;
386 std::cout << " • iostream uses 31% of Flash!" << std::endl;
387 std::cout << " • printf uses 3% of Flash" << std::endl;
388 }
389
390 // =====
391 // 8. PROBLEM: RECURSION (STACK OVERFLOW)
392 // =====
393
394 uint32_t factorial_recursive(uint32_t n) {
395     if (n <= 1) return 1;
396     return n * factorial_recursive(n - 1); // Stack grows
397 }
398
399 uint32_t factorial_iterative(uint32_t n) {
400     uint32_t result = 1;
401     for (uint32_t i = 2; i <= n; ++i) {
402         result *= i;
403     }
404     return result; // Constant stack
405 }
406
407 void demonstrate_recursion_danger() {
408     std::cout << "\n== 8. PROBLEM: RECURSION (STACK OVERFLOW) ==" << std::endl;
409
410     std::cout << "\n STACK CONSTRAINTS:" << std::endl;
411     std::cout << " • Total stack: 4KB (4096 bytes)" << std::endl;
412     std::cout << " • Stack frame: ~32 bytes per function call" << std::endl;
413     std::cout << " • Maximum depth: ~128 calls" << std::endl;
414     std::cout << " • NO PROTECTION: Stack overflow = silent corruption!" << std::endl;
415
416     std::cout << "\n BAD CODE (Recursive factorial):" << std::endl;
417     std::cout << R"( 
418     uint32_t factorial(uint32_t n) {
419         if (n <= 1) return 1;
420         return n * factorial(n - 1); // Each call uses stack
421     }
422
423 // factorial(10) = 10 stack frames = 320 bytes OK
```

```
424 // factorial(100) = 100 stack frames = 3200 bytes Close!
425 // factorial(150) = 150 stack frames = 4800 bytes OVERFLOW!
426 )" << std::endl;
427
428 std::cout << "\n WHAT HAPPENS ON OVERFLOW:" << std::endl;
429 std::cout << " 1. Stack grows downward into heap" << std::endl;
430 std::cout << " 2. Corrupts heap data structures" << std::endl;
431 std::cout << " 3. Corrupts global variables" << std::endl;
432 std::cout << " 4. System crashes (hard fault)" << std::endl;
433 std::cout << " 5. NO WARNING! Silent death!" << std::endl;
434
435 std::cout << "\n REAL EXAMPLE: JSON Parser" << std::endl;
436 std::cout << R"(

437 void parse_json(JsonNode* node) {
438     if (node->type == Object) {
439         for (auto& child : node->children) {
440             parse_json(child); // Recursion!
441         }
442     }
443 }

444 // Deeply nested JSON (100 levels) = STACK OVERFLOW!
445 )" << std::endl;
446
447 std::cout << "\n SOLUTION: Iterative with explicit stack" << std::endl;
448 std::cout << R"(

449 uint32_t factorial(uint32_t n) {
450     uint32_t result = 1;
451     for (uint32_t i = 2; i <= n; ++i) {
452         result *= i;
453     }
454     return result; // Constant 8 bytes stack
455 }
456

457 )" << std::endl;
458
459 std::cout << "\n STACK USAGE COMPARISON:" << std::endl;
460 std::cout << " Recursive: 32 bytes x depth (unbounded)" << std::endl;
461 std::cout << " Iterative: 8-16 bytes (constant)" << std::endl;
462
463 std::cout << "\nTest with n=10:" << std::endl;
464 std::cout << " factorial_recursive(10) = " << factorial_recursive(10) <<
465 std::endl;
466 std::cout << " factorial_iterative(10) = " << factorial_iterative(10) <<
467 std::endl;
468 }

469 // =====
470 // MAIN FUNCTION
471 // =====
472 int main() {
473     std::cout << "\n
474     =====" <<
475     std::endl;
```

```
474     std::cout << "    WHY AVOID THESE IN EMBEDDED SYSTEMS" << std::endl;
475     std::cout << "
476         ====="
477     std::endl;
478
479     std::cout << "\n TARGET SYSTEM SPECIFICATION:" << std::endl;
480     std::cout << "    MCU: ARM Cortex-M4F @ 80MHz" << std::endl;
481     std::cout << "    Flash: 256KB (code + constants)" << std::endl;
482     std::cout << "    RAM: 64KB (data + stack + heap)" << std::endl;
483     std::cout << "        - Stack: 4KB (main task)" << std::endl;
484     std::cout << "        - Heap: 8KB (if enabled)" << std::endl;
485     std::cout << "        - .bss/.data: ~52KB available" << std::endl;
486     std::cout << "    No MMU (no virtual memory)" << std::endl;
487     std::cout << "    No OS (bare metal or lightweight RTOS)" << std::endl;
488     std::cout << "    Real-time: 1ms task deadlines" << std::endl;
489     std::cout << "    Power: Battery powered (sleep modes important)" << std::endl;
490
491     demonstrate_heap_fragmentation();
492     demonstrate_vector_problems();
493     demonstrate_string_problems();
494     demonstrate_virtual_function_overhead();
495     demonstrate_rtti_overhead();
496     demonstrate_exception_overhead();
497     demonstrate_iostream_bloat();
498     demonstrate_recursion_danger();
499
500     std::cout << "\n"
501         =====
502     std::endl;
503     std::cout << "    SUMMARY: RESOURCE IMPACT" << std::endl;
504     std::cout << "
505         ====="
506     std::endl;
507
508     std::cout << "\n FLASH USAGE (256KB total):" << std::endl;
509     std::cout << "                                " << std::endl;
510     std::cout << "    iostream:      80KB (31%)          " << std::endl;
511     std::cout << "    Exceptions:   30KB (12%)          " << std::endl;
512     std::cout << "    RTTI:          8KB (3%)           " << std::endl;
513     std::cout << "    Virtual tables: 5KB (2%)          " << std::endl;
514     std::cout << "    TOTAL WASTE:   123KB (48%)         " << std::endl;
515     std::cout << "                                " << std::endl;
516     std::cout << "    Your code:     133KB (52%)         " << std::endl;
517     std::cout << "                                " << std::endl;
518
519     std::cout << "\n RAM USAGE (64KB total):" << std::endl;
520     std::cout << "                                " << std::endl;
521     std::cout << "    Heap:          8KB (12.5%)        " << std::endl;
522     std::cout << "    Stack:         4KB (6.25%)        " << std::endl;
523     std::cout << "    iostream:      2KB (3.12%)        " << std::endl;
524     std::cout << "    vtable ptrs:   1KB (1.56%)        " << std::endl;
525     std::cout << "                                " << std::endl;
526     std::cout << "    Your data:     49KB (76.6%)       " << std::endl;
```

```

521     std::cout << "                                     " << std::endl;
522
523     std::cout << "\n REAL-TIME IMPACT:" << std::endl;
524     std::cout << "  Task deadline: 1ms = 80,000 CPU cycles" << std::endl;
525     std::cout << "\n  Direct function call: 2 cycles (40,000 calls per ms)"
526           << std::endl;
527     std::cout << "  Virtual call:          20 cycles (4,000 calls per ms)" <<
528           std::endl;
529     std::cout << "  std::vector::push:      50 cycles (1,600 calls per ms)" <<
530           std::endl;
531     std::cout << "  std::vector realloc:   4,000 cycles (20 calls per ms)" <<
532           std::endl;
533     std::cout << "  Exception throw:      40,000 cycles (2 per ms = DEADLINE
534           MISS!)" << std::endl;
535
536     std::cout << "\n BEST PRACTICES FOR EMBEDDED:" << std::endl;
537     std::cout << "\n    USE:" << std::endl;
538     std::cout << "    •    std::array (fixed-size, stack)" << std::endl;
539     std::cout << "    •    Memory pools (controlled allocation)" << std::endl;
540     std::cout << "    •    Static polymorphism (CRTP, templates)" << std::endl;
541     std::cout << "    •    Error codes, std::optional (no exceptions)" << std::
542           endl;
543     std::cout << "    •    printf/snprintf (smaller than iostream)" << std::endl;
544     std::cout << "    •    Iterative algorithms (constant stack)" << std::endl;
545     std::cout << "    •    constexpr (compile-time computation)" << std::endl;
546     std::cout << "    •    std::variant (type-safe unions)" << std::endl;
547
548     std::cout << "\n    AVOID:" << std::endl;
549     std::cout << "    •    new/delete, malloc/free" << std::endl;
550     std::cout << "    •    std::vector, std::string, std::map" << std::endl;
551     std::cout << "    •    Virtual functions (use sparingly)" << std::endl;
552     std::cout << "    •    RTTI (typeid, dynamic_cast)" << std::endl;
553     std::cout << "    •    Exceptions (try/catch/throw)" << std::endl;
554     std::cout << "    •    iostream (cout, cin, etc.)" << std::endl;
555     std::cout << "    •    Recursion (unbounded depth)" << std::endl;
556
557     std::cout << "\n COMPILER FLAGS FOR EMBEDDED:" << std::endl;
558     std::cout << "    -fno-exceptions      (saves 15-40KB Flash)" << std::endl;
559     std::cout << "    -fno-rtti            (saves 5-10KB Flash)" << std::endl;
560     std::cout << "    -fno-threadsafe-statics (saves 2-5KB Flash)" << std::endl;
561     std::cout << "    -ffunction-sections  (enables dead code removal)" << std::
562           endl;
563     std::cout << "    -fdata-sections      (enables dead data removal)" << std::
564           endl;
565     std::cout << "    -Wl,--gc-sections    (linker removes unused code)" << std
566           ::endl;
567     std::cout << "    -Os                  (optimize for size)" << std::endl;
568
569     std::cout << "\n MEMORY SAVINGS SUMMARY:" << std::endl;
570     std::cout << "  Disabling features above: ~130KB Flash savings!" << std::
571           endl;
572     std::cout << "  From 256KB Flash → 126KB available (49% → 98% usable!)" <<
573           std::endl;

```

```
564     std::cout << "\n"
565     ======\n
566     std::endl;
567
568     return 0;
569 }
```

23 Source Code: EmbeddedSystemsProgramming.cpp

File: src/EmbeddedSystemsProgramming.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <cstdint>
4 #include <cstring>
5 #include <type_traits>
6 #include <utility>
7 #include <optional>
8 #include <cassert>
9
10 // =====
11 // EMBEDDED SYSTEMS PROGRAMMING IN MODERN C++
12 // =====
13 // This file demonstrates embedded C++ patterns and best practices:
14 // - No dynamic allocation (no new/delete)
15 // - Fixed-size buffers
16 // - Compile-time computation
17 // - RAII for hardware resources
18 // - Static polymorphism (no vtables)
19 // - Memory pools
20 // - Interrupt-safe techniques
21 // =====
22
23 // =====
24 // 1. MEMORY POOL (NO HEAP ALLOCATION)
25 // =====
26
27 template<typename T, size_t PoolSize>
28 class MemoryPool {
29 private:
30     alignas(T) uint8_t storage[PoolSize * sizeof(T)];
31     bool used[PoolSize] = {};
32
33 public:
34     template<typename... Args>
35     T* allocate(Args&&... args) {
36         for (size_t i = 0; i < PoolSize; ++i) {
37             if (!used[i]) {
38                 used[i] = true;
39                 T* ptr = reinterpret_cast<T*>(&storage[i * sizeof(T)]);
40                 new (ptr) T(std::forward<Args>(args)...); // Placement new
41                 return ptr;
42             }
43         }
44         return nullptr; // Pool exhausted
45     }
46
47     void deallocate(T* ptr) {
48         if (!ptr) return;
49     }
```

```
50     size_t index = (reinterpret_cast<uint8_t*>(ptr) - storage) / sizeof(T)
51     ;
52     if (index < PoolSize && used[index]) {
53         ptr->~T();
54         used[index] = false;
55     }
56 }
57
58 size_t available() const {
59     size_t count = 0;
60     for (size_t i = 0; i < PoolSize; ++i) {
61         if (!used[i]) ++count;
62     }
63     return count;
64 }
65
66 size_t capacity() const { return PoolSize; }
67 };
68
69 void example_memory_pool() {
70     std::cout << "\n==== 1. MEMORY POOL (NO HEAP) ====" << std::endl;
71
72     struct Sensor {
73         int id;
74         float value;
75         Sensor(int i, float v) : id(i), value(v) {
76             std::cout << "      Sensor " << id << " created" << std::endl;
77         }
78         ~Sensor() {
79             std::cout << "      Sensor " << id << " destroyed" << std::endl;
80         }
81     };
82
83     MemoryPool<Sensor, 5> pool;
84     std::cout << "  Pool capacity: " << pool.capacity() << std::endl;
85
86     std::cout << "\nAllocating sensors:" << std::endl;
87     Sensor* s1 = pool.allocate(1, 25.5f);
88     Sensor* s2 = pool.allocate(2, 30.2f);
89     Sensor* s3 = pool.allocate(3, 28.7f);
90
91     std::cout << "  Available slots: " << pool.available() << std::endl;
92
93     std::cout << "\nDeallocating sensor 2:" << std::endl;
94     pool.deallocate(s2);
95     std::cout << "  Available slots: " << pool.available() << std::endl;
96
97     std::cout << "\nAllocating new sensor:" << std::endl;
98     Sensor* s4 = pool.allocate(4, 27.1f);
99
100    std::cout << "\nCleanup:" << std::endl;
101    pool.deallocate(s1);
102    pool.deallocate(s3);
103    pool.deallocate(s4);
```

```
103     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
104     std::cout << " • No heap fragmentation" << std::endl;
105     std::cout << " • Deterministic allocation time" << std::endl;
106     std::cout << " • Fixed memory footprint" << std::endl;
107     std::cout << " • Suitable for real-time systems" << std::endl;
108 }
109
110 // =====
111 // 2. CIRCULAR BUFFER (RING BUFFER)
112 // =====
113
114
115 template<typename T, size_t Size>
116 class CircularBuffer {
117 private:
118     std::array<T, Size> buffer;
119     size_t head = 0;
120     size_t tail = 0;
121     size_t count = 0;
122
123 public:
124     bool push(const T& item) {
125         if (is_full()) return false;
126
127         buffer[head] = item;
128         head = (head + 1) % Size;
129         ++count;
130         return true;
131     }
132
133     bool pop(T& item) {
134         if (is_empty()) return false;
135
136         item = buffer[tail];
137         tail = (tail + 1) % Size;
138         --count;
139         return true;
140     }
141
142     bool is_empty() const { return count == 0; }
143     bool is_full() const { return count == Size; }
144     size_t size() const { return count; }
145     size_t capacity() const { return Size; }
146 };
147
148 void example_circular_buffer() {
149     std::cout << "\n==== 2. CIRCULAR BUFFER (INTERRUPT-SAFE) ===" << std::endl;
150
151     CircularBuffer<uint8_t, 8> uart_rx_buffer;
152
153     std::cout << "\nSimulating UART receive (ISR):" << std::endl;
154     for (uint8_t i = 0; i < 5; ++i) {
155         if (uart_rx_buffer.push(0x30 + i)) {
156             std::cout << " [ISR] Received: 0x" << std::hex
```

```
157             << (int)(0x30 + i) << std::dec << std::endl;
158     }
159 }
160
161 std::cout << "\nBuffer status: " << uart_rx_buffer.size()
162     << "/" << uart_rx_buffer.capacity() << std::endl;
163
164 std::cout << "\nMain loop processing:" << std::endl;
165 uint8_t data;
166 while (uart_rx_buffer.pop(data)) {
167     std::cout << " [Main] Processing: 0x" << std::hex
168         << (int)data << std::dec << std::endl;
169 }
170
171 std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
172 std::cout << " • Lock-free for single producer/consumer" << std::endl;
173 std::cout << " • Constant-time operations" << std::endl;
174 std::cout << " • ISR-safe data transfer" << std::endl;
175 std::cout << " • No dynamic allocation" << std::endl;
176 }
177
178 // =====
179 // 3. HARDWARE REGISTER ABSTRACTION (RAII)
180 // =====
181
182 // Simulate hardware registers
183 struct HardwareRegisters {
184     static inline uint32_t GPIO_CONFIG = 0;
185     static inline uint32_t GPIO_OUTPUT = 0;
186     static inline uint32_t ADC_CONTROL = 0;
187 };
188
189 enum class PinMode : uint8_t {
190     Input = 0,
191     Output = 1,
192     Analog = 2
193 };
194
195 class GpioPin {
196 private:
197     uint8_t pin_number;
198     PinMode original_mode;
199
200     static constexpr uint32_t get_pin_mask(uint8_t pin) {
201         return 1u << pin;
202     }
203
204 public:
205     GpioPin(uint8_t pin, PinMode mode)
206         : pin_number(pin)
207         , original_mode(static_cast<PinMode>(
208             (HardwareRegisters::GPIO_CONFIG >> (pin * 2)) & 0x3)) {
209
210         // Configure pin mode
```

```
211     uint32_t mask = 0x3u << (pin * 2);
212     HardwareRegisters::GPIO_CONFIG &= ~mask;
213     HardwareRegisters::GPIO_CONFIG |= (static_cast<uint32_t>(mode) << (pin
214         * 2));
215
215     std::cout << "    GPIO Pin " << (int)pin_number
216         << " configured as " << (mode == PinMode::Output ? "Output"
217             : "Input")
218             << std::endl;
219 }
220
220 ~GpioPin() {
221     // Restore original mode (RAII cleanup)
222     uint32_t mask = 0x3u << (pin_number * 2);
223     HardwareRegisters::GPIO_CONFIG &= ~mask;
224     HardwareRegisters::GPIO_CONFIG |= (static_cast<uint32_t>(original_mode
225         ) << (pin_number * 2));
226
226     std::cout << "    GPIO Pin " << (int)pin_number
227         << " restored to original mode" << std::endl;
228 }
229
230 // Prevent copying (hardware resources are unique)
231 GpioPin(const GpioPin&) = delete;
232 GpioPin& operator=(const GpioPin&) = delete;
233
234 // Allow moving
235 GpioPin(GpioPin&& other) noexcept
236     : pin_number(other.pin_number)
237     , original_mode(other.original_mode) {
238     other.pin_number = 0xFF; // Mark as moved
239 }
240
241 void write(bool value) {
242     if (value) {
243         HardwareRegisters::GPIO_OUTPUT |= get_pin_mask(pin_number);
244     } else {
245         HardwareRegisters::GPIO_OUTPUT &= ~get_pin_mask(pin_number);
246     }
247 }
248
249 bool read() const {
250     return (HardwareRegisters::GPIO_OUTPUT & get_pin_mask(pin_number)) !=
251         0;
252 }
253
254 void example_hardware_raii() {
255     std::cout << "\n==== 3. HARDWARE REGISTER ABSTRACTION (RAII) ===" << std::
256         endl;
257
257     std::cout << "\nConfiguring LED pin:" << std::endl;
258     {
259         GpioPin led(5, PinMode::Output);
```

```
260     std::cout << " Setting LED ON" << std::endl;
261     led.write(true);
262
263     std::cout << " LED state: " << (led.read() ? "ON" : "OFF") << std::
264         endl;
265
266     // RAI: Pin automatically restored when going out of scope
267 }
268 std::cout << " (Pin automatically restored)\n" << std::endl;
269
270 std::cout << " EMBEDDED BENEFITS:" << std::endl;
271 std::cout << " • Automatic resource cleanup" << std::endl;
272 std::cout << " • Exception-safe (if exceptions enabled)" << std::endl;
273 std::cout << " • Can't forget to restore state" << std::endl;
274 std::cout << " • Move semantics for ownership transfer" << std::endl;
275 }
276
277 // =====
278 // 4. STATIC POLYMORPHISM (NO VTABLES)
279 // =====
280
281 // CRTP (Curiously Recurring Template Pattern)
282 template<typename Derived>
283 class SensorBase {
284 public:
285     float read() {
286         return static_cast<Derived*>(this)->read_impl();
287     }
288
289     const char* name() {
290         return static_cast<Derived*>(this)->name_impl();
291     }
292 };
293
294 class TemperatureSensor : public SensorBase<TemperatureSensor> {
295 public:
296     float read_impl() { return 25.5f; }
297     const char* name_impl() { return "Temperature"; }
298 };
299
300 class HumiditySensor : public SensorBase<HumiditySensor> {
301 public:
302     float read_impl() { return 65.2f; }
303     const char* name_impl() { return "Humidity"; }
304 };
305
306 template<typename Sensor>
307 void process_sensor(Sensor& sensor) {
308     std::cout << " Reading " << sensor.name() << " sensor: "
309             << sensor.read() << std::endl;
310 }
311
312 void example_static_polymorphism() {
```

```
313     std::cout << "\n==== 4. STATIC POLYMORPHISM (NO VTABLES) ===" << std::endl;
314
315     TemperatureSensor temp;
316     HumiditySensor humid;
317
318     std::cout << "\nReading sensors (compile-time dispatch):" << std::endl;
319     process_sensor(temp);
320     process_sensor(humid);
321
322     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
323     std::cout << " • No vtable overhead (saves RAM)" << std::endl;
324     std::cout << " • No runtime indirection (faster)" << std::endl;
325     std::cout << " • Fully inlineable" << std::endl;
326     std::cout << " • Smaller code size" << std::endl;
327 }
328
329 // =====
330 // 5. COMPILE-TIME COMPUTATION (constexpr)
331 // =====
332
333 constexpr uint32_t calculate_baud_rate_register(uint32_t system_clock,
334                                                 uint32_t baud_rate) {
335     return (system_clock / (16 * baud_rate)) - 1;
336 }
337
338 constexpr uint32_t calculate_pwm_period(uint32_t timer_clock, uint32_t
339                                         frequency) {
340     return timer_clock / frequency;
341 }
342
343 template<size_t N>
344 constexpr uint32_t fibonacci() {
345     if constexpr (N <= 1) {
346         return N;
347     } else {
348         return fibonacci<N-1>() + fibonacci<N-2>();
349     }
350 }
351
352 void example_compile_time() {
353     std::cout << "\n==== 5. COMPILE-TIME COMPUTATION (constexpr) ===" << std::endl;
354
355     // Computed at compile time!
356     constexpr uint32_t BAUD_115200 = calculate_baud_rate_register(16000000,
357                                                                 115200);
358     constexpr uint32_t PWM_1KHZ = calculate_pwm_period(1000000, 1000);
359     constexpr uint32_t FIB_10 = fibonacci<10>();
360
361     std::cout << "\nCompile-time computed values:" << std::endl;
362     std::cout << "    UART baud rate register: 0x" << std::hex << BAUD_115200 <<
363             std::dec << std::endl;
364     std::cout << "    PWM period (1kHz): " << PWM_1KHZ << std::endl;
365     std::cout << "    Fibonacci(10): " << FIB_10 << std::endl;
```

```
362     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
363     std::cout << " • Zero runtime overhead" << std::endl;
364     std::cout << " • Compile-time error checking" << std::endl;
365     std::cout << " • Values in ROM, not computed" << std::endl;
366     std::cout << " • No initialization code needed" << std::endl;
367 }
368
369 // =====
370 // 6. FIXED-SIZE STRING (NO STD::STRING)
371 // =====
372
373
374 template<size_t MaxSize>
375 class FixedString {
376     private:
377         char data[MaxSize + 1] = {};// +1 for null terminator
378         size_t length = 0;
379
380     public:
381         FixedString() = default;
382
383         FixedString(const char* str) {
384             if (str) {
385                 length = 0;
386                 while (str[length] && length < MaxSize) {
387                     data[length] = str[length];
388                     ++length;
389                 }
390                 data[length] = '\0';
391             }
392         }
393
394         bool append(char c) {
395             if (length < MaxSize) {
396                 data[length++] = c;
397                 data[length] = '\0';
398                 return true;
399             }
400             return false;
401         }
402
403         bool append(const char* str) {
404             if (!str) return false;
405
406             while (*str && length < MaxSize) {
407                 data[length++] = *str++;
408             }
409             data[length] = '\0';
410             return *str == '\0';// True if entire string was appended
411         }
412
413         void clear() {
414             length = 0;
415             data[0] = '\0';
416         }
417 }
```

```
416     }
417
418     const char* c_str() const { return data; }
419     size_t size() const { return length; }
420     size_t capacity() const { return MaxSize; }
421     bool is_full() const { return length >= MaxSize; }
422 };
423
424 void example_fixed_string() {
425     std::cout << "\n==== 6. FIXED-SIZE STRING (NO HEAP) ===" << std::endl;
426
427     FixedString<32> msg("Sensor: ");
428
429     std::cout << "\nBuilding message:" << std::endl;
430     std::cout << "    Initial: \" " << msg.c_str() << "\" " << std::endl;
431
432     msg.append("Temp=");
433     msg.append("25.5");
434     msg.append("C");
435
436     std::cout << "    Final: \" " << msg.c_str() << "\" " << std::endl;
437     std::cout << "    Size: " << msg.size() << "/" << msg.capacity() << std::endl;
438
439     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
440     std::cout << "    • No heap allocation" << std::endl;
441     std::cout << "    • Fixed memory footprint" << std::endl;
442     std::cout << "    • Predictable behavior" << std::endl;
443     std::cout << "    • Stack-based storage" << std::endl;
444 }
445
446 // =====
447 // 7. STATE MACHINE (EMBEDDED PATTERN)
448 // =====
449
450 enum class State {
451     Idle,
452     Reading,
453     Processing,
454     Sending,
455     Error
456 };
457
458 enum class Event {
459     StartRead,
460     DataReady,
461     ProcessComplete,
462     SendComplete,
463     ErrorOccurred,
464     Reset
465 };
466
467 class StateMachine {
468 private:
```

```
469     State current_state = State::Idle;
470
471 public:
472     void process_event(Event event) {
473         std::cout << " [" << state_name(current_state) << "] -> Event: "
474             << event_name(event);
475
476         State new_state = current_state;
477
478         switch (current_state) {
479             case State::Idle:
480                 if (event == Event::StartRead) {
481                     new_state = State::Reading;
482                 }
483                 break;
484
485             case State::Reading:
486                 if (event == Event::DataReady) {
487                     new_state = State::Processing;
488                 } else if (event == Event::ErrorOccurred) {
489                     new_state = State::Error;
490                 }
491                 break;
492
493             case State::Processing:
494                 if (event == Event::ProcessComplete) {
495                     new_state = State::Sending;
496                 } else if (event == Event::ErrorOccurred) {
497                     new_state = State::Error;
498                 }
499                 break;
500
501             case State::Sending:
502                 if (event == Event::SendComplete) {
503                     new_state = State::Idle;
504                 } else if (event == Event::ErrorOccurred) {
505                     new_state = State::Error;
506                 }
507                 break;
508
509             case State::Error:
510                 if (event == Event::Reset) {
511                     new_state = State::Idle;
512                 }
513                 break;
514         }
515
516         if (new_state != current_state) {
517             current_state = new_state;
518             std::cout << " -> [" << state_name(current_state) << "] " << std::
519                 endl;
520         } else {
521             std::cout << " (no transition)" << std::endl;
522         }
523     }
```

```
522     }
523
524     State get_state() const { return current_state; }
525
526 private:
527     static const char* state_name(State s) {
528         switch (s) {
529             case State::Idle: return "Idle";
530             case State::Reading: return "Reading";
531             case State::Processing: return "Processing";
532             case State::Sending: return "Sending";
533             case State::Error: return "Error";
534             default: return "Unknown";
535         }
536     }
537
538     static const char* event_name(Event e) {
539         switch (e) {
540             case Event::StartRead: return "StartRead";
541             case Event::DataReady: return "DataReady";
542             case Event::ProcessComplete: return "ProcessComplete";
543             case Event::SendComplete: return "SendComplete";
544             case Event::ErrorOccurred: return "ErrorOccurred";
545             case Event::Reset: return "Reset";
546             default: return "Unknown";
547         }
548     }
549 };
550
551 void example_state_machine() {
552     std::cout << "\n==== 7. STATE MACHINE (EMBEDDED PATTERN) ===" << std::endl;
553
554     StateMachine sm;
555
556     std::cout << "\nNormal operation sequence:" << std::endl;
557     sm.process_event(Event::StartRead);
558     sm.process_event(Event::DataReady);
559     sm.process_event(Event::ProcessComplete);
560     sm.process_event(Event::SendComplete);
561
562     std::cout << "\nError handling:" << std::endl;
563     sm.process_event(Event::StartRead);
564     sm.process_event(Event::ErrorOccurred);
565     sm.process_event(Event::Reset);
566
567     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
568     std::cout << " • Clear, predictable behavior" << std::endl;
569     std::cout << " • Easy to validate and test" << std::endl;
570     std::cout << " • Common in embedded protocols" << std::endl;
571     std::cout << " • No dynamic dispatch overhead" << std::endl;
572 }
573
574 // =====
575 // 8. BIT MANIPULATION UTILITIES
```

```
576 // =====
577
578 namespace BitOps {
579     template<typename T>
580     constexpr void set_bit(T& reg, uint8_t bit) {
581         reg |= (static_cast<T>(1) << bit);
582     }
583
584     template<typename T>
585     constexpr void clear_bit(T& reg, uint8_t bit) {
586         reg &= ~(static_cast<T>(1) << bit);
587     }
588
589     template<typename T>
590     constexpr void toggle_bit(T& reg, uint8_t bit) {
591         reg ^= (static_cast<T>(1) << bit);
592     }
593
594     template<typename T>
595     constexpr bool test_bit(T reg, uint8_t bit) {
596         return (reg & (static_cast<T>(1) << bit)) != 0;
597     }
598
599     template<typename T>
600     constexpr void write_bits(T& reg, uint8_t start_bit, uint8_t num_bits, T
601         value) {
602         T mask = ((static_cast<T>(1) << num_bits) - 1) << start_bit;
603         reg = (reg & ~mask) | ((value << start_bit) & mask);
604     }
605
606 void example_bit_manipulation() {
607     std::cout << "\n==== 8. BIT MANIPULATION UTILITIES ===" << std::endl;
608
609     uint32_t control_reg = 0;
610
611     std::cout << "\nManipulating control register:" << std::endl;
612     std::cout << "    Initial value: 0x" << std::hex << control_reg << std::dec
613         << std::endl;
614
615     BitOps::set_bit(control_reg, 0); // Enable bit 0
616     std::cout << "    After set bit 0: 0x" << std::hex << control_reg << std::dec
617         << std::endl;
618
619     BitOps::set_bit(control_reg, 5); // Enable bit 5
620     std::cout << "    After set bit 5: 0x" << std::hex << control_reg << std::dec
621         << std::endl;
622
623     BitOps::write_bits(control_reg, 2, 3, 0b101u); // Write 3 bits starting
624         at bit 2
625     std::cout << "    After write bits 2-4: 0x" << std::hex << control_reg <<
626         std::dec << std::endl;
627
628     std::cout << "\nTesting bits:" << std::endl;
```

```
624     std::cout << "  Bit 0 is " << (BitOps::test_bit(control_reg, 0) ? "SET" :
625         "CLEAR") << std::endl;
626     std::cout << "  Bit 1 is " << (BitOps::test_bit(control_reg, 1) ? "SET" :
627         "CLEAR") << std::endl;
628
629     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
630     std::cout << " • Type-safe bit operations" << std::endl;
631     std::cout << " • Constexpr for compile-time use" << std::endl;
632     std::cout << " • Clear, readable code" << std::endl;
633     std::cout << " • No magic numbers" << std::endl;
634 }
635
636 // =====
637 // MAIN FUNCTION
638 // =====
639
640 int main() {
641     std::cout << "\n"
642         =====" <<
643         std::endl;
644     std::cout << "  EMBEDDED SYSTEMS PROGRAMMING IN MODERN C++" << std::endl;
645     std::cout << "
646         =====" <<
647         std::endl;
648
649     example_memory_pool();
650     example_circular_buffer();
651     example_hardware_raii();
652     example_static_polymorphism();
653     example_compile_time();
654     example_fixed_string();
655     example_state_machine();
656     example_bit_manipulation();
657
658     std::cout << "\n"
659         =====" <<
660         std::endl;
661     std::cout << "  EMBEDDED C++ BEST PRACTICES SUMMARY" << std::endl;
662     std::cout << "
663         =====" <<
664         std::endl;
665
666     std::cout << "\n KEY PRINCIPLES FOR EMBEDDED C++:" << std::endl;
667
668     std::cout << "\n1. NO DYNAMIC ALLOCATION" << std::endl;
669     std::cout << " • Use memory pools instead of new/delete" << std::endl;
670     std::cout << " • Fixed-size containers (std::array)" << std::endl;
671     std::cout << " • Stack allocation preferred" << std::endl;
672     std::cout << " • Predictable memory usage" << std::endl;
673
674     std::cout << "\n2. COMPILE-TIME COMPUTATION" << std::endl;
675     std::cout << " • constexpr functions for configuration" << std::endl;
676     std::cout << " • Template metaprogramming" << std::endl;
677     std::cout << " • if constexpr for conditional compilation" << std::endl;
```

```

668     std::cout << " • Zero runtime overhead" << std::endl;
669
670     std::cout << "\n3. STATIC POLYMORPHISM" << std::endl;
671     std::cout << " • CRTP instead of virtual functions" << std::endl;
672     std::cout << " • No vtable overhead" << std::endl;
673     std::cout << " • Fully inlineable" << std::endl;
674     std::cout << " • Saves RAM and Flash" << std::endl;
675
676     std::cout << "\n4. RAI FOR HARDWARE" << std::endl;
677     std::cout << " • Automatic resource management" << std::endl;
678     std::cout << " • Scope-based cleanup" << std::endl;
679     std::cout << " • Move semantics for ownership" << std::endl;
680     std::cout << " • Exception-safe (if enabled)" << std::endl;
681
682     std::cout << "\n5. INTERRUPT-SAFE PATTERNS" << std::endl;
683     std::cout << " • Circular buffers for ISR->Main communication" << std::endl;
684     std::cout << " • Atomic operations" << std::endl;
685     std::cout << " • Lock-free data structures" << std::endl;
686     std::cout << " • Minimal ISR processing" << std::endl;
687
688     std::cout << "\n6. DETERMINISTIC BEHAVIOR" << std::endl;
689     std::cout << " • No recursion (or limited)" << std::endl;
690     std::cout << " • Bounded loops" << std::endl;
691     std::cout << " • Fixed execution time" << std::endl;
692     std::cout << " • Real-time constraints" << std::endl;
693
694     std::cout << "\n MODERN C++ FEATURES FOR EMBEDDED:" << std::endl;
695     std::cout << "     constexpr (C++11/14/17) - Compile-time computation" << std::endl;
696     std::cout << "     std::array (C++11) - Fixed-size arrays" << std::endl;
697     std::cout << "     std::optional (C++17) - Error handling without exceptions" << std::endl;
698     std::cout << "     if constexpr (C++17) - Conditional compilation" << std::endl;
699     std::cout << "     Templates - Static polymorphism" << std::endl;
700     std::cout << "     Move semantics (C++11) - Efficient ownership transfer" << std::endl;
701     std::cout << "     RAI - Automatic resource management" << std::endl;
702     std::cout << "     Type traits - Compile-time type checking" << std::endl;
703
704     std::cout << "\n AVOID IN EMBEDDED:" << std::endl;
705     std::cout << "     new/delete (use memory pools)" << std::endl;
706     std::cout << "     std::vector, std::string (dynamic allocation)" << std::endl;
707     std::cout << "     Virtual functions (unless justified)" << std::endl;
708     std::cout << "     RTTI (enable only if needed)" << std::endl;
709     std::cout << "     Exceptions (often disabled in embedded)" << std::endl;
710     std::cout << "     iostream (large code size)" << std::endl;
711     std::cout << "     Recursion (stack overflow risk)" << std::endl;
712
713     std::cout << "\n EMBEDDED C++ IDIOMS:" << std::endl;
714     std::cout << " • Singleton pattern for hardware peripherals" << std::endl;

```

```
715     std::cout << " • State machines for protocol handling" << std::endl;
716     std::cout << " • Circular buffers for data streaming" << std::endl;
717     std::cout << " • Memory pools for dynamic-like allocation" << std::endl;
718     std::cout << " • CRTP for zero-cost abstraction" << std::endl;
719     std::cout << " • Register classes with bit fields" << std::endl;
720
721     std::cout << "\n TYPICAL MEMORY CONSTRAINTS:" << std::endl;
722     std::cout << " • Flash: 32KB - 2MB (code storage)" << std::endl;
723     std::cout << " • RAM: 4KB - 256KB (runtime data)" << std::endl;
724     std::cout << " • Stack: 1KB - 8KB (limited depth)" << std::endl;
725     std::cout << " • No heap or tiny heap (fragmentation risk)" << std::endl
726     ;
727
728     std::cout << "\n REAL-TIME CONSIDERATIONS:" << std::endl;
729     std::cout << " • Interrupt latency: <10µs typical" << std::endl;
730     std::cout << " • Task scheduling: RTOS or bare-metal" << std::endl;
731     std::cout << " • Timing critical sections" << std::endl;
732     std::cout << " • Watchdog timer management" << std::endl;
733
734     std::cout << "\n RECOMMENDED READING:" << std::endl;
735     std::cout << " • \"Embedded C++ Coding Standard\" by BARR Group" << std
736         ::endl;
737     std::cout << " • \"Real-Time C++\" by Christopher Kormanyos" << std::
738         endl;
739     std::cout << " • \"Effective Modern C++\" (embedded-applicable patterns)
740         " << std::endl;
741
742     std::cout << "\n"
743     ======\n" << std::endl;
744
745     return 0;
746 }
```

24 Source Code: ErrorHandling.cpp

File: src/ErrorHandling.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <stdexcept>
3 #include <string>
4 #include <memory>
5 #include <vector>
6 #include <optional>
7 #include <variant>
8 #include <fstream>
9 #include <system_error>
10 #include <cassert>
11 #include <type_traits>
12
13 // =====
14 // C++ ERROR HANDLING: COMPREHENSIVE EXAMPLES
15 // =====
16 // Demonstrates:
17 // 1. Throw by value, catch by reference (BEST PRACTICE)
18 // 2. Standard exception hierarchy
19 // 3. Custom exceptions
20 // 4. Exception safety guarantees
21 // 5. Compile-time error detection
22 // 6. Alternative error handling patterns
23 // =====
24
25 // =====
26 // 1. STANDARD EXCEPTIONS - THROW BY VALUE, CATCH BY REFERENCE
27 // =====
28
29 void demonstrate_basic_exception_handling() {
30     std::cout << "\n== 1. BASIC EXCEPTION HANDLING ==" << std::endl;
31     std::cout << "Rule: THROW BY VALUE, CATCH BY REFERENCE" << std::endl;
32
33     // Example 1: std::runtime_error
34     try {
35         std::cout << "\nThrowing std::runtime_error..." << std::endl;
36         throw std::runtime_error("Something went wrong at runtime!"); // Throw by value
37     }
38     catch (const std::runtime_error& e) { // Catch by const reference
39         std::cout << "Caught runtime_error: " << e.what() << std::endl;
40     }
41
42     // Example 2: std::logic_error
43     try {
44         std::cout << "\nThrowing std::logic_error..." << std::endl;
45         throw std::logic_error("Logic error in the program!"); // Throw by value
46     }
47     catch (const std::logic_error& e) { // Catch by const reference
```

```
48     std::cout << "Caught logic_error: " << e.what() << std::endl;
49 }
50
51 // Example 3: std::invalid_argument
52 try {
53     std::cout << "\nThrowing std::invalid_argument..." << std::endl;
54     throw std::invalid_argument("Invalid argument provided!"); // Throw
55     by value
56 }
57 catch (const std::invalid_argument& e) { // Catch by const reference
58     std::cout << "Caught invalid_argument: " << e.what() << std::endl;
59 }
60
61 // Example 4: std::out_of_range
62 try {
63     std::cout << "\nThrowing std::out_of_range..." << std::endl;
64     throw std::out_of_range("Index out of range!"); // Throw by value
65 }
66 catch (const std::out_of_range& e) { // Catch by const reference
67     std::cout << "Caught out_of_range: " << e.what() << std::endl;
68 }
69
70 // =====
71 // 2. STANDARD EXCEPTION HIERARCHY
72 // =====
73
74 void demonstrate_exception_hierarchy() {
75     std::cout << "\n== 2. EXCEPTION HIERARCHY ==" << std::endl;
76     std::cout << "std::exception (base)" << std::endl;
77     std::cout << "    std::logic_error" << std::endl;
78     std::cout << "        std::invalid_argument" << std::endl;
79     std::cout << "        std::domain_error" << std::endl;
80     std::cout << "        std::length_error" << std::endl;
81     std::cout << "        std::out_of_range" << std::endl;
82     std::cout << "        std::runtime_error" << std::endl;
83     std::cout << "        std::range_error" << std::endl;
84     std::cout << "        std::overflow_error" << std::endl;
85     std::cout << "        std::underflow_error" << std::endl;
86
87     // Catch base class to handle all derived exceptions
88     try {
89         std::cout << "\nThrowing derived exception..." << std::endl;
90         throw std::overflow_error("Integer overflow occurred!");
91     }
92     catch (const std::runtime_error& e) { // Catches std::overflow_error (
93         derived)
94         std::cout << "Caught via base class runtime_error: " << e.what() <<
95         std::endl;
96     }
97
98     // Multiple catch blocks - order matters!
99     try {
100         std::cout << "\nDemonstrating catch order..." << std::endl;
```

```
99     throw std::invalid_argument("Bad argument");
100 }
101 catch (const std::invalid_argument& e) { // Specific exception first
102     std::cout << "Caught specific: invalid_argument: " << e.what() << std
103         ::endl;
104 }
105 catch (const std::logic_error& e) { // Base class second
106     std::cout << "Caught base: logic_error: " << e.what() << std::endl;
107 }
108 catch (const std::exception& e) { // Most general last
109     std::cout << "Caught most general: exception: " << e.what() << std::
110         endl;
111 }
112 // =====
113 // 3. CUSTOM EXCEPTIONS
114 // =====
115
116 // Custom exception class - inherit from std::exception
117 class CameraException : public std::runtime_error {
118 private:
119     int error_code;
120
121 public:
122     explicit CameraException(const std::string& message, int code = 0)
123         : std::runtime_error(message), error_code(code) {}
124
125     int get_error_code() const noexcept { return error_code; }
126 };
127
128 class CameraNotConnectedException : public CameraException {
129 public:
130     explicit CameraNotConnectedException(const std::string& camera_name)
131         : CameraException("Camera not connected: " + camera_name, 100) {}
132 };
133
134 class CameraConfigurationException : public CameraException {
135 public:
136     explicit CameraConfigurationException(const std::string& config_error)
137         : CameraException("Configuration error: " + config_error, 200) {}
138 };
139
140 void demonstrate_custom_exceptions() {
141     std::cout << "\n== 3. CUSTOM EXCEPTIONS ==" << std::endl;
142
143     // Throw custom exception by value
144     try {
145         std::cout << "\nThrowing CameraNotConnectedException..." << std::endl;
146         throw CameraNotConnectedException("USB-CAM-001"); // Throw by value
147     }
148     catch (const CameraNotConnectedException& e) { // Catch by const
149         reference
150         std::cout << "Caught: " << e.what() << std::endl;
```

```
150     std::cout << "Error code: " << e.get_error_code() << std::endl;
151 }
152
153 // Catch hierarchy with custom exceptions
154 try {
155     std::cout << "\nThrowing CameraConfigurationException..." << std::endl
156     ;
157     throw CameraConfigurationException("Invalid resolution: 9999x9999");
158 }
159 catch (const CameraException& e) { // Catch base custom exception
160     std::cout << "Caught via base CameraException: " << e.what() << std::
161     endl;
162     std::cout << "Error code: " << e.get_error_code() << std::endl;
163 }
164 catch (const std::exception& e) { // Catch any std::exception
165     std::cout << "Caught via std::exception: " << e.what() << std::endl;
166 }
167
168 // =====
169 // 4. EXCEPTION SAFETY GUARANTEES
170 // =====
171
172 class SafeVector {
173 private:
174     std::vector<int> data;
175
176 public:
177     // Basic guarantee: No resources leaked, but object state may change
178     void push_back_basic(int value) {
179         data.push_back(value); // May throw, but vector cleans up
180     }
181
182     // Strong guarantee: Operation succeeds or has no effect (rollback)
183     void push_back_strong(int value) {
184         std::vector<int> temp = data; // Copy current state
185         temp.push_back(value); // Modify copy (if this throws,
186         // original unchanged)
187         data = std::move(temp); // Commit (noexcept move)
188     }
189
190     // No-throw guarantee: Marked noexcept
191     size_t size() const noexcept {
192         return data.size();
193     }
194
195     // No-throw guarantee: Never throws
196     void clear() noexcept {
197         data.clear();
198     }
199
200     int& at(size_t index) {
201         return data.at(index); // May throw std::out_of_range
202     }
```

```
201 };
```

```
202
203 void demonstrate_exception_safety() {
204     std::cout << "\n==== 4. EXCEPTION SAFETY GUARANTEES ===" << std::endl;
205
206     std::cout << "\nException Safety Levels:" << std::endl;
207     std::cout << "1. No-throw guarantee (noexcept): Never throws" << std::endl;
208         ;
209     std::cout << "2. Strong guarantee: Rollback on exception" << std::endl;
210     std::cout << "3. Basic guarantee: No resource leaks" << std::endl;
211     std::cout << "4. No guarantee: May leak resources" << std::endl;
212
213     SafeVector vec;
214     vec.push_back_basic(1);
215     vec.push_back_basic(2);
216
217     try {
218         std::cout << "\nAccessing valid index: vec.at(0)" << std::endl;
219         std::cout << "Value: " << vec.at(0) << std::endl;
220
221         std::cout << "\nAccessing invalid index: vec.at(100)" << std::endl;
222         vec.at(100); // Throws std::out_of_range
223     }
224     catch (const std::out_of_range& e) {
225         std::cout << "Caught: " << e.what() << std::endl;
226         std::cout << "Vector is still valid, size: " << vec.size() << std::endl;
227     }
228 }
229
230 // =====
231 // 5. RAI AND EXCEPTION SAFETY
232 // =====
233
234 class FileHandle {
235 private:
236     std::string filename;
237     FILE* file;
238
239 public:
240     explicit FileHandle(const std::string& fname, const char* mode)
241         : filename(fname), file(nullptr) {
242         file = fopen(fname.c_str(), mode);
243         if (!file) {
244             throw std::runtime_error("Failed to open file: " + fname);
245         }
246         std::cout << "File opened: " << filename << std::endl;
247     }
248
249     ~FileHandle() {
250         if (file) {
251             fclose(file);
252             std::cout << "File closed: " << filename << std::endl;
253     }
```

```
253     }
254
255     // Delete copy operations
256     FileHandle(const FileHandle&) = delete;
257     FileHandle& operator=(const FileHandle&) = delete;
258
259     // Move operations
260     FileHandle(FileHandle&& other) noexcept
261         : filename(std::move(other.filename)), file(other.file) {
262         other.file = nullptr;
263     }
264
265     FILE* get() const noexcept { return file; }
266 };
267
268 void demonstrate_raii() {
269     std::cout << "\n==== 5. RAI AND EXCEPTION SAFETY ===" << std::endl;
270
271     try {
272         std::cout << "\nOpening file (will throw)..." << std::endl;
273         FileHandle handle("nonexistent_file_xyz.txt", "r");
274         std::cout << "This won't print" << std::endl;
275     }
276     catch (const std::runtime_error& e) {
277         std::cout << "Caught: " << e.what() << std::endl;
278         std::cout << "No resource leak - file was never opened!" << std::endl;
279     }
280
281     std::cout << "\nDemonstrating automatic cleanup with scope:" << std::endl;
282     try {
283         // Create temporary file for demo
284         {
285             FileHandle handle1("temp_test.txt", "w");
286             fprintf(handle1.get(), "Test data\n");
287             // File automatically closed when handle1 goes out of scope
288         }
289         std::cout << "File closed automatically (RAII)" << std::endl;
290
291         // Clean up temp file
292         std::remove("temp_test.txt");
293     }
294     catch (const std::exception& e) {
295         std::cout << "Exception: " << e.what() << std::endl;
296     }
297 }
298
299 // =====
300 // 6. COMPILE-TIME ERROR DETECTION
301 // =====
302
303 // Static assertions - compile-time checks
304 template<typename T>
305 class Buffer {
306     private:
```

```
307     std::vector<T> data;
308
309 public:
310     // Compile-time check: Only allow trivially copyable types
311     static_assert(std::is_trivially_copyable_v<T>,
312                   "Buffer only works with trivially copyable types!");
313
314     Buffer(size_t size) : data(size) {}
315
316     T* get_data() { return data.data(); }
317 };
318
319 // constexpr for compile-time evaluation
320 constexpr int divide_compile_time(int a, int b) {
321     // This will cause compile error if b is 0 at compile time
322     return (b == 0) ? throw std::invalid_argument("Division by zero!") : a / b
323     ;
324 }
325
326 // C++20 Concepts for compile-time type checking
327 template<typename T>
328 concept Numeric = std::is_arithmetic_v<T>;
329
330 template<Numeric T>
331 T safe_divide(T a, T b) {
332     if (b == T(0)) {
333         throw std::invalid_argument("Division by zero!");
334     }
335     return a / b;
336 }
337
338 void demonstrate_compile_time_checks() {
339     std::cout << "\n==== 6. COMPILE-TIME ERROR DETECTION ===" << std::endl;
340
341     std::cout << "\n1. Static Assertions:" << std::endl;
342     Buffer<int> int_buffer(10); // OK: int is trivially copyable
343     std::cout << "    Buffer<int> compiles (trivially copyable)" << std::endl
344         ;
345
346     // This would NOT compile:
347     // Buffer<std::string> string_buffer(10); // ERROR: string not trivially
348     // copyable
349     std::cout << "    Buffer<std::string> would fail to compile!" << std::endl;
350
351     std::cout << "\n2. constexpr Functions:" << std::endl;
352     constexpr int result = divide_compile_time(10, 2); // OK at compile time
353     std::cout << "    10 / 2 = " << result << " (evaluated at compile time)" <<
354         std::endl;
355
356     // This would NOT compile:
357     // constexpr int error = divide_compile_time(10, 0); // Compile error!
358     std::cout << "    10 / 0 would fail at compile time!" << std::endl;
359 }
```

```
356     std::cout << "\n3. Concepts (C++20):" << std::endl;
357     try {
358         int a = safe_divide(10, 2);
359         std::cout << "    10 / 2 = " << a << std::endl;
360
361         double b = safe_divide(10.0, 0.0); // Runtime error
362         std::cout << "    This won't print: " << b << std::endl;
363     }
364     catch (const std::invalid_argument& e) {
365         std::cout << "    Caught: " << e.what() << std::endl;
366     }
367
368     // This would NOT compile:
369     // safe_divide(std::string("10"), std::string("2")); // Concept
370     // constraint violated!
371     std::cout << "    safe_divide with std::string would fail to compile!" <<
372     std::endl;
373 }
374
375 // =====
376 // 7. NOEXCEPT SPECIFICATION
377 // =====
378
379 class NoexceptDemo {
380 public:
381     // Guaranteed not to throw
382     int get_value() const noexcept {
383         return 42;
384     }
385
386     // May throw
387     int divide(int a, int b) {
388         if (b == 0) {
389             throw std::invalid_argument("Division by zero");
390         }
391         return a / b;
392     }
393
394     // Conditionally noexcept based on template parameter
395     template<typename T>
396     void swap(T& a, T& b) noexcept(std::is_nothrow_move_constructible_v<T>) {
397         T temp = std::move(a);
398         a = std::move(b);
399         b = std::move(temp);
400     }
401 };
402
403 void demonstrate_noexcept() {
404     std::cout << "\n==== 7. NOEXCEPT SPECIFICATION ===" << std::endl;
405
406     NoexceptDemo demo;
407
408     std::cout << "\nnoexcept functions:" << std::endl;
409     std::cout << "    get_value() is noexcept: "
```

```
408         << noexcept(demo.get_value()) << std::endl;
409     std::cout << "    divide() is noexcept: "
410             << noexcept(demo.divide(10, 2)) << std::endl;
411
412     std::cout << "\nBenefits of noexcept:" << std::endl;
413     std::cout << " • Compiler optimizations" << std::endl;
414     std::cout << " • Move constructors in std::vector" << std::endl;
415     std::cout << " • Enables certain optimizations in algorithms" << std::
416             endl;
417     std::cout << " • Self-documenting code" << std::endl;
418
419     std::cout << "\n  If noexcept function throws: std::terminate() is called
420           !" << std::endl;
421 }
422
423 // =====
424 // 8. ALTERNATIVE ERROR HANDLING: std::optional
425 // =====
426
427 std::optional<int> safe_divide_optional(int a, int b) {
428     if (b == 0) {
429         return std::nullopt; // Return empty optional instead of throwing
430     }
431     return a / b;
432 }
433
434 void demonstrate_optional() {
435     std::cout << "\n== 8. ERROR HANDLING WITH std::optional ==" << std::endl
436         ;
437     std::cout << "Alternative to exceptions for expected failures" << std::
438             endl;
439
440     auto result1 = safe_divide_optional(10, 2);
441     if (result1) {
442         std::cout << "\n10 / 2 = " << *result1 << " " << std::endl;
443     } else {
444         std::cout << "\n10 / 2 failed " << std::endl;
445     }
446
447     auto result2 = safe_divide_optional(10, 0);
448     if (result2) {
449         std::cout << "10 / 0 = " << *result2 << " " << std::endl;
450     } else {
451         std::cout << "10 / 0 failed (expected) " << std::endl;
452     }
453
454     std::cout << "\nBenefits:" << std::endl;
455     std::cout << " • No exception overhead" << std::endl;
456     std::cout << " • Makes errors explicit in return type" << std::endl;
457     std::cout << " • Good for expected failures" << std::endl;
458 }
459
460 // =====
461 // 9. ALTERNATIVE ERROR HANDLING: std::variant
```

```
458 // =====
459
460 struct Error {
461     int code;
462     std::string message;
463 };
464
465 std::variant<int, Error> safe_divide_variant(int a, int b) {
466     if (b == 0) {
467         return Error{1, "Division by zero"};
468     }
469     return a / b;
470 }
471
472 void demonstrate_variant() {
473     std::cout << "\n== 9. ERROR HANDLING WITH std::variant ==" << std::endl;
474     std::cout << "Return either result or error" << std::endl;
475
476     auto result1 = safe_divide_variant(10, 2);
477     if (std::holds_alternative<int>(result1)) {
478         std::cout << "\n10 / 2 = " << std::get<int>(result1) << " " << std::endl;
479     } else {
480         const auto& err = std::get<Error>(result1);
481         std::cout << "Error " << err.code << ": " << err.message << " " << std::endl;
482     }
483
484     auto result2 = safe_divide_variant(10, 0);
485     if (std::holds_alternative<int>(result2)) {
486         std::cout << "10 / 0 = " << std::get<int>(result2) << " " << std::endl;
487     } else {
488         const auto& err = std::get<Error>(result2);
489         std::cout << "Error " << err.code << ": " << err.message << " " << std::endl;
490     }
491
492     std::cout << "\nBenefits:" << std::endl;
493     std::cout << " • Can return detailed error information" << std::endl;
494     std::cout << " • Type-safe error handling" << std::endl;
495     std::cout << " • No exception overhead" << std::endl;
496 }
497
498 // =====
499 // 10. RETHROWING AND NESTED EXCEPTIONS
500 // =====
501
502 void inner_function() {
503     throw std::runtime_error("Error in inner function");
504 }
505
506 void middle_function() {
507     try {
```

```
508     inner_function();
509 }
510 catch (...) {
511     std::cout << "middle_function: Caught exception, rethrowing..." << std
512         ::endl;
513     throw; // Rethrow the same exception
514 }
515
516 void demonstrate_rethrowing() {
517     std::cout << "\n==== 10. RETHROWING EXCEPTIONS ===" << std::endl;
518
519     try {
520         middle_function();
521     }
522     catch (const std::runtime_error& e) {
523         std::cout << "Caught in demonstrate_rethrowing: " << e.what() << std::
524             endl;
525
526         std::cout << "\nRethrow with throw; (not throw e;)" << std::endl;
527         std::cout << "    throw; - Rethrows original exception (correct)" << std::
528             endl;
529         std::cout << "    throw e; - Creates new exception (slicing!)" << std::endl;
530     }
531 // =====
532 // MAIN FUNCTION
533 // =====
534
535 int main() {
536     std::cout << "\n
537         ====="
538     std::endl;
539     std::cout << "    C++ ERROR HANDLING: COMPREHENSIVE GUIDE" << std::endl;
540     std::cout << "
541         ====="
542     std::endl;
543
544     demonstrate_basic_exception_handling();
545     demonstrate_exception_hierarchy();
546     demonstrate_custom_exceptions();
547     demonstrate_exception_safety();
548     demonstrate_raii();
549     demonstrate_compile_time_checks();
550     demonstrate_noexcept();
551     demonstrate_optional();
552     demonstrate_variant();
553     demonstrate_rethrowing();
554
555     std::cout << "\n
556         ====="
557     std::endl;
558     std::cout << "    BEST PRACTICES SUMMARY" << std::endl;
```

```
553     std::cout << "  
554         =====" <<  
555         std::endl;  
556  
557     std::cout << "\n EXCEPTION HANDLING RULES:" << std::endl;  
558     std::cout << "n1. THROW BY VALUE, CATCH BY REFERENCE" << std::endl;  
559     std::cout << "    throw std::runtime_error(\"message\");" << std::endl;  
560     std::cout << "    catch (const std::runtime_error& e)" << std::endl;  
561     std::cout << "    throw new std::runtime_error(\"message\"); // NO!" <<  
562         std::endl;  
563     std::cout << "    catch (std::runtime_error e) // Slicing!" << std::endl;  
564         ;  
565  
566     std::cout << "\n2. CATCH ORDER MATTERS" << std::endl;  
567     std::cout << " • Catch specific exceptions first" << std::endl;  
568     std::cout << " • Catch base classes last" << std::endl;  
569     std::cout << " • catch(...) for unknown exceptions" << std::endl;  
570  
571     std::cout << "\n3. USE STANDARD EXCEPTIONS" << std::endl;  
572     std::cout << " • std::runtime_error - Runtime failures" << std::endl;  
573     std::cout << " • std::logic_error - Programming errors" << std::endl;  
574     std::cout << " • std::invalid_argument - Bad function arguments" << std  
575         ::endl;  
576     std::cout << " • std::out_of_range - Index out of bounds" << std::endl;  
577  
578     std::cout << "\n4. RAI FOR EXCEPTION SAFETY" << std::endl;  
579     std::cout << " • Use smart pointers (std::unique_ptr, std::shared_ptr)"  
580         << std::endl;  
581     std::cout << " • RAI wrappers for resources" << std::endl;  
582     std::cout << " • Destructors never throw" << std::endl;  
583  
584     std::cout << "\n5. NOEXCEPT FOR NON-THROWING FUNCTIONS" << std::endl;  
585     std::cout << " • Mark functions that never throw" << std::endl;  
586     std::cout << " • Enables compiler optimizations" << std::endl;  
587     std::cout << " • Move constructors should be noexcept" << std::endl;  
588  
589     std::cout << "\n6. COMPILE-TIME ERROR DETECTION" << std::endl;  
590     std::cout << " • static_assert for compile-time checks" << std::endl;  
591     std::cout << " • constexpr for compile-time evaluation" << std::endl;  
592     std::cout << " • Concepts (C++20) for type constraints" << std::endl;  
593     std::cout << " • Template SFINAE for type checking" << std::endl;  
594  
595     std::cout << "\n7. ALTERNATIVES TO EXCEPTIONS" << std::endl;  
596     std::cout << " • std::optional<T> - For expected failures" << std::endl;  
597     std::cout << " • std::variant<T, Error> - Return result or error" << std  
598         ::endl;  
599     std::cout << " • Error codes - For performance-critical code" << std::  
600         endl;  
601     std::cout << " • std::expected<T, E> (C++23) - Best of both worlds" <<  
602         std::endl;  
603  
604     std::cout << "\n WHEN TO USE WHAT:" << std::endl;  
605     std::cout << "\nExceptions:" << std::endl;  
606     std::cout << "    Unexpected errors (file not found, network failure)" <<
```

```
      std::endl;
598  std::cout << "    Constructor failures" << std::endl;
599  std::cout << "    Deep call stacks (error propagation)" << std::endl;
600  std::cout << "    Performance-critical code" << std::endl;
601  std::cout << "    Expected failures (validation)" << std::endl;
602
603  std::cout << "\nstd::optional:" << std::endl;
604  std::cout << "    Expected failures (search not found)" << std::endl;
605  std::cout << "    Optional return values" << std::endl;
606  std::cout << "    Performance-critical code" << std::endl;
607  std::cout << "    Need detailed error information" << std::endl;
608
609  std::cout << "\nstd::variant<T, Error>:" << std::endl;
610  std::cout << "    Need detailed error information" << std::endl;
611  std::cout << "    Multiple error types" << std::endl;
612  std::cout << "    Performance-critical code" << std::endl;
613  std::cout << "    Simple success/failure cases" << std::endl;
614
615  std::cout << "\nCompile-time checks:" << std::endl;
616  std::cout << "    Type constraints" << std::endl;
617  std::cout << "    API misuse prevention" << std::endl;
618  std::cout << "    Zero runtime cost" << std::endl;
619  std::cout << "    Early error detection" << std::endl;
620
621  std::cout << "\n PERFORMANCE NOTES:" << std::endl;
622  std::cout << " • Exceptions have zero cost if not thrown (modern
623    compilers)" << std::endl;
624  std::cout << " • Throwing exception is expensive (~1000x slower than
625    return)" << std::endl;
626  std::cout << " • noexcept enables optimizations (especially in std::
627    vector)" << std::endl;
628  std::cout << " • Compile-time checks have zero runtime cost" << std::endl
629  ;
630
631  std::cout << "\n"
632  ======\n" <<
633  std::endl;
634
635  return 0;
636 }
```

25 Source Code: ErrorHandlingStroustrup.cpp

File: src/ErrorHandlingStroustrup.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // ERROR HANDLING STRATEGIES - Following Bjarne Stroustrup's Guidance
3 // Based on "A Tour of C++", 3rd Edition, Chapter 4
4 // =====
5 //
6 // Three approaches to error handling:
7 // 1. RETURN VALUES - When function can't complete the task
8 // 2. EXCEPTIONS - When constructor can't establish invariants
9 // 3. TERMINATION - When continuing would be dangerous
10 //
11 // Key Principles:
12 // - Constructors cannot return values → must throw or terminate
13 // - Partially constructed objects are dangerous
14 // - RAII ensures proper cleanup even with exceptions
15 // - Return values for expected/recoverable errors
16 // - Exceptions for unexpected/exceptional situations
17 // - Terminate for programming errors/invariant violations
18 // =====
19
20 #include <iostream>
21 #include <string>
22 #include <vector>
23 #include <optional>
24 #include <memory>
25 #include <fstream>
26 #include <cstdlib>
27 #include <stdexcept>
28 #include <cassert>
29
30 // =====
31 // 1. RETURN VALUES - For Expected/Recoverable Errors
32 // =====
33
34 // Use case: Function can't complete task, but caller can handle it
35 // Appropriate when: Error is expected and can be recovered
36
37 class ConfigParser {
38 public:
39     // Return std::optional - error is expected (file might not exist)
40     static std::optional<std::string> read_config_value(const std::string& key
41         ) {
42         std::cout << "[1.1] Reading config key: " << key << std::endl;
43
44         // Simulate config lookup
45         if (key == "server_url") {
46             return "http://localhost:8080";
47         }
48         if (key == "timeout") {
49             return "30";
50     }
51 }
```

```
49     }
50
51     // Key not found - this is EXPECTED, not exceptional
52     std::cout << "      Config key '" << key << "' not found (expected
53         scenario)" << std::endl;
54     return std::nullopt; // Caller can provide default or retry
55 }
56
57 // Return int with special value - traditional C-style
58 static int parse_integer(const std::string& str, int default_value = -1) {
59     std::cout << "[1.2] Parsing integer from: " << str << std::endl;
60
61     try {
62         return std::stoi(str);
63     } catch (...) {
64         // Parsing failed - return sentinel value
65         std::cout << "      Parse failed, returning default: " <<
66             default_value << std::endl;
67         return default_value;
68     }
69 }
70
71 // Return bool with output parameter - when you need to return value too
72 static bool try_connect(const std::string& url, int& out_status_code) {
73     std::cout << "[1.3] Attempting connection to: " << url << std::endl;
74
75     // Simulate connection attempt
76     if (url.find("localhost") != std::string::npos) {
77         out_status_code = 200;
78         std::cout << "      Connected successfully, status: " <<
79             out_status_code << std::endl;
80         return true; // Success
81     }
82
83     out_status_code = 404;
84     std::cout << "      Connection failed, status: " << out_status_code <<
85         std::endl;
86     return false; // Expected failure - caller can retry
87 }
88
89 void demonstrate_return_values() {
90     std::cout << "\n== 1. RETURN VALUES - Expected/Recoverable Errors ==" <<
91         std::endl;
92     std::cout << "Use when: Function can't complete, but caller can handle it"
93         << std::endl;
94
95     // Example 1: Optional value
96     auto url = ConfigParser::read_config_value("server_url");
97     if (url) {
98         std::cout << "  Found URL: " << *url << std::endl;
99     } else {
100         std::cout << "  Using default URL" << std::endl;
101 }
```

```
97 // Missing key - caller provides default
98 auto missing = ConfigParser::read_config_value("missing_key");
99 std::string final_value = missing.value_or("default_value");
100 std::cout << " Using value: " << final_value << std::endl;
101
102 // Example 2: Integer parsing with default
103 int timeout = ConfigParser::parse_integer("abc", 10);
104 std::cout << " Timeout value: " << timeout << " seconds" << std::endl;
105
106 // Example 3: Try pattern
107 int status_code;
108 if (ConfigParser::try_connect("http://invalid.url", status_code)) {
109     std::cout << " Connected" << std::endl;
110 } else {
111     std::cout << " Connection failed with code: " << status_code << " (
112         retry possible)" << std::endl;
113 }
114
115 std::cout << "\n When to use RETURN VALUES:" << std::endl;
116 std::cout << " • Error is EXPECTED (file not found, network timeout)" <<
117     std::endl;
118 std::cout << " • Caller can RECOVER (retry, use default, ask user)" <<
119     std::endl;
120 std::cout << " • Normal flow of control" << std::endl;
121 std::cout << " • Performance-critical code" << std::endl;
122 }
123
124 // =====
125 // 2. EXCEPTIONS - For Constructors and Unexpected Errors
126 // =====
127
128 // Problem: Partially constructed objects are dangerous!
129
130 class FileHandler_BAD {
131     std::string filename;
132     FILE* file_ptr; // Raw pointer - dangerous!
133     bool is_valid; // Flag to track construction success
134
135 public:
136     // BAD: Constructor can't return error, uses flag instead
137     FileHandler_BAD(const std::string& fname)
138         : filename(fname), file_ptr(nullptr), is_valid(false) {
139
140         std::cout << "\n[2.1 BAD] Attempting to open file: " << fname << std::endl;
141
142         file_ptr = fopen(fname.c_str(), "r");
143         if (file_ptr == nullptr) {
144             // PROBLEM: Can't return error from constructor
145             // Object is partially constructed with invalid state!
146             std::cout << " File open failed, but object still created!" << std::endl;
147             is_valid = false; // Caller must check this flag
148 }
```

```
146         return;
147     }
148
149     is_valid = true;
150 }
151
152 // Every member function must check is_valid!
153 bool read_line(std::string& line) {
154     if (!is_valid || !file_ptr) {
155         return false; // Undefined behavior if caller forgets to check!
156     }
157     // ... read logic
158     return true;
159 }
160
161 ~FileHandler_BAD() {
162     if (file_ptr) {
163         fclose(file_ptr);
164     }
165 }
166
167 bool valid() const { return is_valid; }
168 };
169
170 // Solution: Use RAII and throw from constructor
171
172 class FileHandler_GOOD {
173     std::string filename;
174     std::unique_ptr<FILE, decltype(&fclose)> file_ptr; // RAII wrapper
175
176 public:
177     // GOOD: Constructor either succeeds completely or throws
178     FileHandler_GOOD(const std::string& fname)
179         : filename(fname), file_ptr(nullptr, &fclose) {
180
181         std::cout << "\n[2.2 GOOD] Attempting to open file: " << fname << std
182             ::endl;
183
184         FILE* raw_ptr = fopen(fname.c_str(), "r");
185         if (raw_ptr == nullptr) {
186             // THROW: Constructor can't establish invariant
187             std::cout << "           Throwing exception - no partial object!" <<
188                 std::endl;
189             throw std::runtime_error("Failed to open file: " + fname);
190         }
191
192         file_ptr.reset(raw_ptr);
193         std::cout << "           File opened successfully, object fully
194             constructed" << std::endl;
195
196         // Invariant established: file_ptr is valid
197         // No need for is_valid flag - if object exists, it's valid!
198     }
199 }
```

```
197 // No need to check validity - if object exists, it's valid
198 std::string read_line() {
199     // Can safely use file_ptr - invariant guaranteed by constructor
200     char buffer[256];
201     if (fgets(buffer, sizeof(buffer), file_ptr.get())) {
202         return std::string(buffer);
203     }
204     return "";
205 }
206
207 // Destructor automatically called even if constructor throws
208 // unique_ptr ensures file is closed
209 ~FileHandler_GOOD() {
210     std::cout << "      Closing file: " << filename << std::endl;
211     // file_ptr's destructor automatically closes file
212 }
213 };
214
215 // Another example: Vector with invariants
216
217 class BoundedVector_BAD {
218     std::vector<int> data;
219     size_t max_size;
220     bool is_valid;
221
222 public:
223     // BAD: Doesn't enforce invariant in constructor
224     BoundedVector_BAD(size_t max_sz, const std::vector<int>& initial)
225         : max_size(max_sz), is_valid(false) {
226
227         std::cout << "\n[2.3 BAD] Creating bounded vector, max_size="
228             << max_sz << ", initial.size()=" << initial.size() << std::endl;
229
230         if (initial.size() > max_sz) {
231             // PROBLEM: Partial construction!
232             std::cout << "      Initial size exceeds max, but object created
233                 anyway!" << std::endl;
234             is_valid = false;
235             return;
236         }
237
238         data = initial;
239         is_valid = true;
240     }
241
242     bool push_back(int value) {
243         if (!is_valid) return false; // Must check everywhere!
244         if (data.size() >= max_size) return false;
245         data.push_back(value);
246         return true;
247     }
248
249     bool valid() const { return is_valid; }
```

```
249 };
```

```
250 
```

```
251 class BoundedVector_GOOD {
252     std::vector<int> data;
253     size_t max_size;
254 
```

```
255 public:
256     // GOOD: Enforces invariant, throws if violated
257     BoundedVector_GOOD(size_t max_sz, const std::vector<int>& initial)
258         : max_size(max_sz) {
259 
260         std::cout << "\n[2.4 GOOD] Creating bounded vector, max_size="
261             << max_sz << ", initial.size()=" << initial.size() << std::
262             endl;
263 
264         if (initial.size() > max_sz) {
265             // THROW: Invariant cannot be established
266             std::cout << "           Throwing - initial size exceeds maximum!" <<
267                 std::endl;
268             throw std::invalid_argument(
269                 "Initial size " + std::to_string(initial.size()) +
270                 " exceeds maximum " + std::to_string(max_sz)
271             );
272         }
273 
274         data = initial;
275         std::cout << "           Bounded vector created, invariant satisfied" <<
276             std::endl;
277 
278         // Invariant: data.size() <= max_size
279         // Guaranteed for object's entire lifetime!
280     }
281 
```

```
282     void push_back(int value) {
283         // Invariant guaranteed - no need to check is_valid
284         if (data.size() >= max_size) {
285             throw std::length_error("Vector at maximum capacity");
286         }
287         data.push_back(value);
288     }
289 
```

```
290     size_t size() const { return data.size(); }
291 };
292 
```

```
293 // RAII Example: Exception safety with resource management
294 
```

```
295 class ResourceManager {
296     std::unique_ptr<int[]> buffer;
297     FILE* log_file;
298     bool initialized;
299 
```

```
300 public:
301     // RAII: Resources acquired in constructor
302     ResourceManager(size_t buffer_size, const std::string& log_path)
```

```
300     : buffer(nullptr), log_file(nullptr), initialized(false) {
301
302     std::cout << "\n[2.5] Constructing ResourceManager..." << std::endl;
303
304     // Step 1: Allocate buffer (RAII with unique_ptr)
305     buffer = std::make_unique<int[]>(buffer_size);
306     std::cout << "           Buffer allocated" << std::endl;
307
308     // Step 2: Open log file
309     log_file = fopen(log_path.c_str(), "a");
310     if (!log_file) {
311         std::cout << "           Log file open failed - throwing..." << std::endl;
312         // buffer automatically deallocated by unique_ptr destructor!
313         throw std::runtime_error("Failed to open log file");
314     }
315     std::cout << "           Log file opened" << std::endl;
316
317     initialized = true;
318     std::cout << "           ResourceManager fully constructed" << std::endl;
319 }
320
321 ~ResourceManager() {
322     std::cout << "           Cleaning up ResourceManager..." << std::endl;
323
324     if (log_file) {
325         fclose(log_file);
326         std::cout << "           Log file closed" << std::endl;
327     }
328
329     // buffer automatically deallocated by unique_ptr
330     std::cout << "           Buffer deallocated" << std::endl;
331 }
332
333 // Disable copy to prevent resource issues
334 ResourceManager(const ResourceManager&) = delete;
335 ResourceManager& operator=(const ResourceManager&) = delete;
336
337 // Enable move for transfer of ownership
338 ResourceManager(ResourceManager&& other) noexcept
339     : buffer(std::move(other.buffer))
340     , log_file(other.log_file)
341     , initialized(other.initialized) {
342     other.log_file = nullptr;
343     other.initialized = false;
344 }
345 };
346
347 void demonstrate_exceptions() {
348     std::cout << "\n== 2. EXCEPTIONS - Constructors and Invariants ==" <<
349     std::endl;
350     std::cout << "Use when: Constructor can't establish object invariants" <<
351     std::endl;
```

```
351 // Example 2.1: BAD - Partially constructed object
352 std::cout << "\n--- Demonstrating BAD approach ---" << std::endl;
353 {
354     FileHandler_BAD bad_handler("nonexistent_file.txt");
355     if (!bad_handler.valid()) {
356         std::cout << " Object exists but is invalid - DANGEROUS!" << std
357             ::endl;
358         std::cout << " Every function must check valid() flag" << std::
359             endl;
360     }
361 }
362
363 // Example 2.2: GOOD - Exception prevents partial construction
364 std::cout << "\n--- Demonstrating GOOD approach ---" << std::endl;
365 try {
366     FileHandler_GOOD good_handler("nonexistent_file.txt");
367     // This line never executes if file doesn't exist
368     std::cout << " Object constructed, guaranteed valid" << std::endl;
369 } catch (const std::exception& e) {
370     std::cout << " Exception caught: " << e.what() << std::endl;
371     std::cout << " No object exists - no invalid state possible!" << std
372         ::endl;
373 }
374
375 // Example 2.3: BAD - Invariant violation
376 std::cout << "\n--- Bounded Vector: BAD approach ---" << std::endl;
377 {
378     std::vector<int> too_large = {1, 2, 3, 4, 5};
379     BoundedVector_BAD bad_vec(3, too_large); // max_size=3, but initial
380         has 5
381     if (!bad_vec.valid()) {
382         std::cout << " Invalid object exists with violated invariant!" <<
383             std::endl;
384     }
385 }
386
387 // Example 2.4: GOOD - Exception prevents invariant violation
388 std::cout << "\n--- Bounded Vector: GOOD approach ---" << std::endl;
389 try {
390     std::vector<int> too_large = {1, 2, 3, 4, 5};
391     BoundedVector_GOOD good_vec(3, too_large); // Will throw
392 } catch (const std::invalid_argument& e) {
393     std::cout << " Exception caught: " << e.what() << std::endl;
394     std::cout << " Invariant violation prevented!" << std::endl;
395 }
396
397 // Example 2.5: RAII ensures cleanup even with exceptions
398 std::cout << "\n--- RAII with Exception ---" << std::endl;
399 try {
400     ResourceManager mgr(1024, "/invalid/path/log.txt"); // Will fail
401 } catch (const std::exception& e) {
402     std::cout << " Exception caught: " << e.what() << std::endl;
403     std::cout << " Buffer was automatically cleaned up (RAII)!" << std::
404         endl;
```

```
399    }
400
401    std::cout << "\n When to use EXCEPTIONS:" << std::endl;
402    std::cout << " • Constructor can't establish invariants" << std::endl;
403    std::cout << " • Partially constructed object would be dangerous" << std
        ::endl;
404    std::cout << " • Error is UNEXPECTED (programming error, resource
        exhaustion)" << std::endl;
405    std::cout << " • Can't return error value (constructors, operators)" <<
        std::endl;
406    std::cout << " • RAII ensures cleanup even if exception thrown" << std::
        endl;
407 }
408
409 // =====
410 // 3. TERMINATION - For Unrecoverable Errors
411 // =====
412
413 // Use case: Programming error or invariant violation where continuing is
414 // dangerous
415
416 class CriticalSystem {
417     int* data_ptr;
418     size_t size;
419
420     // Internal invariant check
421     void checkInvariant() const {
422         if (data_ptr == nullptr && size > 0) {
423             // PROGRAMMING ERROR: Inconsistent state!
424             std::cerr << "\n FATAL: Invariant violated - nullptr with size >
0" << std::endl;
425             std::cerr << "    This should never happen - terminating!" << std::
426             endl;
427             std::terminate(); // Cannot continue safely
428         }
429     }
430
431     CriticalSystem(size_t sz) : data_ptr(nullptr), size(sz) {
432         if (sz == 0) {
433             std::cerr << "\n FATAL: Zero-size system not allowed" << std::
434             endl;
435             std::terminate(); // Precondition violation
436         }
437
438         data_ptr = new int[sz];
439         std::cout << "[3.1] CriticalSystem constructed with size " << sz <<
440             std::endl;
441     }
442
443     void setValue(size_t index, int value) {
444         checkInvariant(); // Verify internal consistency
445
446         if (index >= size) {
```

```
444         // PROGRAMMING ERROR: Out of bounds access
445         std::cerr << "\n FATAL: Index " << index << " out of bounds [0, "
446             << size << ")" << std::endl;
447         std::cerr << "    This indicates a bug - terminating!" << std::endl
448             ;
449         std::abort(); // Cannot recover from logic error
450     }
451
452     data_ptr[index] = value;
453 }
454
455 int get_value(size_t index) const {
456     // Use assert for debug builds (removed in release with NDEBUG)
457     assert(index < size && "Index out of bounds");
458
459     if (index >= size) {
460         std::cerr << "\n FATAL: Index out of bounds in release build" <<
461             std::endl;
462         std::terminate();
463     }
464
465     return data_ptr[index];
466 }
467
468 ~CriticalSystem() {
469     delete[] data_ptr;
470 }
471 // Comparison: When to use each approach
472
473 class SafetyLevel {
474 public:
475     enum class Level {
476         INFO,           // Normal operation
477         WARNING,        // Something unexpected but recoverable
478         ERROR,          // Error that can be handled
479         CRITICAL,       // Error requiring immediate attention
480         FATAL           // Cannot continue
481     };
482
483     // Different error handling based on severity
484     static void handle_error(Level level, const std::string& message) {
485         switch (level) {
486             case Level::INFO:
487                 // Just log - continue normally
488                 std::cout << "\n INFO: " << message << std::endl;
489                 break;
490
491             case Level::WARNING:
492                 // Log and return - caller handles it
493                 std::cout << "\n WARNING: " << message << std::endl;
494                 // Return value or optional
495                 break;
496         }
497     }
498 }
```

```
496
497     case Level::ERROR:
498         // Throw exception - caller can catch and recover
499         std::cout << "\n ERROR: " << message << std::endl;
500         throw std::runtime_error(message);
501
502     case Level::CRITICAL:
503         // Log critical error, attempt emergency cleanup
504         std::cerr << "\n CRITICAL: " << message << std::endl;
505         std::cerr << "    Attempting emergency save..." << std::endl;
506         // ... emergency cleanup ...
507         throw std::runtime_error("Critical: " + message);
508
509     case Level::FATAL:
510         // Cannot continue - terminate immediately
511         std::cerr << "\n FATAL: " << message << std::endl;
512         std::cerr << "    Cannot continue safely - terminating!" << std::endl;
513         std::terminate();
514     }
515 }
516 };
517
518 void demonstrate_termination() {
519     std::cout << "\n--- 3. TERMINATION - Unrecoverable Errors ---" << std::endl;
520     std::cout << "Use when: Continuing would be dangerous or impossible" << std::endl;
521
522     // Example: Normal operation
523     std::cout << "\n--- Normal operation ---" << std::endl;
524     {
525         CriticalSystem sys(10);
526         sys.set_value(0, 42);
527         sys.set_value(5, 100);
528         std::cout << "    Values set successfully" << std::endl;
529     }
530
531     // Example: Safety levels
532     std::cout << "\n--- Different safety levels ---" << std::endl;
533
534     // INFO - just logging
535     SafetyLevel::handle_error(SafetyLevel::Level::INFO, "System started");
536
537     // WARNING - caller can ignore or handle
538     SafetyLevel::handle_error(SafetyLevel::Level::WARNING, "Cache miss (using
539         fallback)");
540
541     // ERROR - throw exception
542     try {
543         SafetyLevel::handle_error(SafetyLevel::Level::ERROR, "Network timeout"
544             );
545     } catch (const std::exception& e) {
546         std::cout << " Caught and recovered from ERROR: " << e.what() << std::endl;
```

```
        ::endl;
545 }
546
547 std::cout << "\n When to use TERMINATION:" << std::endl;
548 std::cout << " • PROGRAMMING ERROR detected (invariant violated)" << std
      ::endl;
549 std::cout << " • Precondition violated (contract broken)" << std::endl;
550 std::cout << " • Continuing would corrupt data or cause undefined
      behavior" << std::endl;
551 std::cout << " • Use assert() in debug builds (removed in release)" <<
      std::endl;
552 std::cout << " • Use std::terminate() or std::abort() for fatal errors"
      << std::endl;
553
554 // Note: The examples below would terminate if uncommented
555 std::cout << "\n The following would terminate (commented out):" << std
      ::endl;
556 std::cout << " // CriticalSystem sys(0); // Zero size - would terminate
      " << std::endl;
557 std::cout << " // sys.set_value(999, 42); // Out of bounds - would
      terminate" << std::endl;
558 }
559
560 // =====
561 // SUMMARY: Decision Guide
562 // =====
563
564 void print_decision_guide() {
565     std::cout << "\n
566         =====
567         std::endl;
568     std::cout << " DECISION GUIDE: Which Error Handling Strategy?" << std::
569         endl;
570     std::cout << "
571         =====
572         std::endl;
573
574     std::cout << "\n 1. RETURN VALUES (std::optional, bool, error codes)" <<
575         std::endl;
576     std::cout << "     Use when:" << std::endl;
577     std::cout << " •     Error is EXPECTED and part of normal operation" <<
578         std::endl;
579     std::cout << " •     Caller can and should handle the error" << std::endl
          ;
580     std::cout << " •     Checking for availability (file exists, key found)"
          << std::endl;
581     std::cout << " •     Performance-critical code" << std::endl;
582     std::cout << " •     Parsing/validation where failure is common" << std::
583         endl;
584
585     std::cout << "\n     Examples:" << std::endl;
586     std::cout << " •     std::optional<T> find_user(int id)" << std::endl;
587     std::cout << " •     bool try_connect(const string& url, int& status)" <<
588         std::endl;
589     std::cout << " •     std::expected<Value, Error> parse_config()" << std::
```

```

        endl;

580    std::cout << "\n\n 2. EXCEPTIONS (throw/catch)" << std::endl;
581    std::cout << "      Use when:" << std::endl;
582    std::cout << " •      Constructor cannot establish invariants" << std::
583          endl;
584    std::cout << " •      Partially constructed object would be dangerous" <<
585          std::endl;
585    std::cout << " •      Error is UNEXPECTED (resource exhaustion, logic
586          error)" << std::endl;
586    std::cout << " •      Cannot return error value (constructors, operators)"
587          << std::endl;
587    std::cout << " •      Need to skip multiple stack frames to handler" <<
588          std::endl;
588    std::cout << " •      RAII ensures automatic cleanup" << std::endl;
589    std::cout << "\n      Examples:" << std::endl;
590    std::cout << " •      FileHandle(const string& path) // Constructor" <<
591          std::endl;
591    std::cout << " •      BoundedVector(size_t max, vector<T> initial) //"
592          " Invariant" << std::endl;
592    std::cout << " •      operator[](size_t idx) // Can't return error" <<
593          std::endl;

593
594    std::cout << "\n\n 3. TERMINATION (std::terminate, std::abort, assert)"
595          << std::endl;
595    std::cout << "      Use when:" << std::endl;
596    std::cout << " •      PROGRAMMING ERROR (bug in code)" << std::endl;
597    std::cout << " •      Invariant violated (internal consistency broken)" <<
598          std::endl;
598    std::cout << " •      Precondition not met (contract violated)" << std::
599          endl;
599    std::cout << " •      Continuing would cause data corruption" << std::endl
600          ;
600    std::cout << " •      Undefined behavior would result" << std::endl;
601    std::cout << "\n      Examples:" << std::endl;
602    std::cout << " •      assert(ptr != nullptr); // Debug check" << std::
603          endl;
603    std::cout << " •      if (invariant_broken()) std::terminate();" << std::
604          endl;
604    std::cout << " •      if (out_of_bounds) std::abort();" << std::endl;

605
606    std::cout << "\n\n COMPARISON TABLE:" << std::endl;
607    std::cout << "                                         " << std::endl;
608    std::cout << " Aspect           Return Value   Exception     Termination"
609          " << std::endl;
610    std::cout << "                               " << std::endl;
610    std::cout << " Error frequency   Common       Rare          Never*"
611          " << std::endl;
611    std::cout << " Recoverability     Recoverable   May recover   Fatal"
612          " << std::endl;
612    std::cout << " Caller control     Explicit     Can catch     None"
613          " << std::endl;
613    std::cout << " Performance         Fast         Slow          N/A"
613          " << std::endl;

```

```

614     std::cout << " Constructor use No Yes Yes (rare)"
615         " << std::endl;
616     std::cout << " RAIII cleanup Manual Automatic No
617         " << std::endl;
618     std::cout << "
619         " << std::endl;
620     std::cout << "* \"Never\" = should never happen in correct program" << std
621         ::endl;
622
623
624     std::cout << "\n\n BJARNE'S KEY INSIGHTS:" << std::endl;
625     std::cout << "\n 1 \"A constructor establishes the invariant for a
626         class\"" << std::endl;
627     std::cout << " → Must throw if invariant cannot be established" <<
628         std::endl;
629     std::cout << " → No partially constructed objects" << std::endl;
630
631
632     std::cout << "\n 2 \"Use exceptions for exceptional circumstances\""
633         << std::endl;
634     std::cout << " → Not for normal control flow" << std::endl;
635     std::cout << " → When caller can't be expected to check every call"
636         << std::endl;
637
638     std::cout << "\n 3 \"Use error codes when errors are expected\""
639         << std::endl;
640     std::cout << " → File not found, network timeout, parse error" << std
641         ::endl;
642     std::cout << " → Caller should handle explicitly" << std::endl;
643
644     std::cout << "\n 4 \"Terminate when continuing would be dangerous\""
645         << std::endl;
646     std::cout << " → Programming errors (bugs)" << std::endl;
647     std::cout << " → Invariant violations" << std::endl;
648
649     std::cout << "\n 5 \"RAII is fundamental to exception safety\""
650         << std
651         ::endl;
652     std::cout << " → Resources acquired in constructor" << std::endl;
653     std::cout << " → Released in destructor" << std::endl;
654     std::cout << " → Cleanup happens even with exceptions" << std::endl;
655
656
657     std::cout << "\n"
658         =====
659         std::endl;
660 }
661
662 // =====
663 // MAIN
664 // =====
665
666
667
668 int main() {
669     std::cout << "\n"
670         =====
671         std::endl;
672     std::cout << "  ERROR HANDLING STRATEGIES" << std::endl;
673     std::cout << "  Following Bjarne Stroustrup's Philosophy" << std::endl;
674     std::cout << "

```

```
===== " <<
std::endl;

653
654 try {
655     demonstrate_return_values();
656     demonstrate_exceptions();
657     demonstrate_termination();
658     print_decision_guide();

659     std::cout << "\n All demonstrations completed successfully!" << std::
660             endl;

661 } catch (const std::exception& e) {
662     std::cerr << "\n Unexpected exception: " << e.what() << std::endl;
663     return 1;
664 }
665
666 return 0;
667 }
```

26 Source Code: EventDrivenProgramming_Inheritance.cpp

File: src/EventDrivenProgramming_Inheritance.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <memory>
5 #include <algorithm>
6 #include <queue>
7
8 // =====
9 // EVENT-DRIVEN PROGRAMMING: TRADITIONAL INHERITANCE-BASED APPROACH
10 // =====
11 // This file demonstrates traditional event-driven programming using:
12 // - Abstract base classes
13 // - Virtual functions
14 // - Inheritance hierarchies
15 // - Classic OOP patterns
16 // =====
17
18 // =====
19 // 1. OBSERVER PATTERN (INHERITANCE-BASED)
20 // =====
21
22 // Abstract observer interface
23 class IObserver {
24 public:
25     virtual ~IObserver() = default;
26     virtual void on_notify(const std::string& event) = 0;
27 };
28
29 // Concrete observer implementations
30 class ConsoleObserver : public IObserver {
31 private:
32     std::string name;
33
34 public:
35     ConsoleObserver(std::string n) : name(std::move(n)) {}
36
37     void on_notify(const std::string& event) override {
38         std::cout << "      [" << name << "] Received: " << event << std::endl;
39     }
40 };
41
42 class CountingObserver : public IObserver {
43 private:
44     int count = 0;
45
46 public:
47     void on_notify(const std::string& event) override {
48         count++;
49         std::cout << "      [Counter] Event #" << count << ":" << event << std::endl;
50 }
```

```
        ::endl;
50    }
51
52    int get_count() const { return count; }
53};
54
55 class Subject {
56 private:
57     std::vector<IObserver*> observers; // Raw pointers or shared_ptr
58
59 public:
60     void attach(IObserver* observer) {
61         observers.push_back(observer);
62     }
63
64     void detach(IObserver* observer) {
65         observers.erase(
66             std::remove(observers.begin(), observers.end(), observer),
67             observers.end()
68         );
69     }
70
71     void notify(const std::string& event) {
72         std::cout << " [Subject] Notifying " << observers.size() << "
73             observers" << std::endl;
74         for (auto* observer : observers) {
75             observer->on_notify(event);
76         }
77     }
78 };
79
80 void example_inheritance_observer() {
81     std::cout << "\n==== 1. OBSERVER PATTERN (INHERITANCE-BASED) ===" << std::
82         endl;
83
84     Subject subject;
85
86     // Need to create concrete observer objects
87     ConsoleObserver obs1("Observer1");
88     ConsoleObserver obs2("Observer2");
89     CountingObserver counter;
90
91     subject.attach(&obs1);
92     subject.attach(&obs2);
93     subject.attach(&counter);
94
95     subject.notify("User logged in");
96     subject.notify("Data updated");
97
98     std::cout << "\n DISADVANTAGES:" << std::endl;
99     std::cout << " • Must define observer classes" << std::endl;
100    std::cout << " • Need inheritance hierarchy" << std::endl;
101    std::cout << " • More boilerplate code" << std::endl;
102    std::cout << " • Lifetime management issues (pointers)" << std::endl;
```

```
101 }
102
103 // =====
104 // 2. EVENT HIERARCHY (INHERITANCE-BASED)
105 // =====
106
107 // Abstract event base class
108 class Event {
109 public:
110     virtual ~Event() = default;
111     virtual std::string get_name() const = 0;
112     virtual void print() const = 0;
113 };
114
115 class MouseClickEvent : public Event {
116 private:
117     int x, y;
118     std::string button;
119
120 public:
121     MouseClickEvent(int x, int y, std::string btn)
122         : x(x), y(y), button(std::move(btn)) {}
123
124     std::string get_name() const override { return "MouseClick"; }
125
126     void print() const override {
127         std::cout << "    Mouse clicked: " << button
128             << " at (" << x << "," << y << ")" << std::endl;
129     }
130
131     int get_x() const { return x; }
132     int get_y() const { return y; }
133     const std::string& get_button() const { return button; }
134 };
135
136 class KeyPressEvent : public Event {
137 private:
138     char key;
139     bool ctrl;
140
141 public:
142     KeyPressEvent(char k, bool c) : key(k), ctrl(c) {}
143
144     std::string get_name() const override { return "KeyPress"; }
145
146     void print() const override {
147         std::cout << "    Key pressed: '" << key << "'"
148             << (ctrl ? " (Ctrl)" : "") << std::endl;
149     }
150
151     char get_key() const { return key; }
152     bool has_ctrl() const { return ctrl; }
153 };
154
```

```
155 // Abstract event handler
156 class IEventHandler {
157 public:
158     virtual ~IEventHandler() = default;
159     virtual void handle_event(const Event& event) = 0;
160 };
161
162 class EventLogger : public IEventHandler {
163 public:
164     void handle_event(const Event& event) override {
165         std::cout << "    [Logger] Handling " << event.get_name() << std::endl
166             ;
167         event.print();
168     }
169 };
170
171 class MouseHandler : public IEventHandler {
172 public:
173     void handle_event(const Event& event) override {
174         // Need to use dynamic_cast to access specific event data
175         if (auto* mouse_event = dynamic_cast<const MouseEvent*>(&event))
176         {
177             std::cout << "    [MouseHandler] Processing mouse at "
178                 << mouse_event->get_x() << "," << mouse_event->get_y()
179                 << ")" << std::endl;
180         }
181         // Ignore other event types
182     }
183 };
184
185 class EventDispatcher {
186 private:
187     std::vector<IEventHandler*> handlers;
188
189 public:
190     void subscribe(IEventHandler* handler) {
191         handlers.push_back(handler);
192     }
193
194     void dispatch(const Event& event) {
195         for (auto* handler : handlers) {
196             handler->handle_event(event);
197         }
198     }
199
200     void example_event_hierarchy() {
201         std::cout << "\n==== 2. EVENT HIERARCHY (INHERITANCE-BASED) ===" << std::endl;
202
203         EventDispatcher dispatcher;
204
205         EventLogger logger;
206         MouseHandler mouse_handler;
```

```
205     dispatcher.subscribe(&logger);
206     dispatcher.subscribe(&mouse_handler);
207
208     std::cout << "\nDispatching events:" << std::endl;
209     MouseClickEvent click(100, 200, "left");
210     dispatcher.dispatch(click);
211
212     KeyPressEvent key('A', true);
213     dispatcher.dispatch(key);
214
215     std::cout << "\n DISADVANTAGES:" << std::endl;
216     std::cout << " • Need event class hierarchy" << std::endl;
217     std::cout << " • Must use dynamic_cast (RTTI)" << std::endl;
218     std::cout << " • Pointer semantics required" << std::endl;
219     std::cout << " • More complex type checking" << std::endl;
220 }
221
222 // =====
223 // 3. LISTENER PATTERN (CLASSIC GUI APPROACH)
224 // =====
225
226
227 class IButtonListener {
228 public:
229     virtual ~IButtonListener() = default;
230     virtual void on_button_clicked(const std::string& button_id) = 0;
231 };
232
233 class Button {
234 private:
235     std::string id;
236     std::vector<IButtonListener*> listeners;
237
238 public:
239     Button(std::string button_id) : id(std::move(button_id)) {}
240
241     void add_listener(IButtonListener* listener) {
242         listeners.push_back(listener);
243     }
244
245     void click() {
246         std::cout << "[Button '" << id << "'] Clicked!" << std::endl;
247         for (auto* listener : listeners) {
248             listener->on_button_clicked(id);
249         }
250     }
251 };
252
253 class SaveHandler : public IButtonListener {
254 public:
255     void on_button_clicked(const std::string& button_id) override {
256         std::cout << "[SaveHandler] Saving file..." << std::endl;
257     }
258 };
```

```
259
260 class LogHandler : public IButtonListener {
261 public:
262     void on_button_clicked(const std::string& button_id) override {
263         std::cout << "    [LogHandler] Logging click on " << button_id << std
264             ::endl;
265     }
266 };
267
268 void example_listener_pattern() {
269     std::cout << "\n==== 3. LISTENER PATTERN (CLASSIC GUI) ===" << std::endl;
270
271     Button save_btn("SaveButton");
272
273     SaveHandler save_handler;
274     LogHandler log_handler;
275
276     save_btn.add_listener(&save_handler);
277     save_btn.add_listener(&log_handler);
278
279     save_btn.click();
280
281     std::cout << "\n DISADVANTAGES:" << std::endl;
282     std::cout << " • Need listener interface classes" << std::endl;
283     std::cout << " • Can't define behavior inline" << std::endl;
284     std::cout << " • More classes to maintain" << std::endl;
285     std::cout << " • Harder to share state" << std::endl;
286 }
287
288 // =====
289 // 4. COMMAND PATTERN (INHERITANCE-BASED)
290 // =====
291
292 class ICommand {
293 public:
294     virtual ~ICommand() = default;
295     virtual void execute() = 0;
296     virtual void undo() = 0;
297     virtual std::string get_description() const = 0;
298 };
299
300 class TextCommand : public ICommand {
301 private:
302     std::string& text_ref;
303     std::string new_text;
304     std::string old_text;
305
306     TextCommand(std::string& text, std::string new_val)
307         : text_ref(text), new_text(std::move(new_val)), old_text(text) {}
308
309     void execute() override {
310         std::cout << "    Execute: Set text to '" << new_text << "'" << std::
311             endl;
```

```
311     text_ref = new_text;
312 }
313
314 void undo() override {
315     std::cout << "      Undo: Restore text to '" << old_text << "'";
316     endl;
317     text_ref = old_text;
318 }
319
320 std::string get_description() const override {
321     return "Change text to '" + new_text + "'";
322 }
323
324 class CommandManager {
325 private:
326     std::vector<std::unique_ptr< ICommand>> history;
327     size_t current = 0;
328
329 public:
330     void execute(std::unique_ptr< ICommand> cmd) {
331         cmd->execute();
332
333         // Clear redo history
334         history.erase(history.begin() + current, history.end());
335
336         history.push_back(std::move(cmd));
337         current = history.size();
338     }
339
340     void undo() {
341         if (current > 0) {
342             current--;
343             history[current]->undo();
344         }
345     }
346
347     void redo() {
348         if (current < history.size()) {
349             history[current]->execute();
350             current++;
351         }
352     }
353 };
354
355 void example_command_pattern() {
356     std::cout << "\n==== 4. COMMAND PATTERN (INHERITANCE-BASED) ===" << std::endl;
357
358     std::string document = "Original";
359     CommandManager manager;
360
361     std::cout << "\nExecuting commands:" << std::endl;
362     manager.execute(std::make_unique<TextCommand>(document, "Modified 1"));
```

```
363     std::cout << "      Text: " << document << std::endl;
364
365     manager.execute(std::make_unique<TextCommand>(document, "Modified 2"));
366     std::cout << "      Text: " << document << std::endl;
367
368     std::cout << "\nUndoing commands:" << std::endl;
369     manager.undo();
370     std::cout << "      Text: " << document << std::endl;
371
372     manager.undo();
373     std::cout << "      Text: " << document << std::endl;
374
375     std::cout << "\n DISADVANTAGES:" << std::endl;
376     std::cout << " • Need command class for each operation" << std::endl;
377     std::cout << " • More verbose class definitions" << std::endl;
378     std::cout << " • State management in constructors" << std::endl;
379     std::cout << " • Can't define commands inline" << std::endl;
380 }
381
382 // =====
383 // 5. CALLBACK INTERFACE (OLD-SCHOOL)
384 // =====
385
386 class ICallback {
387 public:
388     virtual ~ICallback() = default;
389     virtual void on_success(int result) = 0;
390     virtual void on_error(const std::string& error) = 0;
391 };
392
393 class AsyncOperation {
394 private:
395     ICallback* callback = nullptr;
396
397 public:
398     void set_callback(ICallback* cb) {
399         callback = cb;
400     }
401
402     void execute(bool should_fail = false) {
403         if (callback) {
404             if (should_fail) {
405                 callback->on_error("Operation failed!");
406             } else {
407                 callback->on_success(42);
408             }
409         }
410     }
411 };
412
413 class MyCallback : public ICallback {
414 public:
415     void on_success(int result) override {
416         std::cout << " Success! Result: " << result << std::endl;
```

```
417     }
418
419     void on_error(const std::string& error) override {
420         std::cout << "    Error: " << error << std::endl;
421     }
422 };
423
424 void example_callback_interface() {
425     std::cout << "\n==> 5. CALLBACK INTERFACE (OLD-SCHOOL) ==<" << std::endl;
426
427     AsyncOperation op;
428     MyCallback callback;
429
430     op.set_callback(&callback);
431
432     std::cout << "\n--- Success case ---" << std::endl;
433     op.execute(false);
434
435     std::cout << "\n--- Error case ---" << std::endl;
436     op.execute(true);
437
438     std::cout << "\n DISADVANTAGES:" << std::endl;
439     std::cout << " • Must define callback class" << std::endl;
440     std::cout << " • Can't chain callbacks easily" << std::endl;
441     std::cout << " • Only one callback per operation" << std::endl;
442     std::cout << " • Less readable than fluent API" << std::endl;
443 }
444
445 // =====
446 // MAIN FUNCTION
447 // =====
448
449 int main() {
450     std::cout << "\n
451         ====="
452         std::endl;
453     std::cout << "    EVENT-DRIVEN PROGRAMMING: TRADITIONAL INHERITANCE APPROACH
454         " << std::endl;
455     std::cout << "
456         ====="
457         std::endl;
458
459     example_inheritance_observer();
460     example_event_hierarchy();
461     example_listener_pattern();
462     example_command_pattern();
463     example_callback_interface();
464
465     std::cout << "\n
466         ====="
467         std::endl;
468     std::cout << "    SUMMARY: PROBLEMS WITH INHERITANCE-BASED APPROACH" << std
469         ::endl;
470     std::cout << "
```

```
=====
        << std::endl;

463    std::cout << "\n DISADVANTAGES OF INHERITANCE-BASED APPROACH:" << std::endl;
464
465    std::cout << "\n1. BOILERPLATE CODE" << std::endl;
466    std::cout << " • Must define interface classes (IObserver, IListener,
467      etc.)" << std::endl;
468    std::cout << " • Must define concrete implementations" << std::endl;
469    std::cout << " • Each behavior needs a new class" << std::endl;
470    std::cout << " • Lots of virtual functions" << std::endl;
471
472    std::cout << "\n2. INFLEXIBILITY" << std::endl;
473    std::cout << " • Can't define behavior inline" << std::endl;
474    std::cout << " • Hard to share state between callbacks" << std::endl;
475    std::cout << " • Difficult to compose behaviors" << std::endl;
476    std::cout << " • Rigid class hierarchies" << std::endl;
477
478    std::cout << "\n3. LIFETIME MANAGEMENT" << std::endl;
479    std::cout << " • Raw pointers cause dangling reference bugs" << std::endl;
480    std::cout << " • shared_ptr adds complexity and overhead" << std::endl;
481    std::cout << " • Must manage attach/detach carefully" << std::endl;
482    std::cout << " • Who owns the observer objects?" << std::endl;
483
484    std::cout << "\n4. POOR READABILITY" << std::endl;
485    std::cout << " • Behavior scattered across multiple files" << std::endl;
486    std::cout << " • Must jump between class definitions" << std::endl;
487    std::cout << " • Harder to see full picture" << std::endl;
488    std::cout << " • Intent hidden in class names" << std::endl;
489
490    std::cout << "\n5. RTTI AND CASTING" << std::endl;
491    std::cout << " • Need dynamic_cast for event hierarchies" << std::endl;
492    std::cout << " • Runtime type checking (slower)" << std::endl;
493    std::cout << " • Can fail at runtime" << std::endl;
494    std::cout << " • Not as type-safe" << std::endl;
495
496    std::cout << "\n6. MAINTENANCE BURDEN" << std::endl;
497    std::cout << " • More files to maintain" << std::endl;
498    std::cout << " • More classes in codebase" << std::endl;
499    std::cout << " • Harder to refactor" << std::endl;
500    std::cout << " • Changes ripple through hierarchy" << std::endl;
501
502    std::cout << "\n WHEN INHERITANCE IS JUSTIFIED:" << std::endl;
503    std::cout << " • Polymorphic object collections" << std::endl;
504    std::cout << " • Complex state machines" << std::endl;
505    std::cout << " • Need object identity (not just behavior)" << std::endl;
506    std::cout << " • Multiple related virtual methods" << std::endl;
507    std::cout << " • Performance critical (no std::function overhead)" <<
508      std::endl;
509    std::cout << " • Plugin architectures" << std::endl;
510
511    std::cout << "\n MODERN ALTERNATIVE:" << std::endl;
```

```
511     std::cout << "    Use EventDrivenProgramming_Lambdas.cpp for:" << std::endl
      ;
512     std::cout << "    std::function + lambdas (no inheritance)" << std::endl;
513     std::cout << "    std::variant (no event hierarchy)" << std::endl;
514     std::cout << "    Inline behavior definitions" << std::endl;
515     std::cout << "    Automatic state capture" << std::endl;
516     std::cout << "    Much less boilerplate" << std::endl;
517
518     std::cout << "\n COMPARISON:" << std::endl;
519     std::cout << "    Inheritance approach: ~200 lines for basic observer" <<
      std::endl;
520     std::cout << "    Lambda approach:           ~50 lines for same functionality"
      << std::endl;
521     std::cout << "    Code reduction:          75% less code!" << std::endl;
522
523     std::cout << "\n"
      =====\n" <<
      std::endl;
524
525     return 0;
526 }
```

27 Source Code: EventDrivenProgramming_Lambdas.cpp

File: src/EventDrivenProgramming_Lambdas.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <functional>
3 #include <string>
4 #include <vector>
5 #include <map>
6 #include <memory>
7 #include <variant>
8 #include <algorithm>
9 #include <queue>
10 #include <typeindex>
11
12 // =====
13 // EVENT-DRIVEN PROGRAMMING: MODERN LAMBDA-BASED APPROACH
14 // =====
15 // This file demonstrates event-driven programming using:
16 // - std::function
17 // - Lambdas with captures
18 // - std::variant
19 // - No inheritance hierarchies needed!
20 // =====
21
22 // =====
23 // 1. OBSERVER PATTERN (LAMBDA-BASED)
24 // =====
25
26 class Subject {
27 private:
28     std::vector<std::function<void(const std::string&)>> observers;
29
30 public:
31     void subscribe(std::function<void(const std::string&)> observer) {
32         observers.push_back(std::move(observer));
33     }
34
35     void notify(const std::string& event) {
36         std::cout << " [Subject] Notifying " << observers.size() << " "
37             observers" << std::endl;
38         for (auto& observer : observers) {
39             observer(event);
40         }
41     }
42 };
43 void example_lambda_observer() {
44     std::cout << "\n==== 1. OBSERVER PATTERN (LAMBDA-BASED) ===" << std::endl;
45
46     Subject subject;
47
48     // No observer class needed! Just pass lambdas
```

```
49     subject.subscribe([](const std::string& event) {
50         std::cout << "    Lambda Observer 1: " << event << std::endl;
51     });
52
53     // Can capture state inline
54     int count = 0;
55     subject.subscribe([&count](const std::string& event) {
56         std::cout << "    Lambda Observer 2 (count=" << ++count << "): " <<
57             event << std::endl;
58     });
59
60     // Can define behavior at subscription time
61     std::string prefix = "CustomPrefix";
62     subject.subscribe([prefix](const std::string& event) {
63         std::cout << "    [" << prefix << "] " << event << std::endl;
64     });
65
66     subject.notify("User logged in");
67     subject.notify("Data updated");
68
69     std::cout << "\n ADVANTAGES:" << std::endl;
70     std::cout << " • No observer interface/base class needed" << std::endl;
71     std::cout << " • Inline behavior definition" << std::endl;
72     std::cout << " • Can capture local state" << std::endl;
73     std::cout << " • Less boilerplate code" << std::endl;
74 }
75
76 // =====
77 // 2. SIGNAL/SLOT PATTERN (MODERN)
78 // =====
79 template<typename... Args>
80 class Signal {
81 private:
82     std::vector<std::function<void(Args...)>> slots;
83
84 public:
85     void connect(std::function<void(Args...)> slot) {
86         slots.push_back(std::move(slot));
87     }
88
89     void emit(Args... args) {
90         for (auto& slot : slots) {
91             slot(args...);
92         }
93     }
94
95     void operator()(Args... args) { emit(args...); }
96 };
97
98 class Button {
99 public:
100     Signal<const std::string&> clicked;
101     Signal<int, int> positionChanged;
```

```
102     std::string id;
103
104     Button(std::string id) : id(std::move(id)) {}
105 };
106
107
108 void example_signal_slot() {
109     std::cout << "\n==> 2. SIGNAL/SLOT PATTERN (MODERN) ==>" << std::endl;
110
111     Button btn("SaveButton");
112
113     // Connect signals to lambdas (no slot classes needed!)
114     btn.clicked.connect([](const std::string& id) {
115         std::cout << "    Handler 1: Button " << id << " was clicked" << std::endl;
116     });
117
118     btn.clicked.connect([](const std::string& id) {
119         std::cout << "    Handler 2: Logging click on " << id << std::endl;
120     });
121
122     btn.positionChanged.connect([](int x, int y) {
123         std::cout << "    Position handler: Moved to (" << x << ", " << y << ")"
124             << std::endl;
125     });
126
127     std::cout << "\nTriggering signals:" << std::endl;
128     btn.clicked.emit("SaveButton");
129     btn.positionChanged.emit(150, 200);
130
131     std::cout << "\n ADVANTAGES:" << std::endl;
132     std::cout << " • Type-safe (template-based)" << std::endl;
133     std::cout << " • No slot base class needed" << std::endl;
134     std::cout << " • Multiple handlers per signal" << std::endl;
135     std::cout << " • Clean, declarative syntax" << std::endl;
136 }
137
138 // =====
139 // 3. EVENT DISPATCHER WITH std::variant
140 // =====
141
142 struct MouseClick { int x; int y; std::string button; };
143 struct KeyPress { char key; bool ctrl; bool shift; };
144 struct WindowResize { int width; int height; };
145
146 using UIEvent = std::variant<MouseClick, KeyPress, WindowResize>;
147
148 class EventDispatcher {
149 private:
150     std::vector<std::function<void(const UIEvent&)>> handlers;
151
152 public:
153     void subscribe(std::function<void(const UIEvent&)> handler) {
154         handlers.push_back(std::move(handler));
155 }
```

```
154     }
155
156     void dispatch(const UIEvent& event) {
157         for (auto& handler : handlers) {
158             handler(event);
159         }
160     }
161 };
162
163 void example_variant_dispatcher() {
164     std::cout << "\n==== 3. EVENT DISPATCHER WITH std::variant ===" << std::endl;
165
166     EventDispatcher dispatcher;
167
168     // Subscribe with lambda that uses std::visit
169     dispatcher.subscribe([](const UIEvent& event) {
170         std::visit([](const auto& e) {
171             using T = std::decay_t<decltype(e)>;
172
173             if constexpr (std::is_same_v<T, MouseClick>) {
174                 std::cout << "    Mouse clicked: " << e.button
175                     << " at (" << e.x << "," << e.y << ")" << std::endl;
176             } else if constexpr (std::is_same_v<T, KeyPress>) {
177                 std::cout << "    Key pressed: '" << e.key << "'"
178                     << (e.ctrl ? "(Ctrl)" : "") 
179                     << (e.shift ? "(Shift)" : "") << std::endl;
180             } else if constexpr (std::is_same_v<T, WindowResize>) {
181                 std::cout << "    Window resized: " << e.width << "x" << e.
182                     height << std::endl;
183             }
184         }, event);
185     });
186
187     // Another handler that only cares about mouse clicks
188     dispatcher.subscribe([](const UIEvent& event) {
189         if (auto* click = std::get_if<MouseClick>(&event)) {
190             std::cout << "[Logger] Mouse event at (" << click->x << "," <<
191                 click->y << ")" << std::endl;
192         }
193     });
194
195     std::cout << "\nDispatching events:" << std::endl;
196     dispatcher.dispatch(MouseClick{100, 200, "left"});
197     dispatcher.dispatch_KeyPress{'A', true, false});
198     dispatcher.dispatch(WindowResize{1920, 1080});
199
200     std::cout << "\n ADVANTAGES:" << std::endl;
201     std::cout << " • No event hierarchy needed" << std::endl;
202     std::cout << " • Type-safe with std::variant" << std::endl;
203     std::cout << " • Compile-time dispatch with std::visit" << std::endl;
204     std::cout << " • Value semantics (no pointers)" << std::endl;
205 }
```

```
205 // =====
206 // 4. CALLBACK COMPOSITION (FLUENT API)
207 // =====
208
209 class AsyncTask {
210 private:
211     std::function<void(int)> success_callback;
212     std::function<void(const std::string&)> error_callback;
213     std::function<void()> finally_callback;
214
215 public:
216     AsyncTask& on_success(std::function<void(int)> callback) {
217         success_callback = std::move(callback);
218         return *this;
219     }
220
221     AsyncTask& on_error(std::function<void(const std::string&)> callback) {
222         error_callback = std::move(callback);
223         return *this;
224     }
225
226     AsyncTask& finally(std::function<void()> callback) {
227         finally_callback = std::move(callback);
228         return *this;
229     }
230
231     void execute(bool should_fail = false) {
232         try {
233             if (should_fail) {
234                 if (error_callback) error_callback("Task failed!");
235             } else {
236                 if (success_callback) success_callback(42);
237             }
238         } catch (...) {
239             if (error_callback) error_callback("Exception occurred");
240         }
241
242         if (finally_callback) finally_callback();
243     }
244 };
245
246 void example_callback_composition() {
247     std::cout << "\n== 4. CALLBACK COMPOSITION (FLUENT API) ==" << std::endl;
248     ;
249
250     std::cout << "\n--- Success case ---" << std::endl;
251     AsyncTask task1;
252     task1.on_success([](int result) {
253         std::cout << "    Success! Result: " << result << std::endl;
254     })
255     .on_error([](const std::string& error) {
256         std::cout << "    Error: " << error << std::endl;
257     })
258     .finally([]() {
```

```
258         std::cout << "      Cleanup completed" << std::endl;
259     })
260     .execute(false);
261
262     std::cout << "\n--- Error case ---" << std::endl;
263     AsyncTask task2;
264     task2.on_success([](int result) {
265         std::cout << "      Success! Result: " << result << std::endl;
266     })
267     .on_error([](const std::string& error) {
268         std::cout << "      Error: " << error << std::endl;
269     })
270     .finally([]() {
271         std::cout << "      Cleanup completed" << std::endl;
272     })
273     .execute(true);
274
275     std::cout << "\n ADVANTAGES:" << std::endl;
276     std::cout << " • No callback interface classes" << std::endl;
277     std::cout << " • Readable, sequential setup" << std::endl;
278     std::cout << " • Similar to JavaScript Promises" << std::endl;
279     std::cout << " • Fluent API (method chaining)" << std::endl;
280 }
281
282 // =====
283 // 5. REACTIVE OBSERVABLE
284 // =====
285
286 template<typename T>
287 class Observable {
288 private:
289     T value;
290     std::vector<std::function<void(const T&)>> subscribers;
291
292 public:
293     Observable(T initial) : value(std::move(initial)) {}
294
295     void subscribe(std::function<void(const T&)> subscriber) {
296         subscriber(value); // Immediate notification
297         subscribers.push_back(std::move(subscriber));
298     }
299
300     void set(T new_value) {
301         if (value != new_value) {
302             value = std::move(new_value);
303             for (auto& subscriber : subscribers) {
304                 subscriber(value);
305             }
306         }
307     }
308
309     const T& get() const { return value; }
310 };
311
```

```
312 void example_reactive_observable() {
313     std::cout << "\n==== 5. REACTIVE OBSERVABLE ===" << std::endl;
314
315     Observable<int> counter(0);
316
317     // Subscribe with lambdas
318     counter.subscribe([](int value) {
319         std::cout << "    Subscriber 1: Counter = " << value << std::endl;
320     });
321
322     counter.subscribe([](int value) {
323         if (value > 0 && value % 2 == 0) {
324             std::cout << "    Subscriber 2: Even number " << value << std::endl;
325         }
326     });
327
328     std::cout << "\nUpdating counter:" << std::endl;
329     counter.set(1);
330     counter.set(2);
331     counter.set(3);
332     counter.set(4);
333
334     std::cout << "\n ADVANTAGES:" << std::endl;
335     std::cout << " • Automatic propagation" << std::endl;
336     std::cout << " • No observer base class" << std::endl;
337     std::cout << " • Declarative subscriptions" << std::endl;
338     std::cout << " • Great for UI data binding" << std::endl;
339 }
340
341 // =====
342 // 6. EVENT QUEUE WITH LAMBDAS
343 // =====
344
345 class EventQueue {
346 private:
347     std::queue<std::function<void()>> events;
348
349 public:
350     void post(std::function<void()> event) {
351         events.push(std::move(event));
352     }
353
354     void process_all() {
355         while (!events.empty()) {
356             auto event = std::move(events.front());
357             events.pop();
358             event();
359         }
360     }
361
362     size_t size() const { return events.size(); }
363 };
364
```

```
365 void example_event_queue() {
366     std::cout << "\n==== 6. EVENT QUEUE WITH LAMBDAS ===" << std::endl;
367
368     EventQueue queue;
369
370     // Post events as lambdas (no event classes needed!)
371     queue.post([]() {
372         std::cout << "    Event 1: Initialize" << std::endl;
373     });
374
375     queue.post([]() {
376         std::cout << "    Event 2: Load config" << std::endl;
377     });
378
379     int data = 42;
380     queue.post([data]() {
381         std::cout << "    Event 3: Process data: " << data << std::endl;
382     });
383
384     std::cout << "\nProcessing " << queue.size() << " events:" << std::endl;
385     queue.process_all();
386
387     std::cout << "\n ADVANTAGES:" << std::endl;
388     std::cout << " • No event class hierarchy" << std::endl;
389     std::cout << " • Can capture context in closure" << std::endl;
390     std::cout << " • Extremely flexible" << std::endl;
391     std::cout << " • Minimal boilerplate" << std::endl;
392 }
393
394 // =====
395 // 7. COMMAND PATTERN WITH LAMBDAS
396 // =====
397
398 class Command {
399 private:
400     std::function<void()> execute_func;
401     std::function<void()> undo_func;
402     std::string description;
403
404 public:
405     Command(std::function<void()> exec, std::function<void()> undo, std::
406             string desc)
407         : execute_func(std::move(exec))
408         , undo_func(std::move(undo))
409         , description(std::move(desc)) {}
410
411     void execute() {
412         std::cout << "    Execute: " << description << std::endl;
413         if (execute_func) execute_func();
414     }
415
416     void undo() {
417         std::cout << "    Undo: " << description << std::endl;
418         if (undo_func) undo_func();
419 }
```

```
418     }
419 };
420
421 void example_lambda_command() {
422     std::cout << "\n==== 7. COMMAND PATTERN WITH LAMBDAS ===" << std::endl;
423
424     std::string text = "Original";
425     std::vector<Command> history;
426
427     // Create commands with lambdas (no command classes!)
428     history.emplace_back(
429         [&text]() { text = "Modified 1"; },
430         [&text]() { text = "Original"; },
431         "Change to 'Modified 1'"
432     );
433
434     history.emplace_back(
435         [&text]() { text = "Modified 2"; },
436         [&text]() { text = "Modified 1"; },
437         "Change to 'Modified 2'"
438     );
439
440     std::cout << "\nExecuting commands:" << std::endl;
441     for (auto& cmd : history) {
442         cmd.execute();
443         std::cout << "      Text: " << text << std::endl;
444     }
445
446     std::cout << "\nUndoing commands:" << std::endl;
447     for (auto it = history.rbegin(); it != history.rend(); ++it) {
448         it->undo();
449         std::cout << "      Text: " << text << std::endl;
450     }
451
452     std::cout << "\n ADVANTAGES:" << std::endl;
453     std::cout << " • No command class hierarchy" << std::endl;
454     std::cout << " • Define behavior inline" << std::endl;
455     std::cout << " • Capture state automatically" << std::endl;
456     std::cout << " • Very concise" << std::endl;
457 }
458
459 // =====
460 // MAIN FUNCTION
461 // =====
462
463 int main() {
464     std::cout << "\n
465         =====" << std::endl;
466     std::cout << "  EVENT-DRIVEN PROGRAMMING: MODERN LAMBDA-BASED APPROACH" <<
467         std::endl;
468     std::cout << "
469         =====" << std::endl;
```

```
467
468     example_lambda_observer();
469     example_signal_slot();
470     example_variant_dispatcher();
471     example_callback_composition();
472     example_reactive_observable();
473     example_event_queue();
474     example_lambda_command();
475
476     std::cout << "\n"
477             ===== " <<
478             std::endl;
477     std::cout << "    SUMMARY: WHY LAMBDAS ARE BETTER" << std::endl;
478     std::cout << "
479             ===== " <<
480             std::endl;
480
481     std::cout << "\n ADVANTAGES OF LAMBDA-BASED APPROACH:" << std::endl;
482     std::cout << "\n1. LESS BOILERPLATE" << std::endl;
483     std::cout << " • No need to define observer/listener classes" << std::
484             endl;
485     std::cout << " • No inheritance hierarchies" << std::endl;
486     std::cout << " • Behavior defined at point of use" << std::endl;
487
488     std::cout << "\n2. MORE FLEXIBLE" << std::endl;
489     std::cout << " • Can capture local state [=], [&]" << std::endl;
490     std::cout << " • Different behavior per subscription" << std::endl;
491     std::cout << " • Easy to compose and chain" << std::endl;
492
493     std::cout << "\n3. BETTER READABILITY" << std::endl;
494     std::cout << " • Callback logic near subscription point" << std::endl;
495     std::cout << " • No jumping between class definitions" << std::endl;
496     std::cout << " • Intent is clear and local" << std::endl;
497
498     std::cout << "\n4. TYPE SAFETY" << std::endl;
499     std::cout << " • std::function provides type checking" << std::endl;
500     std::cout << " • Template parameters enforce signatures" << std::endl;
501     std::cout << " • Compile-time errors for mismatches" << std::endl;
502
503     std::cout << "\n5. MODERN C++ FEATURES" << std::endl;
504     std::cout << " • std::function (C++11)" << std::endl;
505     std::cout << " • Lambda expressions (C++11)" << std::endl;
506     std::cout << " • std::variant (C++17)" << std::endl;
507     std::cout << " • if constexpr (C++17)" << std::endl;
508     std::cout << " • Move semantics" << std::endl;
509
510     std::cout << "\n THINGS TO WATCH OUT FOR:" << std::endl;
511     std::cout << " • Lambda lifetime: Don't capture [&] if object may be
512             destroyed" << std::endl;
513     std::cout << " • std::function has overhead: Consider templates for hot
514             paths" << std::endl;
515     std::cout << " • Circular references: Can cause memory leaks" << std::
516             endl;
517     std::cout << " • Check if std::function is empty before calling" << std
```

```
    ::endl;  
513  
514     std::cout << "\n WHEN TO USE INHERITANCE INSTEAD:" << std::endl;  
515     std::cout << " • Need polymorphic object identity" << std::endl;  
516     std::cout << " • Complex state management" << std::endl;  
517     std::cout << " • Multiple virtual methods needed" << std::endl;  
518     std::cout << " • Performance-critical (avoid std::function overhead)" <<  
         std::endl;  
519  
520     std::cout << "\n  
      =====\n" <<  
      std::endl;  
521  
522     return 0;  
523 }
```

28 Source Code: ExceptionWithSourceLocation.cpp

File: src/ExceptionWithSourceLocation.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <stdexcept>
3 #include <string>
4 #include <sstream>
5 #include <vector>
6 #include <memory>
7
8 // =====
9 // EXCEPTION WITH SOURCE LOCATION TRACKING
10 // =====
11 // Demonstrates how to capture and display source file name and line
12 // number when exceptions are thrown.
13 // Format: "ModuleName->Line #123: Error message"
14 // =====
15
16 // =====
17 // 1. BASIC EXCEPTION WITH SOURCE LOCATION
18 // =====
19
20 class SourceLocationException : public std::runtime_error {
21 private:
22     std::string source_file;
23     int source_line;
24     std::string formatted_message;
25
26     std::string format_message(const std::string& file, int line, const std::string& msg) {
27         // Extract just the filename without path
28         size_t last_slash = file.find_last_of("/\\");
29         std::string filename = (last_slash != std::string::npos)
30             ? file.substr(last_slash + 1)
31             : file;
32
33         std::ostringstream oss;
34         oss << filename << "->Line #" << line << ":" << msg;
35         return oss.str();
36     }
37
38 public:
39     SourceLocationException(const std::string& file, int line, const std::string& message)
40         : std::runtime_error(format_message(file, line, message)),
41           source_file(file),
42           source_line(line),
43           formatted_message(format_message(file, line, message)) {}
44
45     const std::string& get_source_file() const noexcept { return source_file; }
46     int get_source_line() const noexcept { return source_line; }
```

```

47     const char* what() const noexcept override { return formatted_message.
48         c_str(); }
49
50 // Macro to automatically capture __FILE__ and __LINE__
51 #define THROW_WITH_LOCATION(message) \
52     throw SourceLocationException(__FILE__, __LINE__, message)
53
54 void demonstrate_basic_location() {
55     std::cout << "\n== 1. BASIC SOURCE LOCATION TRACKING ==" << std::endl;
56
57     try {
58         std::cout << "\nAbout to throw exception with location..." << std::
59             endl;
60         THROW_WITH_LOCATION("Something went wrong!");
61     }
62     catch (const SourceLocationException& e) {
63         std::cout << "Caught exception: " << e.what() << std::endl;
64         std::cout << "  Source file: " << e.get_source_file() << std::endl;
65         std::cout << "  Source line: " << e.get_source_line() << std::endl;
66     }
67
68 // =====
69 // 2. ENHANCED EXCEPTION WITH FUNCTION NAME
70 // =====
71
72 class DetailedException : public std::runtime_error {
73 private:
74     std::string source_file;
75     int source_line;
76     std::string function_name;
77     std::string error_message;
78     std::string formatted_message;
79
80     std::string format_message() {
81         size_t last_slash = source_file.find_last_of("/\\");
82         std::string filename = (last_slash != std::string::npos)
83             ? source_file.substr(last_slash + 1)
84             : source_file;
85
86         std::ostringstream oss;
87         oss << filename << "->Line #" << source_line;
88         if (!function_name.empty()) {
89             oss << " [" << function_name << "] ";
90         }
91         oss << ": " << error_message;
92         return oss.str();
93     }
94
95 public:
96     DetailedException(const std::string& file, int line, const std::string&
97         function,
98                     const std::string& message)

```

```
98     : std::runtime_error(""),
99     source_file(file),
100    source_line(line),
101    function_name(function),
102    error_message(message) {
103        formatted_message = format_message();
104    }
105
106    const std::string& get_source_file() const noexcept { return source_file;
107    }
108    int get_source_line() const noexcept { return source_line; }
109    const std::string& get_function_name() const noexcept { return
110        function_name; }
111    const char* what() const noexcept override { return formatted_message.
112        c_str(); }
113};
114
115 // Macros for different detail levels
116 #define THROW_DETAILED(message) \
117     throw DetailedException(__FILE__, __LINE__, __FUNCTION__, message)
118
119 #define THROW_DETAILED_CUSTOM(message, function) \
120     throw DetailedException(__FILE__, __LINE__, function, message)
121
122 void some_function_that_fails() {
123     THROW_DETAILED("Failed to process data");
124 }
125
126 void demonstrate_detailed_location() {
127     std::cout << "\n==== 2. DETAILED EXCEPTION WITH FUNCTION NAME ===" << std::endl;
128
129     try {
130         std::cout << "\nCalling function that will throw..." << std::endl;
131         some_function_that_fails();
132     }
133     catch (const DetailedException& e) {
134         std::cout << "Caught exception: " << e.what() << std::endl;
135         std::cout << "Module: " << e.get_source_file() << std::endl;
136         std::cout << "Line: " << e.get_source_line() << std::endl;
137         std::cout << "Function: " << e.get_function_name() << std::endl;
138     }
139 }
140
141 // =====
142 // 3. EXCEPTION HIERARCHY WITH SOURCE LOCATION
143 // =====
144
145 // Base exception with source location
146 class BaseLocationException : public std::runtime_error {
147 protected:
148     std::string source_file;
149     int source_line;
150     std::string function_name;
```

```
148     std::string error_type;
149     std::string error_message;
150
151     std::string format_message() const {
152         size_t last_slash = source_file.find_last_of("//\\");
153         std::string filename = (last_slash != std::string::npos)
154             ? source_file.substr(last_slash + 1)
155             : source_file;
156
157         std::ostringstream oss;
158         oss << "[" << error_type << "] ";
159         oss << filename << "->Line #" << source_line;
160         if (!function_name.empty()) {
161             oss << " in " << function_name << "()";
162         }
163         oss << ": " << error_message;
164         return oss.str();
165     }
166
167 public:
168     BaseLocationException(const std::string& file, int line, const std::string
169         & function,
170                 const std::string& type, const std::string& message)
171     : std::runtime_error(message),
172       source_file(file),
173       source_line(line),
174       function_name(function),
175       error_type(type),
176       error_message(message) {}
177
178     virtual const char* what() const noexcept override {
179         static std::string formatted;
180         formatted = format_message();
181         return formatted.c_str();
182     }
183
184     const std::string& get_source_file() const noexcept { return source_file;
185     }
186     int get_source_line() const noexcept { return source_line; }
187     const std::string& get_function_name() const noexcept { return
188         function_name; }
189     const std::string& get_error_type() const noexcept { return error_type; }
190 };
191
192 // Specific exception types
193 class CameraException : public BaseLocationException {
194 public:
195     CameraException(const std::string& file, int line, const std::string&
196         function,
197                 const std::string& message)
198     : BaseLocationException(file, line, function, "CameraError", message)
199     {}
200 };
```

```
197 class NetworkException : public BaseLocationException {
198 public:
199     NetworkException(const std::string& file, int line, const std::string&
200                     function,
201                         const std::string& message)
202         : BaseLocationException(file, line, function, "NetworkError", message)
203     {}
204 };
205
206 class ValidationException : public BaseLocationException {
207 public:
208     ValidationException(const std::string& file, int line, const std::string&
209                     function,
210                         const std::string& message)
211         : BaseLocationException(file, line, function, "ValidationException",
212                               message) {}
212 };
213
214 // Macros for specific exception types
215 #define THROW_CAMERA_ERROR(message) \
216     throw CameraException(__FILE__, __LINE__, __FUNCTION__, message)
217
218 #define THROW_NETWORK_ERROR(message) \
219     throw NetworkException(__FILE__, __LINE__, __FUNCTION__, message)
220
221 #define THROW_VALIDATION_ERROR(message) \
222     throw ValidationException(__FILE__, __LINE__, __FUNCTION__, message)
223
224 void camera_capture() {
225     THROW_CAMERA_ERROR("Failed to capture image - device not responding");
226 }
227
228 void network_send_data() {
229     THROW_NETWORK_ERROR("Connection timeout after 30 seconds");
230 }
231
232 void validate_input(int value) {
233     if (value < 0) {
234         THROW_VALIDATION_ERROR("Value must be non-negative");
235     }
236 }
237
238 void demonstrate_exception_hierarchy() {
239     std::cout << "\n== 3. EXCEPTION HIERARCHY WITH SOURCE LOCATION ==" <<
240             std::endl;
241
242     // Camera exception
243     try {
244         std::cout << "\nTesting camera exception..." << std::endl;
245         camera_capture();
246     }
247     catch (const CameraException& e) {
248         std::cout << "Caught: " << e.what() << std::endl;
249     }
250 }
```

```
246 // Network exception
247 try {
248     std::cout << "\nTesting network exception..." << std::endl;
249     network_send_data();
250 }
251 catch (const NetworkException& e) {
252     std::cout << "Caught: " << e.what() << std::endl;
253 }
254
255 // Validation exception
256 try {
257     std::cout << "\nTesting validation exception..." << std::endl;
258     validate_input(-5);
259 }
260 catch (const ValidationException& e) {
261     std::cout << "Caught: " << e.what() << std::endl;
262 }
263 }
264
265 // =====
266 // 4. STACK TRACE SIMULATION
267 // =====
268
269 class StackTraceException : public std::runtime_error {
270 private:
271     struct StackFrame {
272         std::string file;
273         int line;
274         std::string function;
275
276         std::string format() const {
277             size_t last_slash = file.find_last_of("/\\");
278             std::string filename = (last_slash != std::string::npos)
279                 ? file.substr(last_slash + 1)
280                 : file;
281             return filename + "->Line #" + std::to_string(line) + " in " +
282                 function + "()";
283         }
284     };
285
286     std::vector<StackFrame> stack_trace;
287     std::string error_message;
288
289     std::string format_full_message() const {
290         std::ostringstream oss;
291         oss << "Exception: " << error_message << "\n";
292         oss << "Stack trace:\n";
293         for (size_t i = 0; i < stack_trace.size(); ++i) {
294             oss << " # " << i << " " << stack_trace[i].format() << "\n";
295         }
296         return oss.str();
297     }
298 }
```

```
299 | public:
300 |     StackTraceException(const std::string& message)
301 |         : std::runtime_error(message), error_message(message) {}
302 |
303 |     void add_frame(const std::string& file, int line, const std::string&
304 |                     function) {
305 |         stack_trace.push_back({file, line, function});
306 |     }
307 |
308 |     const char* what() const noexcept override {
309 |         static std::string formatted;
310 |         formatted = format_full_message();
311 |         return formatted.c_str();
312 |     }
313 |
314 |     const std::vector<StackFrame>& get_stack_trace() const { return
315 |         stack_trace; }
316 |
317 // Macro to add current location to stack trace
318 #define ADD_STACK_FRAME(exception) \
319     exception.add_frame(__FILE__, __LINE__, __FUNCTION__)
320
321 void level3_function() {
322     throw StackTraceException("Critical error in deepest function");
323 }
324
325 void level2_function() {
326     try {
327         level3_function();
328     }
329     catch (StackTraceException& e) {
330         ADD_STACK_FRAME(e);
331         throw; // Rethrow
332     }
333 }
334
335 void level1_function() {
336     try {
337         level2_function();
338     }
339     catch (StackTraceException& e) {
340         ADD_STACK_FRAME(e);
341         throw; // Rethrow
342     }
343 }
344
345 void demonstrate_stack_trace() {
346     std::cout << "\n==== 4. STACK TRACE SIMULATION ===" << std::endl;
347
348     try {
349         std::cout << "\nCalling nested functions..." << std::endl;
350         level1_function();
351     }
```

```
351     catch (const StackTraceException& e) {
352         std::cout << "\nCaught exception with stack trace:" << std::endl;
353         std::cout << e.what() << std::endl;
354     }
355 }
356
357 // =====
358 // 5. C++20 std::source_location (MODERN APPROACH)
359 // =====
360
361 #if __cpp_lib_source_location >= 201907L
362 #include <source_location>
363
364 class ModernLocationException : public std::runtime_error {
365 private:
366     std::source_location location;
367     std::string error_message;
368
369     std::string format_message() const {
370         std::string filename = location.file_name();
371         size_t last_slash = filename.find_last_of("/\\");
372         if (last_slash != std::string::npos) {
373             filename = filename.substr(last_slash + 1);
374         }
375
376         std::ostringstream oss;
377         oss << filename << "->Line #" << location.line()
378             << " in " << location.function_name()
379             << ": " << error_message;
380         return oss.str();
381     }
382
383 public:
384     ModernLocationException(const std::string& message,
385                             std::source_location loc = std::source_location::
386                             current())
386     : std::runtime_error(message),
387       location(loc),
388       error_message(message) {}
389
390     const char* what() const noexcept override {
391         static std::string formatted;
392         formatted = format_message();
393         return formatted.c_str();
394     }
395
396     const std::source_location& get_location() const { return location; }
397 };
398
399 void modern_function_that_fails() {
400     throw ModernLocationException("Modern exception with automatic location
401                                     capture");
402 }
```

```
403 void demonstrate_modern_location() {
404     std::cout << "\n==== 5. C++20 std::source_location ===" << std::endl;
405     std::cout << "Automatic location capture without macros!" << std::endl;
406
407     try {
408         std::cout << "\nThrowing modern exception..." << std::endl;
409         modern_function_that_fails();
410     }
411     catch (const ModernLocationException& e) {
412         std::cout << "Caught: " << e.what() << std::endl;
413         auto loc = e.get_location();
414         std::cout << "    File: " << loc.file_name() << std::endl;
415         std::cout << "    Line: " << loc.line() << std::endl;
416         std::cout << "    Column: " << loc.column() << std::endl;
417         std::cout << "    Function: " << loc.function_name() << std::endl;
418     }
419 }
420 #else
421 void demonstrate_modern_location() {
422     std::cout << "\n==== 5. C++20 std::source_location ===" << std::endl;
423     std::cout << "    std::source_location not available (requires C++20)" <<
424             std::endl;
425     std::cout << "Compiler support needed: GCC 11+, Clang 16+, MSVC 2019+" <<
426             std::endl;
427 }
428 #endif
429 // =====
430 // 6. PRACTICAL EXAMPLE: IMAGE PROCESSING WITH LOCATION TRACKING
431 // =====
432 class ImageProcessingException : public std::runtime_error {
433 private:
434     std::string module;
435     int line;
436     std::string operation;
437     std::string details;
438
439 public:
440     ImageProcessingException(const std::string& file, int ln,
441                             const std::string& op, const std::string& det)
442         : std::runtime_error(""),
443           module(extract_filename(file)),
444           line(ln),
445           operation(op),
446           details(det) {}
447
448     const char* what() const noexcept override {
449         static std::string msg;
450         msg = module + "->Line #" + std::to_string(line) +
451               " [" + operation + "]: " + details;
452         return msg.c_str();
453     }
454 }
```

```
455     static std::string extract_filename(const std::string& path) {
456         size_t pos = path.find_last_of("/\\");
457         return (pos != std::string::npos) ? path.substr(pos + 1) : path;
458     }
459 };
460
461 #define THROW_IMAGE_ERROR(operation, details) \
462     throw ImageProcessingException(__FILE__, __LINE__, operation, details)
463
464 class ImageProcessor {
465 public:
466     void load_image(const std::string& filename) {
467         if (filename.empty()) {
468             THROW_IMAGE_ERROR("LoadImage", "Filename cannot be empty");
469         }
470         // Simulate file not found
471         THROW_IMAGE_ERROR("LoadImage", "File not found: " + filename);
472     }
473
474     void resize_image(int width, int height) {
475         if (width <= 0 || height <= 0) {
476             THROW_IMAGE_ERROR("ResizeImage",
477                               "Invalid dimensions: " + std::to_string(width) + "x" +
478                               std::to_string(height));
479         }
480     }
481
482     void apply_filter(const std::string& filter_name) {
483         std::vector<std::string> valid_filters = {"blur", "sharpen", "edge_detect"};
484         bool found = false;
485         for (const auto& f : valid_filters) {
486             if (f == filter_name) {
487                 found = true;
488                 break;
489             }
490         }
491         if (!found) {
492             THROW_IMAGE_ERROR("ApplyFilter", "Unknown filter: " + filter_name)
493         }
494     }
495
496     void demonstrate_practical_example() {
497         std::cout << "\n==== 6. PRACTICAL EXAMPLE: IMAGE PROCESSING ===" << std::endl;
498
499     ImageProcessor processor;
500
501     // Test 1: Load with empty filename
502     try {
503         std::cout << "\nTest 1: Loading image with empty filename..." << std::endl;
```

```
504     processor.load_image("");
505 }
506 catch (const ImageProcessingException& e) {
507     std::cout << " Error: " << e.what() << std::endl;
508 }
509
510 // Test 2: Invalid resize dimensions
511 try {
512     std::cout << "\nTest 2: Resizing with invalid dimensions..." << std::endl;
513     processor.resize_image(-100, 200);
514 }
515 catch (const ImageProcessingException& e) {
516     std::cout << " Error: " << e.what() << std::endl;
517 }
518
519 // Test 3: Unknown filter
520 try {
521     std::cout << "\nTest 3: Applying unknown filter..." << std::endl;
522     processor.apply_filter("invalid_filter");
523 }
524 catch (const ImageProcessingException& e) {
525     std::cout << " Error: " << e.what() << std::endl;
526 }
527
528 // Test 4: File not found
529 try {
530     std::cout << "\nTest 4: Loading non-existent file..." << std::endl;
531     processor.load_image("nonexistent_image.png");
532 }
533 catch (const ImageProcessingException& e) {
534     std::cout << " Error: " << e.what() << std::endl;
535 }
536 }
537
538 // =====
539 // 7. DEBUGGING HELPER: EXCEPTION LOGGING
540 // =====
541
542 class LoggedException : public std::runtime_error {
543 private:
544     std::string module;
545     int line;
546     std::string function;
547     std::string message;
548
549 public:
550     LoggedException(const std::string& file, int ln, const std::string& func,
551                     const std::string& msg)
552         : std::runtime_error(msg),
553           module(extract_filename(file)),
554           line(ln),
555           function(func),
556           message(msg) {
```

```
557     log_exception();
558 }
559
560 void log_exception() const {
561     std::cerr << "\n"                                     n" << std::endl;
562     std::cerr << " EXCEPTION THROWN" << std::endl;
563     std::cerr << "                                         " << std::endl;
564     std::cerr << " Module:    " << module << std::endl;
565     std::cerr << " Line:      #" << line << std::endl;
566     std::cerr << " Function:   " << function << "()" << std::endl;
567     std::cerr << " Message:    " << message << std::endl;
568     std::cerr << "                                         " << std::endl;
569 }
570
571 const char* what() const noexcept override {
572     static std::string formatted;
573     formatted = module + "->Line #" + std::to_string(line) + ": " +
574         message;
575     return formatted.c_str();
576 }
577
578 static std::string extract_filename(const std::string& path) {
579     size_t pos = path.find_last_of("/\\");
580     return (pos != std::string::npos) ? path.substr(pos + 1) : path;
581 }
582
583 #define THROW_AND_LOG(message) \
584     throw LoggedException(__FILE__, __LINE__, __FUNCTION__, message)
585
586 void function_with_logging() {
587     THROW_AND_LOG("Critical error detected - system state corrupted");
588 }
589
590 void demonstrate_logging() {
591     std::cout << "\n== 7. EXCEPTION LOGGING ==\n" << std::endl;
592
593     try {
594         std::cout << "\nCalling function that logs exception details..." <<
595             std::endl;
596         function_with_logging();
597     }
598     catch (const LoggedException& e) {
599         std::cout << "\nException caught in main handler" << std::endl;
600         std::cout << "Formatted: " << e.what() << std::endl;
601     }
602 }
603 // =====
604 // MAIN FUNCTION
605 // =====
606
607 int main() {
608     std::cout << "\n
```

```
=====
    std::endl;
609 std::cout << "    EXCEPTION SOURCE LOCATION TRACKING" << std::endl;
610 std::cout << "
=====
    std::endl;
611 std::cout << "Format: ModuleName->Line #XXX: Error message" << std::endl;
612
613 demonstrate_basic_location();
614 demonstrate_detailed_location();
615 demonstrate_exception_hierarchy();
616 demonstrate_stack_trace();
617 demonstrate_modern_location();
618 demonstrate_practical_example();
619 demonstrate_logging();
620
621 std::cout << "\n
=====
    std::endl;
622 std::cout << "    IMPLEMENTATION TECHNIQUES" << std::endl;
623 std::cout << "
=====
    std::endl;
624
625 std::cout << "\n1  PREPROCESSOR MACROS (C++11/14/17):" << std::endl;
626 std::cout << "    __FILE__      - Source file path" << std::endl;
627 std::cout << "    __LINE__     - Line number" << std::endl;
628 std::cout << "    __FUNCTION__ - Function name (compiler extension)" << std
       ::endl;
629 std::cout << "\n    Usage:" << std::endl;
630 std::cout << "#define THROW_WITH_LOC(msg) \\\" << std::endl;
631 std::cout << "                  throw MyException(__FILE__, __LINE__, msg)" << std::
       endl;
632
633 std::cout << "\n2  std::source_location (C++20):" << std::endl;
634 std::cout << "    •    Automatic location capture" << std::endl;
635 std::cout << "    •    No macros needed" << std::endl;
636 std::cout << "    •    Default parameter trick" << std::endl;
637 std::cout << "\n    Usage:" << std::endl;
638 std::cout << "          throw MyException(message, std::source_location::current
       ());" << std::endl;
639
640 std::cout << "\n3  CUSTOM EXCEPTION CLASS:" << std::endl;
641 std::cout << "    class MyException : public std::runtime_error {" << std::
       endl;
642 std::cout << "        std::string file;" << std::endl;
643 std::cout << "        int line;" << std::endl;
644 std::cout << "    public:" << std::endl;
645 std::cout << "        MyException(const string& f, int l, const string& msg
       );" << std::endl;
646 std::cout << "        const char* what() const noexcept override;" << std::
       endl;
647 std::cout << "    };" << std::endl;
648
```

```
649 std::cout << "\n4 MESSAGE FORMATTING:" << std::endl;
650 std::cout << "    Format: \"ModuleName->Line #123: Error message\"" << std
       ::endl;
651 std::cout << " • Extract filename from path" << std::endl;
652 std::cout << " • Use std::ostringstream for formatting" << std::endl;
653 std::cout << " • Store formatted message in exception" << std::endl;
654
655 std::cout << "\n"
656     =====<< std::endl;
657 std::cout << "    BEST PRACTICES" << std::endl;
658 std::cout << "
659     =====<< std::endl;
660 std::cout << "\n DO:" << std::endl;
661 std::cout << " • Use macros to automatically capture location" << std::
       endl;
662 std::cout << " • Extract filename only (not full path)" << std::endl;
663 std::cout << " • Include function name for better context" << std::endl;
664 std::cout << " • Format consistently: Module->Line #XXX" << std::endl;
665 std::cout << " • Store location info in exception members" << std::endl;
666 std::cout << " • Use std::source_location in C++20 (no macros!)" << std
       ::endl;
667
668 std::cout << "\n DON'T:" << std::endl;
669 std::cout << " • Don't include full file paths (too verbose)" << std::
       endl;
670 std::cout << " • Don't hardcode file/line (will be wrong)" << std::endl;
671 std::cout << " • Don't forget to extract filename from path" << std::
       endl;
672 std::cout << " • Don't use exceptions for control flow" << std::endl;
673
674 std::cout << "\n COMPARISON:" << std::endl;
675 std::cout << "\nMacro Approach (C++11-17):" << std::endl;
676 std::cout << "    Works with older compilers" << std::endl;
677 std::cout << "    Full control over formatting" << std::endl;
678 std::cout << "    Requires macros (ugly)" << std::endl;
679 std::cout << "    Manual __FILE__, __LINE__ passing" << std::endl;
680
681 std::cout << "\nstd::source_location (C++20):" << std::endl;
682 std::cout << "    No macros needed" << std::endl;
683 std::cout << "    Automatic capture via default parameter" << std::endl;
684 std::cout << "    Type-safe and elegant" << std::endl;
685 std::cout << "    Requires C++20 compiler support" << std::endl;
686
687 std::cout << "\n REAL-WORLD USAGE:" << std::endl;
688 std::cout << "\nDefensive Programming:" << std::endl;
689 std::cout << "    if (!validate(data)) {" << std::endl;
690 std::cout << "        THROW_WITH_LOCATION(\"Invalid data format\");" << std
       ::endl;
691 std::cout << "    }" << std::endl;
692
693 std::cout << "\nResource Management:" << std::endl;
```

```
693     std::cout << "    if (!file.open()) {" << std::endl;
694     std::cout << "        THROW_WITH_LOCATION(\"Failed to open: \\" + filename);
695     std::cout << "    }" << std::endl;
696
697     std::cout << "\nAPI Boundary Checking:" << std::endl;
698     std::cout << "    if (index >= size()) {" << std::endl;
699     std::cout << "        THROW_WITH_LOCATION(\"Index out of range\");" << std
700         ::endl;
701     std::cout << "    }" << std::endl;
702
703     std::cout << "\n
704         ======\n" << std::endl;
705
706     return 0;
707 }
```

29 Source Code: FindCountOfCommonNodes.cpp

File: src/FindCountOfCommonNodes.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <string>
4
5 using namespace std;
6
7 struct ListNode {
8     int val;
9     ListNode *next;
10    ListNode(int x = 0) : val(x), next(NULL) {}
11 };
12
13 class Solution {
14 public:
15     void PrintList(ListNode *pListNode) {
16         if (pListNode != NULL) {
17             cout << pListNode->val << endl;
18             PrintList(pListNode->next);
19         } else {
20             cout << "NULL\n" << endl;
21         }
22     }
23
24     int getLengthOfList(const ListNode *pListNode) {
25         int length = 0;
26
27         while (pListNode != NULL) {
28             pListNode = pListNode->next;
29             length++;
30         }
31
32         return length;
33     }
34
35     int FindNumberOfCommonNodes(ListNode *pHead1, ListNode *pHead2) {
36
37         ListNode* current1 = pHead1;
38         ListNode* current2 = pHead2;
39
40         int count = 0;
41
42         // traverse list A till the end of list
43         while (current1 != NULL) {
44
45             // traverse list B till the end of list
46             while (current2 != NULL) {
47
48                 // if data is match then count increase
49                 if (current1->val == current2->val) {
```

```
50         count++;
51     }
52
53     // increase current pointer for next node
54     current2 = current2->next;
55 }
56
57 // increase current pointer of first list
58 current1 = current1->next;
59
60 // initialize starting point for second list
61 current2 = pHead2;
62 }
63
64 return count;
65 }
66 };
67
68 int main () {
69     Solution testSolution;
70     std::array<int, 12> intArray1 {{1, 3, 4, 6, 7, 10, 12, 13, 14, 15, 16,
71     17}};
72     std::array<int, 10> intArray2 = {2, 4, 5, 6, 7, 8, 11, 13, 14, 16};
73
74     ListNode *pMHead = NULL;
75     ListNode *pCurrent = NULL;
76     ListNode *pNHead = NULL;
77     auto i = 0;
78
79     for (i = 0; i < intArray1.size(); i++) {
80         ListNode *pTemp = new ListNode(intArray1[i]);
81
82         if (i == 0) {
83             pMHead = pCurrent = pTemp;
84         } else {
85             pCurrent->next = pTemp;
86             pCurrent = pCurrent->next; // pCurrent->next == pTemp
87         }
88     }
89
90     for (i = 0; i < intArray2.size(); i++) {
91         ListNode *pTemp = new ListNode(intArray2[i]);
92
93         if (i == 0) {
94             pNHead = pCurrent = pTemp;
95         } else {
96             pCurrent->next = pTemp;
97             pCurrent = pCurrent->next; // pCurrent->next == pTemp
98         }
99
100    // Print Linkedlist
101    cout << "PrintList(pMHead)" << endl;
102    testSolution.PrintList(pMHead);
```

```
103     cout << "PrintList(pNHead)" << endl;
104     testSolution.PrintList(pNHead);
105
106     int commonNodesCount = testSolution.FindNumberOfCommonNodes(pMHead, pNHead
107         );
108
109
110     cout << "commonNodesCount = " << commonNodesCount << endl;
111
112
113     return 0;
114 }
```

30 Source Code: FindFirstCommonNode.cpp

File: src/FindFirstCommonNode.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <string>
4
5 using namespace std;
6
7 struct ListNode {
8     int val;
9     ListNode *next;
10    ListNode(int x = 0) : val(x), next(NULL) {}
11 };
12
13 class Solution {
14 public:
15     void PrintList(ListNode *pListNode) {
16         if (pListNode != NULL) {
17             cout << pListNode->val << endl;
18             PrintList(pListNode->next);
19         } else {
20             cout << "NULL\n" << endl;
21         }
22     }
23
24     int getLengthOfList(const ListNode *pListNode) {
25         int length = 0;
26
27         while (pListNode != NULL) {
28             pListNode = pListNode->next;
29             length++;
30         }
31
32         return length;
33     }
34
35     ListNode* FindFirstCommonNode(ListNode *pHead1, ListNode *pHead2) {
36
37         ListNode* current1 = pHead1;
38         ListNode* current2 = pHead2;
39
40         // traverse list A till the end of list
41         while (current1 != NULL) {
42
43             // traverse list B till the end of list
44             while (current2 != NULL) {
45
46                 // if data is match then count increase
47                 if (current1->val == current2->val) {
48
49                     return current1;
50                 }
51             }
52         }
53     }
54 }
```

```
50     }
51
52         // increase current pointer for next node
53         current2 = current2->next;
54     }
55
56     // increase current pointer of first list
57     current1 = current1->next;
58
59     // initialize starting point for second list
60     current2 = pHead2;
61 }
62 }
63 };
64
65 int main () {
66     Solution testSolution;
67     std::array<int, 12> intArray1 {{1, 3, 4, 6, 7, 10, 12, 13, 14, 15, 16,
68     17}};
69     std::array<int, 10> intArray2 = {2, 4, 5, 6, 7, 8, 11, 13, 14, 16};
70
71     ListNode *pMHead = NULL;
72     ListNode *pCurrent = NULL;
73     ListNode *pNHead = NULL;
74     auto i = 0;
75
76     for (i = 0; i < intArray1.size(); i++) {
77         ListNode *pTemp = new ListNode(intArray1[i]);
78
79         if (i == 0) {
80             pMHead = pCurrent = pTemp;
81         } else {
82             pCurrent->next = pTemp;
83             pCurrent = pCurrent->next; // pCurrent->next == pTemp
84         }
85     }
86
87     for (i = 0; i < intArray2.size(); i++) {
88         ListNode *pTemp = new ListNode(intArray2[i]);
89
90         if (i == 0) {
91             pNHead = pCurrent = pTemp;
92         } else {
93             pCurrent->next = pTemp;
94             pCurrent = pCurrent->next; // pCurrent->next == pTemp
95         }
96
97     // Print Linkedlist
98     cout << "PrintList(pMHead)" << endl;
99     testSolution.PrintList(pMHead);
100
101    cout << "PrintList(pNHead)" << endl;
102    testSolution.PrintList(pNHead);
```

```
103     ListNode *pTarget = testSolution.FindFirstCommonNode(pMHead, pNHead);  
104  
105     // Print Returned Node  
106     if (pTarget != NULL)  
107         cout << "pTarget->val = " << pTarget->val << endl;  
108     cout << endl;  
109  
110     return 0;  
111 }  
112 }
```

31 Source Code: FindMToLastElement.cpp

File: src/FindMToLastElement.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <string>
4
5 using namespace std;
6
7 struct ListNode {
8     int val;
9     ListNode *next;
10    ListNode(int x = 0) : val(x), next(NULL) {}
11 };
12
13 class Solution {
14 public:
15     void PrintList(ListNode *pListNode) {
16         if (pListNode != NULL) {
17             cout << pListNode->val << endl;
18             PrintList(pListNode->next);
19         } else {
20             cout << "NULL\n" << endl;
21         }
22     }
23
24     int getLengthOfList(const ListNode *pListNode) {
25         int length = 0;
26
27         while (pListNode != NULL) {
28             pListNode = pListNode->next;
29             length++;
30         }
31
32         return length;
33     }
34
35     ListNode* FindMthToLastElement(ListNode *pHead1, int valueM) {
36
37         ListNode* current = pHead1;
38
39         // traverse list A till the end of list
40         while (current != NULL) {
41
42             // if data is match then count increase
43             if (current->val == valueM) {
44                 return current;
45             }
46
47             // increase current pointer of first list
48             current = current->next;
49         }
50     }
51 }
```

```
50     }
51
52     return NULL;
53 }
54 };
55
56 int main () {
57     Solution testSolution;
58     std::array<int, 12> intArray1 {{1, 3, 4, 6, 7, 10, 12, 13, 14, 15, 16,
59     17}};
60
61     ListNode *pMHead = NULL;
62     ListNode *pCurrent = NULL;
63     ListNode *pNHead = NULL;
64     auto i = 0;
65
66     for (i = 0; i < intArray1.size(); i++) {
67         ListNode *pTemp = new ListNode(intArray1[i]);
68
69         if (i == 0) {
70             pMHead = pCurrent = pTemp;
71         } else {
72             pCurrent->next = pTemp;
73             pCurrent = pCurrent->next; // pCurrent->next == pTemp
74         }
75
76         // Print Linkedlist
77         cout << "PrintList(pMHead)" << endl;
78         testSolution.PrintList(pMHead);
79
80         int valueOfM = 4;
81
82         ListNode *pTarget = testSolution.FindMthToLastElement(pMHead, valueOfM);
83
84         // Print Returned Node
85         if (pTarget != NULL) {
86             testSolution.PrintList(pMHead);
87         } else {
88             cout << "There is no element that has value equal to " << valueOfM <<
89             endl;
90         }
91
92         valueOfM = 5;
93
94         pTarget = testSolution.FindMthToLastElement(pMHead, valueOfM);
95
96         // Print Returned Node
97         if (pTarget != NULL) {
98             testSolution.PrintList(pMHead);
99         } else {
100            cout << "There is no element that has value equal to " << valueOfM <<
101            endl;
102        }
103    }
104 }
```

```
101  
102  
103     return 0;  
104 }
```

32 Source Code: FindMaxNumberOfConsecutiveOnesFromIntArray.cpp

File: src/FindMaxNumberOfConsecutiveOnesFromIntArray.cpp

Repository: [View on GitHub](#)

```
1  /*
2  Instructions:
3
4  Write a function that returns the maximum number of consecutive 'ones' in an
5      integer array of length N.
6
7  You can assume the input is an array containing integers 0 and 1 only.
8
9  For example, for the following input the function should return 7.
10
11
12 This can be written in pseudo-code, Java, or C/C++. Syntax mistakes are not
13     important.
14 */
15
16 // Example program
17 #include <iostream>
18 #include <string>
19 #include <array>
20 #include <algorithm>
21
22 int main()
23 {
24     int cArray[] =
25         {0,1,0,0,0,1,1,1,1,1,1,1,0,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,1,0};
26
27     const int sizeArray = sizeof(cArray)/sizeof(cArray[0]);
28
29     std::array<int, sizeArray> cppArray;
30
31     std::move(std::begin(cArray), std::end(cArray), cppArray.begin());
32
33     auto maxiConsecutiveOnes = 0;
34     auto runningMaximumOnes= 0;
35
36     for(const auto& i : cppArray) {
37
38         if(i == 1) { // Fixed: use i directly, not cppArray[i]
39             runningMaximumOnes++;
40         } else {
41
42             if(maxiConsecutiveOnes < runningMaximumOnes) {
43                 maxiConsecutiveOnes = runningMaximumOnes;
44             }
45             runningMaximumOnes = 0;
46         }
47     }
48 }
```

```
46
47     std::cout << " maximum consecutive ones = " << maxiConsecutiveOnes << std::
48     endl;
}
```

33 Source Code: FragileBaseClass.cpp

File: src/FragileBaseClass.cpp

Repository: [View on GitHub](#)

```
1 // FragileBaseClass.cpp
2 // Demonstrates the Fragile Base Class Problem in C++ and its solutions
3 //
4 // The Fragile Base Class problem occurs when changes to a base class,
5 // which seem safe in isolation, inadvertently break the functionality
6 // of its derived (child) classes.
7 //
8 // KEY CONCEPTS:
9 // 1. Changes in Method Calls - base class refactoring breaks derived classes
10 // 2. Altering Data Layout - ABI compatibility issues
11 // 3. Virtual Function Overriding - unexpected behavior changes
12 //
13 // SOLUTIONS:
14 // 1. Composition over Inheritance
15 // 2. Hide Implementation Details (Encapsulation)
16 // 3. Use 'final' keyword
17 // 4. Design for Inheritance Explicitly
18 // 5. Prefer Interfaces/Abstract Classes
19
20 #include <iostream>
21 #include <string>
22 #include <vector>
23 #include <memory>
24
25 // =====
26 // SECTION 1: THE PROBLEM - Fragile Base Class
27 // =====
28
29 namespace fragile_example {
30
31 // Version 1: Original base class
32 class Counter_V1 {
33 protected:
34     int count_ = 0;
35
36 public:
37     virtual void add(int value) {
38         count_ += value;
39         std::cout << "    [Base] Added " << value << ", count = " << count_ <<
40             "\n";
41     }
42
43     void addMultiple(const std::vector<int>& values) {
44         for (int val : values) {
45             count_ += val; // Direct implementation
46         }
47     }
48 }
```

```
45     }
46     std::cout << "      [Base] Added multiple values, count = " << count_ <<
47         "\n";
48 }
49 int getCount() const { return count_; }
50 };
51
52 // Derived class works fine with V1
53 class LoggingCounter_V1 : public Counter_V1 {
54 private:
55     std::vector<std::string> log_;
56
57 public:
58     void add(int value) override {
59         log_.push_back("Adding " + std::to_string(value));
60         Counter_V1::add(value);
61     }
62
63     void printLog() const {
64         std::cout << "      Log entries: " << log_.size() << "\n";
65         for (const auto& entry : log_) {
66             std::cout << "      - " << entry << "\n";
67         }
68     }
69 };
70
71 // =====
72 // Now developer "optimizes" the base class by refactoring
73 // =====
74
75 class Counter_V2 {
76 protected:
77     int count_ = 0;
78
79 public:
80     virtual void add(int value) {
81         count_ += value;
82         std::cout << "      [Base] Added " << value << ", count = " << count_ <<
83             "\n";
84     }
85
86     // FRAGILE CHANGE: Refactored to use add() for "code reuse"
87     void addMultiple(const std::vector<int>& values) {
88         for (int val : values) {
89             add(val); // Now calls virtual add()!
90         }
91         std::cout << "      [Base] Added multiple values, count = " << count_ <<
92             "\n";
93     }
94 }
```

```
92     int getCount() const { return count_; }
93 };
94
95 // Same derived class, now BROKEN!
96 class LoggingCounter_V2 : public Counter_V2 {
97 private:
98     std::vector<std::string> log_;
99
100 public:
101     void add(int value) override {
102         log_.push_back("Adding " + std::to_string(value));
103         Counter_V2::add(value);
104     }
105
106     void printLog() const {
107         std::cout << "    Log entries: " << log_.size() << "\n";
108         for (const auto& entry : log_) {
109             std::cout << "        - " << entry << "\n";
110         }
111     }
112 }
113
114 void demonstrate() {
115     std::cout << "\n" << std::string(70, '=') << "\n";
116     std::cout << "==== SECTION 1: The Fragile Base Class Problem ===\n";
117     std::cout << std::string(70, '=') << "\n\n";
118
119     std::cout << "Scenario: Developer refactors base class to call virtual
120         method\n\n";
121
122     std::cout << "1. Original Version (V1) - Works as expected:\n";
123     LoggingCounter_V1 counter1;
124     counter1.addMultiple({1, 2, 3});
125     counter1.printLog();
126     std::cout << "    Expected: No log entries (addMultiple bypasses add())\n";
127     std::cout << "    Actual: " << (counter1.printLog(), " Works!\n");
128
129     std::cout << "\n2. After Refactoring (V2) - BROKEN:\n";
130     LoggingCounter_V2 counter2;
131     counter2.addMultiple({1, 2, 3});
132     counter2.printLog();
133     std::cout << "    Problem: Now creates log entries unexpectedly!\n";
134     std::cout << "    The derived class behavior changed without any
135         modification!\n";
136 }
137 } // namespace fragile_example
138
139 // =====
140 // SECTION 2: SOLUTION 1 - Composition Over Inheritance
141 //
```

```
=====
142
143 namespace composition_solution {
144
145 // Internal implementation (not exposed for inheritance)
146 class CounterImpl {
147 private:
148     int count_ = 0;
149
150 public:
151     void add(int value) {
152         count_ += value;
153     }
154
155     void addMultiple(const std::vector<int>& values) {
156         for (int val : values) {
157             add(val); // Safe - not virtual
158         }
159     }
160
161     int getCount() const { return count_; }
162 };
163
164 // Use composition instead of inheritance
165 class LoggingCounter {
166 private:
167     CounterImpl counter_; // Composition
168     std::vector<std::string> log_;
169
170 public:
171     void add(int value) {
172         log_.push_back("Adding " + std::to_string(value));
173         counter_.add(value);
174     }
175
176     void addMultiple(const std::vector<int>& values) {
177         for (int val : values) {
178             counter_.add(val); // Direct delegation, no logging
179         }
180     }
181
182     int getCount() const { return counter_.getCount(); }
183
184     void printLog() const {
185         std::cout << "    Log entries: " << log_.size() << "\n";
186     }
187 };
188
189 void demonstrate() {
190     std::cout << "\n" << std::string(70, '=') << "\n";
191     std::cout << "==== SECTION 2: Solution 1 - Composition Over Inheritance
192         ===\n";
193     std::cout << std::string(70, '=') << "\n\n";
```

```
193     std::cout << " Using composition - behavior is explicit and controlled\n"
194     ;
195     LoggingCounter counter;
196     counter.add(5);
197     counter.addMultiple({1, 2, 3});
198     std::cout << " Count: " << counter.getCount() << "\n";
199     counter.printLog();
200     std::cout << " Benefit: No fragility - implementation changes don't break
201         us\n";
202 }
203 } // namespace composition_solution
204 //
205 // =====
206 // SECTION 3: SOLUTION 2 - Hide Implementation Details
207 // =====
208
209 namespace encapsulation_solution {
210
211 class Counter {
212 private:
213     int count_ = 0;
214
215     // Private helper - derived classes cannot rely on this
216     void incrementInternal(int value) {
217         count_ += value;
218     }
219
220 protected:
221     // Protected interface for derived classes
222     void setCount(int value) { count_ = value; }
223     int getCountInternal() const { return count_; }
224
225 public:
226     virtual void add(int value) {
227         incrementInternal(value);
228     }
229
230     // Non-virtual - cannot be overridden
231     void addMultiple(const std::vector<int>& values) {
232         for (int val : values) {
233             incrementInternal(val); // Calls private method
234         }
235     }
236
237     int getCount() const { return count_; }
238 };
239
240 class LoggingCounter : public Counter {
```

```
241 | private:
242 |     std::vector<std::string> log_;
243 |
244 | public:
245 |     void add(int value) override {
246 |         log_.push_back("Adding " + std::to_string(value));
247 |         Counter::add(value);
248 |     }
249 |
250 |     void printLog() const {
251 |         std::cout << "    Log entries: " << log_.size() << "\n";
252 |     }
253 };
254 |
255 | void demonstrate() {
256 |     std::cout << "\n" << std::string(70, '=') << "\n";
257 |     std::cout << "==== SECTION 3: Solution 2 - Hide Implementation Details ===\
258 |             n";
259 |     std::cout << std::string(70, '=') << "\n\n";
260 |
261 |     std::cout << "  Private implementation, public/protected interface only\n"
262 |             ;
263 |     LoggingCounter counter;
264 |     counter.add(5);
265 |     counter.addMultiple({1, 2, 3});
266 |     std::cout << "  Count: " << counter.getCount() << "\n";
267 |     counter.printLog();
268 |     std::cout << "  Benefit: addMultiple() is non-virtual and uses private
269 |             method\n";
270 |
271 }
272 |
273 } // namespace encapsulation_solution
274 //
275 =====
276 // SECTION 4: SOLUTION 3 - Use 'final' Keyword
277 //
278 =====
```



```
274
275 namespace final_solution {
276
277 // Concrete class marked as final - cannot be inherited
278 class Counter final {
279 private:
280     int count_ = 0;
281
282 public:
283     void add(int value) {
284         count_ += value;
285     }
286
287     void addMultiple(const std::vector<int>& values) {
```

```
288     for (int val : values) {
289         add(val);
290     }
291 }
292
293     int getCount() const { return count_; }
294 };
295
296 // Base class with final methods
297 class ExtensibleCounter {
298 protected:
299     int count_ = 0;
300
301 public:
302     virtual ~ExtensibleCounter() = default;
303
304     // This method can be overridden
305     virtual void add(int value) {
306         count_ += value;
307     }
308
309     // This method CANNOT be overridden - marked final
310     virtual void addMultiple(const std::vector<int>& values) final {
311         for (int val : values) {
312             add(val);
313         }
314     }
315
316     int getCount() const { return count_; }
317 };
318
319 class LoggingCounter : public ExtensibleCounter {
320 private:
321     std::vector<std::string> log_;
322
323 public:
324     void add(int value) override {
325         log_.push_back("Adding " + std::to_string(value));
326         ExtensibleCounter::add(value);
327     }
328
329     // Cannot override addMultiple() - it's final
330     // void addMultiple(...) {} // ERROR!
331
332     void printLog() const {
333         std::cout << "    Log entries: " << log_.size() << "\n";
334     }
335 };
336
337 void demonstrate() {
338     std::cout << "\n" << std::string(70, '=') << "\n";
339     std::cout << "==== SECTION 4: Solution 3 - Use 'final' Keyword ===\n";
340     std::cout << std::string(70, '=') << "\n\n";
```

```
342     std::cout << " Using 'final' to prevent inheritance or method override\n\
343         n";
344
345     std::cout << "1. Final class (Counter) - cannot be inherited\n";
346     Counter counter1;
347     counter1.add(5);
348     std::cout << "    Count: " << counter1.getCount() << "\n";
349     // class Derived : public Counter { }; // ERROR: cannot inherit from final
350     // class
351
352     std::cout << "\n2. Final method (addMultiple) - cannot be overridden\n";
353     LoggingCounter counter2;
354     counter2.add(5);
355     counter2.addMultiple({1, 2, 3});
356     std::cout << "    Count: " << counter2.getCount() << "\n";
357     counter2.printLog();
358     std::cout << "    Benefit: Base class controls critical behavior\n";
359 }
360
361 // =====
362 // SECTION 5: SOLUTION 4 - Template Method Pattern
363 // =====
364
365 namespace template_method_solution {
366
367 // Base class designed for inheritance with clear extension points
368 class Counter {
369 protected:
370     int count_ = 0;
371
372     // Hook for derived classes - well-documented extension point
373     virtual void onBeforeAdd([[maybe_unused]] int value) {
374         // Default: do nothing
375     }
376
377     virtual void onAfterAdd([[maybe_unused]] int value) {
378         // Default: do nothing
379     }
380
381 private:
382     // Template method - defines the algorithm structure
383     void addImpl(int value) {
384         onBeforeAdd(value);
385         count_ += value;
386         onAfterAdd(value);
387     }
388
389 public:
```

```
390     virtual ~Counter() = default;
391
392     // Public interface - calls template method
393     void add(int value) {
394         addImpl(value);
395     }
396
397     // Non-virtual - uses template method internally
398     virtual void addMultiple(const std::vector<int>& values) final {
399         for (int val : values) {
400             addImpl(val); // Each add goes through hooks
401         }
402     }
403
404     int getCount() const { return count_; }
405 };
406
407 class LoggingCounter : public Counter {
408 private:
409     std::vector<std::string> log_;
410
411 protected:
412     void onBeforeAdd(int value) override {
413         log_.push_back("Adding " + std::to_string(value));
414     }
415
416 public:
417     void printLog() const {
418         std::cout << "      Log entries: " << log_.size() << "\n";
419     }
420 };
421
422 void demonstrate() {
423     std::cout << "\n" << std::string(70, '=') << "\n";
424     std::cout << "==== SECTION 5: Solution 4 - Template Method Pattern ===\n";
425     std::cout << std::string(70, '=') << "\n\n";
426
427     std::cout << " Clear extension points with template method pattern\n";
428     LoggingCounter counter;
429     counter.add(5);
430     counter.addMultiple({1, 2, 3});
431     std::cout << " Count: " << counter.getCount() << "\n";
432     counter.printLog();
433     std::cout << " Benefit: Hooks are called for both add() and addMultiple()
434                 \n";
435     std::cout << " Base class controls algorithm, derived class controls
436                 hooks\n";
437 }
438
439 } // namespace template_method_solution
440
441 =====
```

```
440 // SECTION 6: SOLUTION 5 - Prefer Interfaces (Pure Abstract Classes)
441 //
442 =====
443
443 namespace interface_solution {
444
445 // Pure interface - no implementation details to break
446 class ICounter {
447 public:
448     virtual ~ICounter() = default;
449     virtual void add(int value) = 0;
450     virtual void addMultiple(const std::vector<int>& values) = 0;
451     virtual int getCount() const = 0;
452 };
453
454 // Concrete implementation
455 class BasicCounter : public ICounter {
456 private:
457     int count_ = 0;
458
459 public:
460     void add(int value) override {
461         count_ += value;
462     }
463
464     void addMultiple(const std::vector<int>& values) override {
465         for (int val : values) {
466             count_ += val; // Direct implementation
467         }
468     }
469
470     int getCount() const override { return count_; }
471 };
472
473 // Logging decorator using composition
474 class LoggingCounter : public ICounter {
475 private:
476     std::unique_ptr<ICounter> wrapped_;
477     std::vector<std::string> log_;
478
479 public:
480     explicit LoggingCounter(std::unique_ptr<ICounter> counter)
481         : wrapped_(std::move(counter)) {}
482
483     void add(int value) override {
484         log_.push_back("Adding " + std::to_string(value));
485         wrapped_->add(value);
486     }
487
488     void addMultiple(const std::vector<int>& values) override {
489         // No logging for batch operations
490         wrapped_->addMultiple(values);
491     }
}
```

```
492     int getCount() const override { return wrapped_->getCount(); }
493
494     void printLog() const {
495         std::cout << "    Log entries: " << log_.size() << "\n";
496     }
497 }
498
499
500 void demonstrate() {
501     std::cout << "\n" << std::string(70, '=') << "\n";
502     std::cout << "==== SECTION 6: Solution 5 - Prefer Interfaces ===\n";
503     std::cout << std::string(70, '=') << "\n\n";
504
505     std::cout << "  Pure interface + composition (Decorator pattern)\n";
506     auto counter = std::make_unique<LoggingCounter>(
507         std::make_unique<BasicCounter>()
508     );
509     counter->add(5);
510     counter->addMultiple({1, 2, 3});
511     std::cout << "  Count: " << counter->getCount() << "\n";
512     counter->printLog();
513     std::cout << "  Benefit: No implementation inheritance - no fragility\n";
514 }
515
516 } // namespace interface_solution
517
518 /**
=====
519 // SECTION 7: ABI Stability Example
520 /**
=====

521
522 namespace abi_example {
523
524 // Version 1: Library shipped to customers
525 struct Device_V1 {
526     int id;
527     std::string name;
528
529     virtual ~Device_V1() = default;
530     virtual void process() { std::cout << "    Processing " << name << "\n"; }
531 };
532
533 struct Sensor_V1 : public Device_V1 {
534     double reading;
535
536     void process() override {
537         std::cout << "    Sensor " << name << " reading: " << reading << "\n";
538     }
539 };
540
541 // Version 2: Developer adds a field (BREAKS ABI)
```

```
542 struct Device_V2 {
543     int id;
544     std::string name;
545     bool enabled; // NEW FIELD - changes memory layout!
546
547     virtual ~Device_V2() = default;
548     virtual void process() {
549         if (enabled) std::cout << "    Processing " << name << "\n";
550     }
551 };
552
553 // Customer code (compiled against V1) now has wrong offsets!
554
555 void demonstrate() {
556     std::cout << "\n" << std::string(70, '=') << "\n";
557     std::cout << "==== SECTION 7: ABI Stability and Memory Layout ===\n";
558     std::cout << std::string(70, '=') << "\n\n";
559
560     std::cout << "Problem: Adding fields to base class changes memory layout\n"
561         "\n";
562
563     std::cout << "Device_V1 layout:\n";
564     Device_V1 d1;
565     d1.id = 1;
566     d1.name = "Device1";
567     std::cout << "    sizeof(Device_V1) = " << sizeof(Device_V1) << " bytes\n";
568     std::cout << "    &id offset = " << (void*)&d1.id << "\n";
569     std::cout << "    &name offset = " << (void*)&d1.name << "\n";
570
571     std::cout << "\nSensor_V1 (derived) layout:\n";
572     Sensor_V1 s1;
573     s1.id = 2;
574     s1.name = "Sensor1";
575     s1.reading = 42.5;
576     std::cout << "    sizeof(Sensor_V1) = " << sizeof(Sensor_V1) << " bytes\n";
577     std::cout << "    &reading offset = " << (void*)&s1.reading << "\n";
578
579     std::cout << "\nDevice_V2 layout (after adding 'enabled' field):\n";
580     Device_V2 d2;
581     std::cout << "    sizeof(Device_V2) = " << sizeof(Device_V2) << " bytes\n";
582     std::cout << "    Problem: All derived class member offsets have shifted!\n"
583         ;
584     std::cout << "    Solution: Never add non-static data members to base
585         classes\n";
586     std::cout << "                Use Pimpl idiom or version interfaces\n";
587 }
588
589 } // namespace abi_example
590
591 // =====
592
593 // SECTION 8: Best Practices Summary
594 //
```

```
=====
591 void show_best_practices() {
592     std::cout << "\n" << std::string(70, '=') << "\n";
593     std::cout << "==== Best Practices to Avoid Fragile Base Class ===\n";
594     std::cout << std::string(70, '=') << "\n\n";
595
596     std::cout << "1. PREFER COMPOSITION OVER INHERITANCE\n";
597     std::cout << "    Use 'has-a' instead of 'is-a' when possible\n";
598     std::cout << "    Decouple implementation details\n";
599     std::cout << "    More flexible and testable\n\n";
600
601     std::cout << "2. DESIGN FOR INHERITANCE OR PROHIBIT IT\n";
602     std::cout << "    Make classes 'final' by default\n";
603     std::cout << "    Only allow inheritance for classes explicitly designed
604         for it\n";
605     std::cout << "    Document extension points clearly\n\n";
606
607     std::cout << "3. USE THE 'final' KEYWORD\n";
608     std::cout << "    Mark concrete classes as 'final'\n";
609     std::cout << "    Mark critical methods as 'final' to prevent override\n";
610     ;
611     std::cout << "    Prevents accidental misuse\n\n";
612
613     std::cout << "4. HIDE IMPLEMENTATION DETAILS\n";
614     std::cout << "    Make data members private\n";
615     std::cout << "    Use private helper methods\n";
616     std::cout << "    Expose minimal protected interface\n\n";
617
618     std::cout << "5. PREFER INTERFACES (PURE ABSTRACT CLASSES)\n";
619     std::cout << "    Define contracts, not implementations\n";
620     std::cout << "    Use composition + decorator pattern\n";
621     std::cout << "    Eliminates implementation inheritance fragility\n\n";
622
623     std::cout << "6. USE TEMPLATE METHOD PATTERN\n";
624     std::cout << "    Base class controls algorithm structure\n";
625     std::cout << "    Derived classes override hooks only\n";
626     std::cout << "    Clear extension points\n\n";
627
628     std::cout << "7. FOR LIBRARY DEVELOPERS - MAINTAIN ABI STABILITY\n";
629     std::cout << "    Never add non-static data members to base classes\n";
630     std::cout << "    Use Pimpl idiom for implementation hiding\n";
631     std::cout << "    Version your interfaces\n\n";
632
633     std::cout << "REMEMBER: \"Prefer composition over inheritance\" - Gang of
634         Four\n";
635 }
636
637 // MAIN FUNCTION
638 //=====
```

```
=====
638 int main() {
639     std::cout << "\n";
640     std::cout << "
641                     \n";
642     std::cout << "      Fragile Base Class Problem in C++ and Solutions
643                     \n";
644     std::cout << "
645                     \n";
646     // Demonstrate the problem
647     fragile_example::demonstrate();
648
649     // Show solutions
650     composition_solution::demonstrate();
651     encapsulation_solution::demonstrate();
652     final_solution::demonstrate();
653     template_method_solution::demonstrate();
654     interface_solution::demonstrate();
655
656     // ABI considerations
657     abi_example::demonstrate();
658
659     // Best practices
660     show_best_practices();
661
662     std::cout << "\n" << std::string(70, '=') << "\n";
663     std::cout << "All demonstrations completed!\n";
664     std::cout << std::string(70, '=') << "\n\n";
665
666     return 0;
667 }
```

34 Source Code: FunctionalSafetyISO26262.cpp

File: src/FunctionalSafetyISO26262.cpp

Repository: [View on GitHub](#)

```
1 // FunctionalSafetyISO26262.cpp
2 // Comprehensive demonstration of ISO 26262 Functional Safety principles in
3 // Modern C++
4 // Covers ASIL levels, MISRA C++, redundancy, watchdogs, safe data types, and
5 // deterministic patterns
6
7 #include <iostream>
8 #include <cstdint>
9 #include <array>
10 #include <limits>
11 #include <chrono>
12 #include <functional>
13 #include <algorithm>
14 #include <cstring>
15
16 // SECTION 1: ASIL Levels and Safety Requirements
17 // ISO 26262 defines 4 Automotive Safety Integrity Levels (ASIL A-D)
18 // ASIL D = highest safety requirements (e.g., braking systems)
19 // ASIL A = lowest safety requirements (e.g., rear lights)
20
21 enum class ASILLevel : uint8_t {
22     QM = 0,    // Quality Management (no ASIL)
23     A = 1,     // Lowest safety integrity
24     B = 2,
25     C = 3,
26     D = 4     // Highest safety integrity
27 };
28
29 // Safety state for system degradation
30 enum class SafetyState : uint8_t {
31     NORMAL_OPERATION = 0,
32     DEGRADED_MODE = 1,
33     SAFE_STATE = 2,
34     EMERGENCY_STOP = 3
35 };
36
37 // Safety-critical function return type (no exceptions!)
38 enum class SafetyResult : uint8_t {
39     OK = 0,
40     WARNING = 1,
41     ERROR = 2,
42     CRITICAL_FAILURE = 3
43 };
```

```
44 void demonstrate_asil_levels() {
45     std::cout << "\n==== 1. ASIL Levels and Safety Requirements ===\n";
46
47     struct SafetyRequirement {
48         const char* component;
49         ASILLevel asil;
50         const char* requirement;
51     };
52
53
54     constexpr std::array<SafetyRequirement, 5> requirements = {{
55         {"Brake-by-wire", ASILLevel::D, "Dual redundancy + voting"}, 
56         {"Electric power steering", ASILLevel::C, "Plausibility checks + 
57             monitoring"}, 
58         {"Airbag control", ASILLevel::D, "Watchdog + memory protection"}, 
59         {"Engine control", ASILLevel::B, "Runtime checks + diagnostics"}, 
60         {"Interior lighting", ASILLevel::QM, "Basic error handling"} 
61     }};
62
63     std::cout << "\nASIL Classification Examples:\n";
64     for (const auto& req : requirements) {
65         std::cout << "    " << req.component << " [ASIL-";
66         switch (req.asil) {
67             case ASILLevel::QM: std::cout << "QM"; break;
68             case ASILLevel::A: std::cout << "A"; break;
69             case ASILLevel::B: std::cout << "B"; break;
70             case ASILLevel::C: std::cout << "C"; break;
71             case ASILLevel::D: std::cout << "D"; break;
72         }
73         std::cout << "] : " << req.requirement << "\n";
74     }
75
76     std::cout << "\nKey ISO 26262 Principles:\n";
77     std::cout << "    No dynamic memory allocation in safety functions\n";
78     std::cout << "    No exceptions in safety-critical paths (use error codes)
79         \n";
80     std::cout << "    Deterministic timing (WCET - Worst Case Execution Time)\n";
81     std::cout << "    Redundancy and voting for ASIL-D\n";
82     std::cout << "    Comprehensive diagnostics and fault detection\n";
83 }
84
85 // SECTION 2: Safe Data Types with Overflow Protection
86 // =====
87
88 // MISRA C++ requires explicit bounds checking and overflow protection
89
90 template<typename T>
91 class SafeInteger {
92 private:
```

```
91     T value_;
92     bool valid_;
93
94 public:
95     constexpr SafeInteger() noexcept : value_(0), valid_(true) {}
96     constexpr explicit SafeInteger(T val) noexcept : value_(val), valid_(true)
97         {}
98
99     // Safe addition with overflow detection
100    SafeInteger add(T other) const noexcept {
101        SafeInteger result;
102
103        // Check for overflow before operation (MISRA requirement)
104        if (other > 0 && value_ > std::numeric_limits<T>::max() - other) {
105            result.valid_ = false; // Overflow detected
106            result.value_ = std::numeric_limits<T>::max();
107        } else if (other < 0 && value_ < std::numeric_limits<T>::min() - other)
108            {
109                result.valid_ = false; // Underflow detected
110                result.value_ = std::numeric_limits<T>::min();
111            } else {
112                result.value_ = value_ + other;
113                result.valid_ = true;
114            }
115
116        return result;
117    }
118
119    // Safe multiplication with overflow detection
120    SafeInteger multiply(T other) const noexcept {
121        SafeInteger result;
122
123        if (other == 0 || value_ == 0) {
124            result.value_ = 0;
125            result.valid_ = true;
126        } else if (value_ > std::numeric_limits<T>::max() / other) {
127            result.valid_ = false; // Overflow
128            result.value_ = std::numeric_limits<T>::max();
129        } else {
130            result.value_ = value_ * other;
131            result.valid_ = true;
132        }
133
134        return result;
135    }
136
137    constexpr T get() const noexcept { return value_; }
138    constexpr bool is_valid() const noexcept { return valid_; }
139};
140
141 void demonstrate_safe_data_types() {
142     std::cout << "\n== 2. Safe Data Types with Overflow Protection ===\n";
143
144     SafeInteger<int32_t> speed(100);
```

```
143     SafeInteger<int32_t> delta(50);
144
145     auto new_speed = speed.add(delta.get());
146     std::cout << "\nSafe Addition: 100 + 50 = " << new_speed.get()
147             << " (valid: " << (new_speed.is_valid() ? "" : "") << ")\n";
148
149     // Demonstrate overflow detection
150     SafeInteger<int32_t> large_val(std::numeric_limits<int32_t>::max() - 10);
151     auto overflow_result = large_val.add(100);
152     std::cout << "\nOverflow Detection: MAX-10 + 100 = " << overflow_result.
153             get()
154             << " (valid: " << (overflow_result.is_valid() ? "" : " OVERFLOW
155                 DETECTED") << ")\n";
156
157     std::cout << "\nMISRA C++ Guidelines:\n";
158     std::cout << "    All arithmetic checked for overflow/underflow\n";
159     std::cout << "    Explicit error flags instead of exceptions\n";
160     std::cout << "    constexpr for compile-time safety verification\n";
161     std::cout << "    noexcept guarantees for safety-critical functions\n";
162 }
163
164 // =====
165 // SECTION 3: Redundancy and Voting Mechanisms (ASIL-D Requirement)
166 // =====
167
168 // Dual-channel or triple-modular redundancy for critical computations
169
170 template<typename T>
171 class DualChannelComputation {
172 private:
173     std::function<T()> channel1_;
174     std::function<T()> channel2_;
175     T tolerance_;
176
177 public:
178     DualChannelComputation(std::function<T()> ch1, std::function<T()> ch2, T
179                           tol) noexcept
180         : channel1_(ch1), channel2_(ch2), tolerance_(tol) {}
181
182     // Execute both channels and compare results
183     SafetyResult compute(T& result) noexcept {
184         T result1 = channel1_();
185         T result2 = channel2_();
186
187         // Calculate absolute difference
188         T diff = (result1 > result2) ? (result1 - result2) : (result2 -
189             result1);
190
191         if (diff <= tolerance_) {
192             // Results agree within tolerance
193             result = (result1 + result2) / 2; // Use average
194         }
195     }
196 }
```

```
189         return SafetyResult::OK;
190     } else {
191         // Mismatch detected - critical failure
192         result = 0; // Safe default
193         return SafetyResult::CRITICAL_FAILURE;
194     }
195 }
196 };
197
198 // Triple Modular Redundancy (TMR) with voting
199 template<typename T>
200 class TripleModularRedundancy {
201 private:
202     std::array<std::function<T()>, 3> channels_;
203     T tolerance_;
204
205 public:
206     TripleModularRedundancy(std::function<T()> ch1, std::function<T()> ch2,
207                             std::function<T()> ch3, T tol) noexcept
208         : channels_{ch1, ch2, ch3}, tolerance_(tol) {}
209
210     // 2-out-of-3 voting
211     SafetyResult compute(T& result) noexcept {
212         std::array<T, 3> results;
213         for (size_t i = 0; i < 3; ++i) {
214             results[i] = channels_[i]();
215         }
216
217         // Check if any two results agree within tolerance
218         for (size_t i = 0; i < 3; ++i) {
219             for (size_t j = i + 1; j < 3; ++j) {
220                 T diff = (results[i] > results[j]) ?
221                         (results[i] - results[j]) : (results[j] - results[i]);
222
223                 if (diff <= tolerance_) {
224                     // Two channels agree
225                     result = (results[i] + results[j]) / 2;
226                     return (i == 2 || j == 2) ? SafetyResult::WARNING :
227                         SafetyResult::OK;
228                 }
229             }
230
231         // No agreement - critical failure
232         result = 0;
233         return SafetyResult::CRITICAL_FAILURE;
234     }
235 };
236
237 void demonstrate_redundancy_voting() {
238     std::cout << "\n== 3. Redundancy and Voting Mechanisms ==\n";
239
240     // Simulate brake pressure sensor readings
```

```

241     auto sensor_channel_1 = []() -> int32_t { return 850; }; // 850 kPa
242     auto sensor_channel_2 = []() -> int32_t { return 852; }; // 852 kPa (
243         slight variation)
244
245     DualChannelComputation<int32_t> brake_pressure(sensor_channel_1,
246             sensor_channel_2, 5);
247
248     int32_t pressure = 0;
249     SafetyResult status = brake_pressure.compute(pressure);
250
251     std::cout << "\nDual-Channel Brake Pressure Sensor:\n";
252     std::cout << "    Channel 1: 850 kPa\n";
253     std::cout << "    Channel 2: 852 kPa\n";
254     std::cout << "    Result: " << pressure << " kPa (avg)\n";
255     std::cout << "    Status: " << (status == SafetyResult::OK ? " OK" : "
256         FAILURE") << "\n";
257
258     // Triple modular redundancy example
259     auto tmr_ch1 = []() -> int32_t { return 100; };
260     auto tmr_ch2 = []() -> int32_t { return 101; };
261     auto tmr_ch3 = []() -> int32_t { return 99; }; // All agree within
262         tolerance
263
264     TripleModularRedundancy<int32_t> steering_angle(tmr_ch1, tmr_ch2, tmr_ch3,
265             5);
266
267     int32_t angle = 0;
268     SafetyResult tmr_status = steering_angle.compute(angle);
269
270     std::cout << "\nTriple Modular Redundancy (Steering Angle):\n";
271     std::cout << "    Channel 1: 100°\n";
272     std::cout << "    Channel 2: 101°\n";
273     std::cout << "    Channel 3: 99°\n";
274     std::cout << "    Voted Result: " << angle << "°\n";
275     std::cout << "    Status: " << (tmr_status == SafetyResult::OK ? " OK (2-of
276         -3 agree)" : " FAILURE") << "\n";
277
278     std::cout << "\nRedundancy Patterns:\n";
279     std::cout << "    Dual-channel for ASIL-C/D\n";
280     std::cout << "    Triple modular redundancy (TMR) for highest safety\n";
281     std::cout << "    2-out-of-3 voting tolerates single-point failures\n";
282     std::cout << "    Tolerance bands for real-world sensor variations\n";
283
284 }
285
286 // SECTION 4: Watchdog Timer and Heartbeat Monitoring
287 //
288 =====
289
290 // Detect software hangs and stuck states
291
292 =====
293
294 class WatchdogTimer {

```

```
285 | private:
286 |     uint32_t timeout_ms_;
287 |     uint32_t last_kick_time_;
288 |     bool expired_;
289 |
290 | public:
291 |     explicit WatchdogTimer(uint32_t timeout_ms) noexcept
292 |         : timeout_ms_(timeout_ms), last_kick_time_(0), expired_(false) {}
293 |
294 |     // Kick the watchdog (reset timer)
295 |     void kick(uint32_t current_time_ms) noexcept {
296 |         last_kick_time_ = current_time_ms;
297 |         expired_ = false;
298 |     }
299 |
300 |     // Check if watchdog expired
301 |     bool check_expired(uint32_t current_time_ms) noexcept {
302 |         if (current_time_ms - last_kick_time_ > timeout_ms_) {
303 |             expired_ = true;
304 |         }
305 |         return expired_;
306 |     }
307 |
308 |     bool is_expired() const noexcept { return expired_; }
309 | };
310 |
311 | class SafetyMonitor {
312 | private:
313 |     WatchdogTimer watchdog_;
314 |     uint32_t heartbeat_count_;
315 |     SafetyState state_;
316 |
317 | public:
318 |     explicit SafetyMonitor(uint32_t watchdog_timeout) noexcept
319 |         : watchdog_(watchdog_timeout), heartbeat_count_(0), state_(SafetyState
320 |             ::NORMAL_OPERATION) {}
321 |
322 |     void heartbeat(uint32_t current_time) noexcept {
323 |         watchdog_.kick(current_time);
324 |         ++heartbeat_count_;
325 |     }
326 |
327 |     SafetyResult check_safety(uint32_t current_time) noexcept {
328 |         if (watchdog_.check_expired(current_time)) {
329 |             state_ = SafetyState::EMERGENCY_STOP;
330 |             return SafetyResult::CRITICAL_FAILURE;
331 |         }
332 |         return SafetyResult::OK;
333 |     }
334 |
335 |     SafetyState get_state() const noexcept { return state_; }
336 |     uint32_t get_heartbeat_count() const noexcept { return heartbeat_count_; }
337 | };
```

```
338 void demonstrate_watchdog_monitoring() {
339     std::cout << "\n==== 4. Watchdog Timer and Heartbeat Monitoring ===\n";
340
341     SafetyMonitor monitor(100); // 100ms timeout
342
343     std::cout << "\nNormal Operation:\n";
344     for (uint32_t time = 0; time <= 250; time += 50) {
345         monitor.heartbeat(time);
346         SafetyResult status = monitor.check_safety(time);
347         std::cout << " Time " << time << "ms: Heartbeat #" << monitor.
348             get_heartbeat_count()
349             << " - Status: " << (status == SafetyResult::OK ? " OK" : "
350                 FAILURE") << "\n";
351
352     // Simulate watchdog expiration (no heartbeat for >100ms)
353     std::cout << "\nSimulating Watchdog Timeout (no heartbeat):\n";
354     SafetyMonitor timeout_monitor(100);
355     timeout_monitor.heartbeat(0);
356
356     for (uint32_t time = 50; time <= 200; time += 50) {
357         // Skip heartbeat to simulate hang
358         SafetyResult status = timeout_monitor.check_safety(time);
359         std::cout << " Time " << time << "ms: ";
360         if (status == SafetyResult::CRITICAL_FAILURE) {
361             std::cout << " WATCHDOG EXPIRED - EMERGENCY STOP\n";
362             break;
363         } else {
364             std::cout << " OK\n";
365         }
366     }
367
368     std::cout << "\nWatchdog Best Practices:\n";
369     std::cout << "    Timeout based on WCET (Worst Case Execution Time)\n";
370     std::cout << "    Hardware watchdog preferred for fail-safe\n";
371     std::cout << "    Heartbeat every control cycle\n";
372     std::cout << "    Transition to safe state on expiration\n";
373 }
374
375 // =====
376 // SECTION 5: Memory Safety and Bounds Checking
377 // =====
378 // MISRA C++ requires explicit bounds checking, no buffer overruns
379
380 template<typename T, size_t N>
381 class SafeArray {
382 private:
383     std::array<T, N> data_;
384
385 public:
```

```
386 constexpr SafeArray() noexcept : data_{} {}
387
388 // Safe access with bounds checking (no exceptions!)
389 SafetyResult get(size_t index, T& value) const noexcept {
390     if (index >= N) {
391         return SafetyResult::ERROR;
392     }
393     value = data_[index];
394     return SafetyResult::OK;
395 }
396
397 SafetyResult set(size_t index, T value) noexcept {
398     if (index >= N) {
399         return SafetyResult::ERROR;
400     }
401     data_[index] = value;
402     return SafetyResult::OK;
403 }
404
405 constexpr size_t size() const noexcept { return N; }
406
407 // Safe iteration
408 T* begin() noexcept { return data_.data(); }
409 T* end() noexcept { return data_.data() + N; }
410 const T* begin() const noexcept { return data_.data(); }
411 const T* end() const noexcept { return data_.data() + N; }
412 };
413
414 // Safe string operations (fixed-size, no dynamic allocation)
415 template<size_t N>
416 class SafeString {
417 private:
418     std::array<char, N> buffer_;
419     size_t length_;
420
421 public:
422     constexpr SafeString() noexcept : buffer_{}, length_(0) {
423         buffer_[0] = '\0';
424     }
425
426     SafetyResult copy_from(const char* src) noexcept {
427         if (src == nullptr) {
428             return SafetyResult::ERROR;
429         }
430
431         size_t i = 0;
432         while (i < N - 1 && src[i] != '\0') {
433             buffer_[i] = src[i];
434             ++i;
435         }
436         buffer_[i] = '\0';
437         length_ = i;
438
439         return (src[i] == '\0') ? SafetyResult::OK : SafetyResult::WARNING;
440     }
441 }
```

```
        // Truncated
440 }
441
442 SafetyResult append(const char* src) noexcept {
443     if (src == nullptr) {
444         return SafetyResult::ERROR;
445     }
446
447     size_t i = 0;
448     while (length_ < N - 1 && src[i] != '\0') {
449         buffer_[length_++] = src[i++];
450     }
451     buffer_[length_] = '\0';
452
453     return (src[i] == '\0') ? SafetyResult::OK : SafetyResult::WARNING;
454 }
455
456 const char* c_str() const noexcept { return buffer_.data(); }
457 size_t length() const noexcept { return length_; }
458 constexpr size_t capacity() const noexcept { return N - 1; }
459 };
460
461 void demonstrate_memory_safety() {
462     std::cout << "\n==== 5. Memory Safety and Bounds Checking ===\n";
463
464     // Safe array with compile-time size
465     SafeArray<int32_t, 10> sensor_readings;
466
467     std::cout << "\nSafe Array Operations:\n";
468     for (size_t i = 0; i < sensor_readings.size(); ++i) {
469         sensor_readings.set(i, static_cast<int32_t>(i * 100));
470     }
471
472     int32_t value = 0;
473     SafetyResult result = sensor_readings.get(5, value);
474     std::cout << "    Reading[5] = " << value << " (status: "
475             << (result == SafetyResult::OK ? " OK" : " ERROR")) << "\n";
476
477     // Attempt out-of-bounds access
478     result = sensor_readings.get(15, value);
479     std::cout << "    Reading[15] = " << (result == SafetyResult::OK ? " Valid" :
480             " OUT OF BOUNDS") << "\n";
481
482     // Safe string operations
483     SafeString<32> device_id;
484     device_id.copy_from("BRAKE_CTRL_");
485     device_id.append("ECU001");
486
487     std::cout << "\nSafe String Operations:\n";
488     std::cout << "    Device ID: " << device_id.c_str() << "\n";
489     std::cout << "    Length: " << device_id.length() << "/" << device_id.
490             capacity() << "\n";
491
492     std::cout << "\nMemory Safety Rules:\n";
```

```
491     std::cout << "    No dynamic allocation (new/malloc) in safety functions\n"
492             "    ";
493     std::cout << "    Fixed-size buffers with compile-time bounds\n";
494     std::cout << "    All array accesses bounds-checked\n";
495     std::cout << "    No pointer arithmetic without validation\n";
496     std::cout << "    Stack-allocated containers only\n";
497 }
498 // -----
499 // SECTION 6: Runtime Diagnostics and Self-Test
500 // -----
501 // Continuous self-monitoring and fault detection
502
503 class DiagnosticMonitor {
504 private:
505     struct DiagnosticCounter {
506         uint32_t total_checks;
507         uint32_t failures;
508         uint32_t warnings;
509     };
510
511     DiagnosticCounter counters_;
512     bool system_healthy_;
513
514 public:
515     DiagnosticMonitor() noexcept
516         : counters_{0, 0, 0}, system_healthy_(true) {}
517
518     // RAM test (simple pattern check)
519     SafetyResult test_ram(uint32_t* test_area, size_t size) noexcept {
520         ++counters_.total_checks;
521
522         // Write pattern
523         constexpr uint32_t PATTERN1 = 0x55555555;
524         constexpr uint32_t PATTERN2 = 0xAAAAAAA;
525
526         for (size_t i = 0; i < size; ++i) {
527             test_area[i] = PATTERN1;
528         }
529
530         // Verify pattern 1
531         for (size_t i = 0; i < size; ++i) {
532             if (test_area[i] != PATTERN1) {
533                 ++counters_.failures;
534                 system_healthy_ = false;
535                 return SafetyResult::CRITICAL_FAILURE;
536             }
537         }
538
539         // Write and verify pattern 2
```

```
540     for (size_t i = 0; i < size; ++i) {
541         test_area[i] = PATTERN2;
542     }
543
544     for (size_t i = 0; i < size; ++i) {
545         if (test_area[i] != PATTERN2) {
546             ++counters_.failures;
547             system_healthy_ = false;
548             return SafetyResult::CRITICAL_FAILURE;
549         }
550     }
551
552     return SafetyResult::OK;
553 }
554
555 // Plausibility check for sensor values
556 SafetyResult check_plausibility(int32_t value, int32_t min, int32_t max)
557     noexcept {
558     ++counters_.total_checks;
559
560     if (value < min || value > max) {
561         ++counters_.failures;
562         return SafetyResult::ERROR;
563     }
564
565     // Warning range (10% from limits)
566     int32_t warning_margin = (max - min) / 10;
567     if (value < min + warning_margin || value > max - warning_margin) {
568         ++counters_.warnings;
569         return SafetyResult::WARNING;
570     }
571
572     return SafetyResult::OK;
573 }
574
575 void get_diagnostics(uint32_t& total, uint32_t& failures, uint32_t&
576 warnings) const noexcept {
577     total = counters_.total_checks;
578     failures = counters_.failures;
579     warnings = counters_.warnings;
580 }
581
582 bool is_healthy() const noexcept { return system_healthy_; }
583 };
584
585 void demonstrate_runtime_diagnostics() {
586     std::cout << "\n==== 6. Runtime Diagnostics and Self-Test ====\n";
587
588     DiagnosticMonitor diagnostics;
589
590     // RAM self-test
591     std::array<uint32_t, 256> test_ram;
592     std::cout << "\nRAM Self-Test:\n";
593     SafetyResult ram_result = diagnostics.test_ram(test_ram.data(), test_ram.
```

```
        size());
592     std::cout << "  Pattern Test (0x55555555/0xAAAAAAA): "
593             << (ram_result == SafetyResult::OK ? "  PASS" : "  FAIL") << "\n"
594             ;
595
596     // Plausibility checks
597     std::cout << "\nSensor Plausibility Checks:\n";
598
599     struct SensorTest {
600         const char* name;
601         int32_t value;
602         int32_t min;
603         int32_t max;
604     };
605
606     constexpr std::array<SensorTest, 4> tests = {{
607         {"Wheel speed", 1200, 0, 3000},           // OK
608         {"Brake pressure", 850, 0, 1000},          // OK
609         {"Steering angle", 950, -900, 900},         // WARNING (near limit)
610         {"Throttle position", 1500, 0, 1000}       // ERROR (out of range)
611     }};
612
613     for (const auto& test : tests) {
614         SafetyResult result = diagnostics.check_plausibility(test.value, test.
615             min, test.max);
616         std::cout << "  " << test.name << " = " << test.value
617             << " [" << test.min << ".." << test.max << "]": " ;
618
619         switch (result) {
620             case SafetyResult::OK:
621                 std::cout << "  OK\n";
622                 break;
623             case SafetyResult::WARNING:
624                 std::cout << "  WARNING (near limit)\n";
625                 break;
626             case SafetyResult::ERROR:
627                 std::cout << "  OUT OF RANGE\n";
628                 break;
629             default:
630                 std::cout << "  CRITICAL\n";
631                 break;
632         }
633     }
634
635     // Diagnostic summary
636     uint32_t total, failures, warnings;
637     diagnostics.get_diagnostics(total, failures, warnings);
638
639     std::cout << "\nDiagnostic Summary:\n";
640     std::cout << "  Total checks: " << total << "\n";
641     std::cout << "  Failures: " << failures << "\n";
642     std::cout << "  Warnings: " << warnings << "\n";
643     std::cout << "  System Health: " << (diagnostics.is_healthy() ? "  HEALTHY"
644             " : "  DEGRADED") << "\n";
```

```
642     std::cout << "\nDiagnostic Coverage:\n";
643     std::cout << "    RAM pattern test (startup + periodic)\n";
644     std::cout << "    Plausibility checks (range validation)\n";
645     std::cout << "    Stuck-at fault detection\n";
646     std::cout << "    Diagnostic Trouble Code (DTC) logging\n";
647 }
648
649 //
650 =====
651 // SECTION 7: Safe State Transitions and Fault Handling
652 //
653 =====
654
655 // Deterministic state machine with safe fallback
656
657 class BrakingController {
658 private:
659     enum class BrakeState : uint8_t {
660         INIT = 0,
661         NORMAL = 1,
662         DEGRADED = 2,
663         FAILSAFE = 3,
664         EMERGENCY = 4
665     };
666
667     BrakeState current_state_;
668     BrakeState previous_state_;
669     uint32_t fault_count_;
670
671 public:
672     BrakingController() noexcept
673         : current_state_(BrakeState::INIT),
674             previous_state_(BrakeState::INIT),
675             fault_count_(0) {}
676
677     SafetyResult initialize() noexcept {
678         if (current_state_ != BrakeState::INIT) {
679             return SafetyResult::ERROR;
680         }
681
682         // Perform self-tests
683         // ... (RAM test, sensor check, actuator test)
684
685         previous_state_ = current_state_;
686         current_state_ = BrakeState::NORMAL;
687         return SafetyResult::OK;
688     }
689
690     SafetyResult handle_fault(SafetyResult fault_severity) noexcept {
691         ++fault_count_;
692         previous_state_ = current_state_;
693     }
694 }
```

```
692     switch (fault_severity) {
693         case SafetyResult::WARNING:
694             // Stay in current state but log warning
695             return SafetyResult::WARNING;
696
697         case SafetyResult::ERROR:
698             // Transition to degraded mode
699             if (current_state_ == BrakeState::NORMAL) {
700                 current_state_ = BrakeState::DEGRADED;
701             }
702             return SafetyResult::ERROR;
703
704         case SafetyResult::CRITICAL_FAILURE:
705             // Immediate transition to emergency
706             current_state_ = BrakeState::EMERGENCY;
707             return SafetyResult::CRITICAL_FAILURE;
708
709         default:
710             return SafetyResult::OK;
711     }
712 }
713
714 SafetyResult apply_brakes(int32_t pressure) noexcept {
715     switch (current_state_) {
716         case BrakeState::INIT:
717             return SafetyResult::ERROR; // Not initialized
718
719         case BrakeState::NORMAL:
720             // Full functionality
721             return apply_normal_braking(pressure);
722
723         case BrakeState::DEGRADED:
724             // Limited functionality (e.g., one channel failed)
725             return apply_degraded_braking(pressure / 2);
726
727         case BrakeState::FAILSAFE:
728         case BrakeState::EMERGENCY:
729             // Maximum braking regardless of input
730             return apply_emergency_braking();
731     }
732
733     return SafetyResult::ERROR;
734 }
735
736 const char* get_state_name() const noexcept {
737     switch (current_state_) {
738         case BrakeState::INIT: return "INIT";
739         case BrakeState::NORMAL: return "NORMAL";
740         case BrakeState::DEGRADED: return "DEGRADED";
741         case BrakeState::FAILSAFE: return "FAILSAFE";
742         case BrakeState::EMERGENCY: return "EMERGENCY";
743         default: return "UNKNOWN";
744     }
745 }
```

```
746     uint32_t get_fault_count() const noexcept { return fault_count_; }
```

```
747
748
749 private:
750     SafetyResult apply_normal_braking(int32_t pressure) noexcept {
751         // Normal braking logic
752         (void)pressure; // Suppress unused warning
753         return SafetyResult::OK;
754     }
755
756     SafetyResult apply_degraded_braking(int32_t pressure) noexcept {
757         // Degraded mode (e.g., mechanical backup)
758         (void)pressure;
759         return SafetyResult::WARNING;
760     }
761
762     SafetyResult apply_emergency_braking() noexcept {
763         // Maximum braking effort
764         return SafetyResult::CRITICAL_FAILURE;
765     }
766 };
767
768 void demonstrate_safe_state_transitions() {
769     std::cout << "\n==== 7. Safe State Transitions and Fault Handling ===\n";
770
771     BrakingController brake_system;
772
773     std::cout << "\nBraking System State Machine:\n";
774     std::cout << "    Initial State: " << brake_system.get_state_name() << "\n";
775
776     // Initialize
777     brake_system.initialize();
778     std::cout << "    After Init: " << brake_system.get_state_name() << "\n";
779
780     // Normal operation
781     SafetyResult result = brake_system.apply_brakes(500);
782     std::cout << "    Apply 500 kPa: " << (result == SafetyResult::OK ? " OK" :
783                               " ERROR") << "\n";
784
785     // Simulate fault
786     std::cout << "\n    Simulating sensor fault...\n";
787     brake_system.handle_fault(SafetyResult::ERROR);
788     std::cout << "    State after fault: " << brake_system.get_state_name() << "\n";
789
790     result = brake_system.apply_brakes(500);
791     std::cout << "    Apply 500 kPa in degraded: "
792           << (result == SafetyResult::WARNING ? " LIMITED" : " ERROR") <<
793           "\n";
794
795     // Critical fault
796     std::cout << "\n    Simulating critical failure...\n";
797     brake_system.handle_fault(SafetyResult::CRITICAL_FAILURE);
798     std::cout << "    State after critical: " << brake_system.get_state_name()
```

```
    << "\n";
797 std::cout << "  Total faults handled: " << brake_system.get_fault_count()
    << "\n";
798
799 std::cout << "\nState Machine Principles:\n";
800 std::cout << "  Deterministic transitions (no race conditions)\n";
801 std::cout << "  Always transition to safe state on fault\n";
802 std::cout << "  No invalid states reachable\n";
803 std::cout << "  Fail-safe defaults (e.g., emergency braking)\n";
804 }
805
806 // =====
807 // SECTION 8: Deterministic Timing and WCET
808 // =====
809 // Predictable execution time for real-time safety functions
810
811 class ExecutionTimeMonitor {
812 private:
813     std::chrono::steady_clock::time_point start_time_;
814     uint32_t wcet_us_; // Worst-case execution time in microseconds
815     bool timingViolation_;
816
817 public:
818     explicit ExecutionTimeMonitor(uint32_t wcet_us) noexcept
819         : wcet_us_(wcet_us), timingViolation_(false) {}
820
821     void start() noexcept {
822         start_time_ = std::chrono::steady_clock::now();
823         timingViolation_ = false;
824     }
825
826     SafetyResult check() noexcept {
827         auto end_time = std::chrono::steady_clock::now();
828         auto elapsed_us = std::chrono::duration_cast<std::chrono::microseconds>(
829             end_time - start_time_).count();
830
831         if (elapsed_us > wcet_us_) {
832             timingViolation_ = true;
833             return SafetyResult::ERROR;
834         }
835
836         return SafetyResult::OK;
837     }
838
839     bool hasViolation() const noexcept { return timingViolation_; }
840 };
841
842 // Safety-critical control loop with deterministic timing
843 SafetyResult safety_control_cycle(ExecutionTimeMonitor& timer) noexcept {
```

```
844     timer.start();  
845  
846     // Read sensors (deterministic)  
847     volatile int32_t sensor1 = 100;  
848     volatile int32_t sensor2 = 200;  
849  
850     // Compute control output (no branches, no loops with variable iterations)  
851     volatile int32_t output = (sensor1 + sensor2) / 2;  
852  
853     // Write actuators  
854     (void)output; // Suppress unused warning  
855  
856     // Check timing constraint  
857     return timer.check();  
858 }  
859  
860 void demonstrate_deterministic_timing() {  
861     std::cout << "\n==== 8. Deterministic Timing and WCET ===\n";  
862  
863     // Set WCET budget to 100 microseconds  
864     ExecutionTimeMonitor timer(100);  
865  
866     std::cout << "\nControl Cycle Timing (WCET = 100 \u00b5s):\n";  
867  
868     for (int i = 0; i < 5; ++i) {  
869         SafetyResult result = safety_control_cycle(timer);  
870         std::cout << " Cycle " << (i + 1) << ":"  
871             << (result == SafetyResult::OK ? " Within WCET" : " TIMING  
872                 VIOLATION") << "\n";  
873     }  
874  
875     std::cout << "\nDeterminism Requirements:\n";  
876     std::cout << "    No dynamic memory allocation (non-deterministic)\n";  
877     std::cout << "    No unbounded loops (use fixed iteration count)\n";  
878     std::cout << "    No recursive functions (stack usage)\n";  
879     std::cout << "    Disable interrupts in critical sections\n";  
880     std::cout << "    Priority-based scheduling (preemptive RTOS)\n";  
881     std::cout << "    WCET analysis tools (e.g., aiT, RapiTime)\n";  
882 }  
883 //  
=====  
884 // SECTION 9: MISRA C++ Compliance Patterns  
885 //  
=====  
886  
887 void demonstrate_misra_compliance() {  
888     std::cout << "\n==== 9. MISRA C++ Compliance Patterns ===\n";  
889  
890     std::cout << "\nKey MISRA C++ 2023 Rules:\n\n";  
891  
892     std::cout << "Rule 5-0-3: Prohibited types and features:\n";
```

```
893     std::cout << "      Avoid: exceptions, RTTI (typeid), dynamic_cast in safety  
894         code\n";  
895     std::cout << "      Use: Error codes, static polymorphism (templates)\n\n";  
896  
897     std::cout << "Rule 5-2-12: No dynamic memory allocation:\n";  
898     std::cout << "      Avoid: new, delete, malloc, free, std::vector (dynamic)\n  
899         n";  
900     std::cout << "      Use: std::array, static buffers, placement new (if  
901         needed)\n\n";  
902  
903  
904     std::cout << "Rule 6-4-5: Unconditional throw/goto prohibited:\n";  
905     std::cout << "      Avoid: throw exceptions in safety functions\n";  
906     std::cout << "      Use: Return error codes (SafetyResult enum)\n\n";  
907  
908     std::cout << "Rule 8-0-1: All functions have one exit point:\n";  
909     std::cout << "      Avoid: Multiple return statements\n";  
910     std::cout << "      Use: Single return with result variable\n\n";  
911  
912     std::cout << "Rule 18-0-3: No library functions with undefined behavior:\n  
913         \";  
914     std::cout << "      Avoid: atoi, gets, sprintf (unsafe)\n";  
915     std::cout << "      Use: strtol with error checking, snprintf\n\n";  
916  
917     std::cout << "Rule 27-0-1: All includes have include guards:\n";  
918     std::cout << "      Use: #pragma once or #ifndef guards\n\n";  
919  
920     std::cout << "Additional Safety Guidelines:\n";  
921     std::cout << "      All arithmetic operations overflow-checked\n";  
922     std::cout << "      All array accesses bounds-checked\n";  
923     std::cout << "      All pointers validated before dereference\n";  
924     std::cout << "      All functions declared noexcept if they don't throw\n";  
925     std::cout << "      constexpr for compile-time evaluation\n";  
926     std::cout << "      Static analysis tools (e.g., LDRA, PC-lint Plus)\n";  
927 }  
928  
929 // SECTION 10: Safety Checklist and Best Practices Summary  
930 //  
931  
932 void demonstrate_safety_checklist() {  
933     std::cout << "\n== 10. ISO 26262 Safety Checklist ==\n";  
934  
935     std::cout << "\n DESIGN PHASE:\n";  
936     std::cout << "[ ] ASIL classification completed\n";  
937     std::cout << "[ ] Hazard analysis and risk assessment (HARA)\n";  
938     std::cout << "[ ] Safety goals defined (fail-safe behavior)\n";  
939     std::cout << "[ ] Redundancy strategy selected (dual/TMR)\n";  
940     std::cout << "[ ] WCET analysis performed\n";  
941     std::cout << "[ ] Diagnostic coverage targets set\n\n";  
942 }
```

```
939     std::cout << " IMPLEMENTATION PHASE:\n";
940     std::cout << " [] MISRA C++ guidelines followed\n";
941     std::cout << " [] No dynamic memory allocation\n";
942     std::cout << " [] No exceptions in safety functions\n";
943     std::cout << " [] All arithmetic overflow-checked\n";
944     std::cout << " [] All arrays bounds-checked\n";
945     std::cout << " [] Watchdog timer implemented\n";
946     std::cout << " [] Safe state transitions verified\n";
947     std::cout << " [] Deterministic timing validated\n\n";
948
949     std::cout << " VERIFICATION PHASE:\n";
950     std::cout << " [] Static analysis (PC-lint, Coverity, PVS-Studio)\n";
951     std::cout << " [] Dynamic testing (functional + fault injection)\n";
952     std::cout << " [] Code reviews (multiple reviewers)\n";
953     std::cout << " [] Requirements traceability matrix\n";
954     std::cout << " [] Coverage analysis (MC/DC for ASIL-D)\n";
955     std::cout << " [] Safety case documentation\n\n";
956
957     std::cout << " VALIDATION PHASE:\n";
958     std::cout << " [] Hardware-in-the-loop (HIL) testing\n";
959     std::cout << " [] Environmental stress testing\n";
960     std::cout << " [] EMC/EMI validation\n";
961     std::cout << " [] Long-term reliability testing\n";
962     std::cout << " [] Safety audit completed\n\n";
963
964     std::cout << "KEY TAKEAWAYS:\n";
965     std::cout << " 1. Safety is a process, not just code\n";
966     std::cout << " 2. Redundancy and diagnostics are essential for ASIL-C/D\n";
967     std::cout << " ";
968     std::cout << " 3. Deterministic behavior is mandatory\n";
969     std::cout << " 4. Always transition to safe state on fault\n";
970     std::cout << " 5. Document everything (traceability is critical)\n";
971     std::cout << " 6. Use certified tools and compilers for final builds\n";
972     std::cout << " 7. Continuous monitoring in production (field data)\n";
973 }
974 // =====
975 // MAIN FUNCTION
976 // =====
977
978 int main() {
979     std::cout << "                                         \n";
980     std::cout << " ISO 26262 Functional Safety - Modern C++ Demonstration\n";
981     std::cout << "                                         \n";
982     std::cout << "                                         \n";
983     std::cout << " Comprehensive examples of safety-critical automotive code\n";
984     std::cout << "                                         \n";
985     std::cout << " covering ASIL levels, MISRA C++, redundancy, and more\n";
986     std::cout << "                                         \n";
```

```
984     std::cout << "\n";
985
986     demonstrate_asil_levels();
987     demonstrate_safe_data_types();
988     demonstrate_redundancy_voting();
989     demonstrate_watchdog_monitoring();
990     demonstrate_memory_safety();
991     demonstrate_runtime_diagnostics();
992     demonstrate_safe_state_transitions();
993     demonstrate_deterministic_timing();
994     demonstrate_misra_compliance();
995     demonstrate_safety_checklist();
996
997     std::cout << "\n" << std::string(68, '=') << "\n";
998     std::cout << "All safety demonstrations completed successfully!\n";
999     std::cout << "Remember: Safety certification requires formal verification
1000           ,\n";
1000     std::cout << "           extensive testing, and compliance with ISO 26262
1001           process.\n";
1001     std::cout << std::string(68, '=') << "\n\n";
1002
1003     return 0;
1004 }
```

35 Source Code: FuturePromiseAsync.cpp

File: src/FuturePromiseAsync.cpp

Repository: [View on GitHub](#)

```
1 // FuturePromiseAsync.cpp
2 // Comprehensive guide to C++ concurrency primitives:
3 // - std::future and std::promise
4 // - std::packaged_task
5 // - std::async
6 // And how they relate to ASIO
7 //
8 // KEY CONCEPTS:
9 // 1. These are NOT alternatives to ASIO - they serve different purposes
10 // 2. future/promise/async are for TASK-BASED concurrency
11 // 3. ASIO is for ASYNCHRONOUS I/O and event-driven programming
12 // 4. They can be used together!
13 //
14 // WHEN TO USE WHAT:
15 // - std::async: Simplest, for fire-and-forget async tasks
16 // - std::promise/future: Manual control, producer-consumer pattern
17 // - std::packaged_task: Wrap callable, control execution timing
18 // - ASIO: Network I/O, timers, serial ports, event-driven architecture
19
20 #include <iostream>
21 #include <future>
22 #include <thread>
23 #include <chrono>
24 #include <functional>
25 #include <vector>
26 #include <queue>
27 #include <random>
28 #include <iomanip>
29
30 using namespace std::chrono_literals;
31
32 //
33 // SECTION 1: std::async - The Simplest Way
34 //
35
36 namespace async_examples {
37
38 // Simple async task
39 int calculate_sum(int a, int b) {
40     std::cout << " [async] Calculating " << a << " + " << b
41             << " on thread " << std::this_thread::get_id() << "\n";
42     std::this_thread::sleep_for(500ms);
43     return a + b;
44 }
```

```

46 // Async task with exception
47 int divide(int a, int b) {
48     std::cout << "  [async] Dividing " << a << " / " << b << "\n";
49     std::this_thread::sleep_for(300ms);
50     if (b == 0) {
51         throw std::invalid_argument("Division by zero!");
52     }
53     return a / b;
54 }
55
56 void demonstrate() {
57     std::cout << "\n" << std::string(70, '=') << "\n";
58     std::cout << "==== SECTION 1: std::async - The Simplest Way ===\n";
59     std::cout << std::string(70, '=') << "\n\n";
60
61     std::cout << "Main thread ID: " << std::this_thread::get_id() << "\n\n";
62
63     // 1. Launch async task (may run in new thread or deferred)
64     std::cout << "1. Basic async (default policy):\n";
65     auto future1 = std::async(std::launch::async, calculate_sum, 10, 20);
66     std::cout << "  Task launched, doing other work...\n";
67     std::this_thread::sleep_for(200ms);
68     std::cout << "  Getting result: " << future1.get() << "\n\n";
69
70     // 2. Force async execution in new thread
71     std::cout << "2. Force async (std::launch::async):\n";
72     auto future2 = std::async(std::launch::async, calculate_sum, 15, 25);
73     std::cout << "  Task running in parallel...\n";
74     std::cout << "  Result: " << future2.get() << "\n\n";
75
76     // 3. Deferred execution (lazy evaluation)
77     std::cout << "3. Deferred execution (std::launch::deferred):\n";
78     std::cout << "  Launching deferred task...\n";
79     auto future3 = std::async(std::launch::deferred, calculate_sum, 5, 10);
80     std::cout << "  Task not started yet!\n";
81     std::cout << "  Calling get()... (task runs NOW on this thread)\n";
82     std::cout << "  Result: " << future3.get() << "\n\n";
83
84     // 4. Exception handling
85     std::cout << "4. Exception handling with async:\n";
86     auto future4 = std::async(std::launch::async, divide, 100, 0);
87     try {
88         std::cout << "  Getting result...\n";
89         int result = future4.get();
90         std::cout << "  Result: " << result << "\n";
91     } catch (const std::exception& e) {
92         std::cout << "    Caught exception: " << e.what() << "\n";
93     }
94
95     std::cout << "\n WHEN TO USE std::async:\n";
96     std::cout << " • Quick fire-and-forget async operations\n";
97     std::cout << " • Simple parallel computations\n";
98     std::cout << " • Don't need fine control over thread management\n";
99     std::cout << " • Want automatic exception propagation\n";

```

```
100 }
101
102 } // namespace async_examples
103
104 // =====
105 // SECTION 2: std::promise and std::future - Producer-Consumer Pattern
106 // =====
107
108 namespace promise_future_examples {
109
110 // Producer thread sets value via promise
111 void produce_value(std::promise<int> promise, int value) {
112     std::cout << "    [Producer] Starting work...\n";
113     std::this_thread::sleep_for(1s);
114     std::cout << "    [Producer] Producing value: " << value << "\n";
115     promise.set_value(value); // Set the value
116     std::cout << "    [Producer] Value set, exiting\n";
117 }
118
119 // Producer that fails
120 void produce_with_error(std::promise<int> promise) {
121     std::cout << "    [Producer] Starting work...\n";
122     std::this_thread::sleep_for(500ms);
123     try {
124         throw std::runtime_error("Production failed!");
125     } catch (...) {
126         std::cout << "    [Producer] Error occurred, setting exception\n";
127         promise.set_exception(std::current_exception());
128     }
129 }
130
131 // Multiple consumers waiting for same value
132 void consume_value(std::shared_future<int> future, int consumer_id) {
133     std::cout << "    [Consumer " << consumer_id << "] Waiting for value...\n";
134     int value = future.get(); // Blocks until value is ready
135     std::cout << "    [Consumer " << consumer_id << "] Got value: " << value <<
136     "\n";
137 }
138
139 void demonstrate() {
140     std::cout << "\n" << std::string(70, '=') << "\n";
141     std::cout << "==== SECTION 2: std::promise and std::future ===\n";
142     std::cout << std::string(70, '=') << "\n\n";
143
144     // 1. Basic promise-future pair
145     std::cout << "1. Basic producer-consumer with promise/future:\n";
146     std::promise<int> promise1;
147     std::future<int> future1 = promise1.get_future();
148
149     std::thread producer1(produce_value, std::move(promise1), 42);
```

```
149
150     std::cout << "    [Consumer] Waiting for result...\n";
151     int result1 = future1.get();
152     std::cout << "    [Consumer] Received: " << result1 << "\n\n";
153     producer1.join();
154
155     // 2. Exception propagation
156     std::cout << "2. Exception handling with promise/future:\n";
157     std::promise<int> promise2;
158     std::future<int> future2 = promise2.get_future();
159
160     std::thread producer2(produce_with_error, std::move(promise2));
161
162     try {
163         std::cout << "    [Consumer] Waiting for result...\n";
164         int result2 = future2.get();
165         std::cout << "    [Consumer] Received: " << result2 << "\n";
166     } catch (const std::exception& e) {
167         std::cout << "    [Consumer] Caught exception: " << e.what() << "\n";
168     }
169     producer2.join();
170     std::cout << "\n";
171
172     // 3. Multiple consumers with shared_future
173     std::cout << "3. Multiple consumers with shared_future:\n";
174     std::promise<int> promise3;
175     std::shared_future<int> shared_future = promise3.get_future().share();
176
177     // Launch multiple consumers
178     std::vector<std::thread> consumers;
179     for (int i = 1; i <= 3; ++i) {
180         consumers.emplace_back(consume_value, shared_future, i);
181     }
182
183     std::this_thread::sleep_for(500ms);
184     std::cout << "    [Main] Setting value 100\n";
185     promise3.set_value(100);
186
187     for (auto& t : consumers) {
188         t.join();
189     }
190
191     std::cout << "\n WHEN TO USE std::promise/future:\n";
192     std::cout << " • Need manual control over when value is set\n";
193     std::cout << " • Producer-consumer pattern across threads\n";
194     std::cout << " • Complex synchronization scenarios\n";
195     std::cout << " • Want to set value from a different location than task
196         creation\n";
197     std::cout << " • Need shared_future for multiple consumers\n";
198 }
199 } // namespace promise_future_examples
200 //
```

```
=====
202 // SECTION 3: std::packaged_task - Wrap Callable, Control Execution
203 //
=====

204
205 namespace packaged_task_examples {
206
207 // Function to be wrapped
208 int compute_factorial(int n) {
209     std::cout << " [Task] Computing factorial of " << n << "\n";
210     std::this_thread::sleep_for(500ms);
211     int result = 1;
212     for (int i = 2; i <= n; ++i) {
213         result *= i;
214     }
215     return result;
216 }
217
218 // Task queue for thread pool simulation
219 class SimpleThreadPool {
220     std::vector<std::thread> threads_;
221     std::queue<std::function<void()>> tasks_;
222     std::mutex mutex_;
223     std::condition_variable cv_;
224     bool stop_ = false;
225
226 public:
227     SimpleThreadPool(size_t num_threads) {
228         for (size_t i = 0; i < num_threads; ++i) {
229             threads_.emplace_back([this, i] {
230                 std::cout << " [Worker " << i << "] Started\n";
231                 while (true) {
232                     std::function<void()> task;
233                     {
234                         std::unique_lock<std::mutex> lock(mutex_);
235                         cv_.wait(lock, [this] { return stop_ || !tasks_.empty()
236                             (); });
237
238                         if (stop_ && tasks_.empty()) {
239                             std::cout << " [Worker " << i << "] Stopping\n";
240                             return;
241                         }
242
243                         task = std::move(tasks_.front());
244                         tasks_.pop();
245                     }
246                     std::cout << " [Worker " << i << "] Executing task\n";
247                     task();
248                 }
249             });
250     }
251 }
```

```
251 ~SimpleThreadPool() {
252 {
253     std::unique_lock<std::mutex> lock(mutex_);
254     stop_ = true;
255 }
256 cv_.notify_all();
257 for (auto& t : threads_) {
258     t.join();
259 }
260 }
261 }
262
263 template<typename F>
264 void enqueue(F&& task) {
265 {
266     std::unique_lock<std::mutex> lock(mutex_);
267     tasks_.push(std::forward<F>(task));
268 }
269 cv_.notify_one();
270 }
271 };
272
273 void demonstrate() {
274 std::cout << "\n" << std::string(70, '=') << "\n";
275 std::cout << "==== SECTION 3: std::packaged_task ===\n";
276 std::cout << std::string(70, '=') << "\n\n";
277
278 // 1. Basic packaged_task
279 std::cout << "1. Basic packaged_task:\n";
280 std::packaged_task<int(int)> task1(compute_factorial);
281 std::future<int> future1 = task1.get_future();
282
283 std::cout << "    Task created but not executed yet\n";
284 std::cout << "    Launching task on new thread...\n";
285 std::thread t1(std::move(task1), 5);
286
287 std::cout << "    Waiting for result...\n";
288 std::cout << "    Factorial(5) = " << future1.get() << "\n";
289 t1.join();
290 std::cout << "\n";
291
292 // 2. Using packaged_task with thread pool
293 std::cout << "2. Thread pool with packaged_task:\n";
294 SimpleThreadPool pool(2);
295
296 std::vector<std::future<int>> futures;
297
298 for (int i = 3; i <= 6; ++i) {
299     std::packaged_task<int(int)> task(compute_factorial);
300     futures.push_back(task.get_future());
301
302     // Enqueue task to thread pool - use shared_ptr for copy-ability
303     auto task_ptr = std::make_shared<std::packaged_task<int(int)>>(std::move(task));
```

```
304     int value = i;
305     pool.enqueue([task_ptr, value]() {
306         (*task_ptr)(value);
307     });
308 }
309
310 std::cout << "\n  All tasks enqueued, waiting for results...\n\n";
311
312 for (size_t i = 0; i < futures.size(); ++i) {
313     int result = futures[i].get();
314     std::cout << "  Result " << (i + 3) << ": factorial = " << result << "
315             "\n";
316 }
317
318 std::cout << "\n WHEN TO USE std::packaged_task:\n";
319 std::cout << " • Wrapping callable objects for later execution\n";
320 std::cout << " • Implementing thread pools or task queues\n";
321 std::cout << " • Need to separate task creation from execution\n";
322 std::cout << " • Want to store tasks in containers\n";
323 std::cout << " • Building custom scheduling systems\n";
324 }
325 } // namespace packaged_task_examples
326
327 //
328 =====
329 // SECTION 4: Comparison Summary
330 // =====
331
332 void show_comparison() {
333     std::cout << "\n" << std::string(70, '=') << "\n";
334     std::cout << "==== SECTION 4: When to Use What? ===\n";
335     std::cout << std::string(70, '=') << "\n\n";
336
337     std::cout << "                                     \n";
338     std::cout << "    MECHANISM           USE CASE      \n";
339     std::cout << "                                     \n";
340     std::cout << "    std::async   •      Simplest way to run async tasks\n";
341     std::cout << "                                     \n";
342     std::cout << "    •                  Fire-and-forget operations\n";
343     std::cout << "                                     \n";
344     std::cout << "    •                  Quick parallel computations\n";
345     std::cout << "                                     \n";
346     std::cout << "    •                  Don't need thread control\n";
347     std::cout << "                                     \n";
348     std::cout << "    •                  Best for: Simple async operations\n";
349     std::cout << "                                     \n";
350     std::cout << "    promise/future • Producer-consumer pattern\n";
351     std::cout << "                                     \n";
```

```

346     std::cout << "    •          Set value from different location
347         \n";
348     std::cout << "    •          Complex synchronization
349         \n";
350     std::cout << "    •          Multiple consumers (shared_future)
351         \n";
352     std::cout << "    •          Best for: Manual control over value
353         \n";
354     std::cout << "    •          packaged_task • Thread pools / task queues
355         \n";
356     std::cout << "    •          Separate creation from execution
357         \n";
358     std::cout << "    •          Store tasks in containers
359         \n";
360     std::cout << "    •          Custom scheduling systems
361         \n";
362     std::cout << "    •          Best for: Building task systems
363         \n";
364     std::cout << "    ";
365 }
366
367 // -----
368 // SECTION 5: Relationship with ASIO
369 // -----
370
371 // -----
372
373 void explain_asio_relationship() {
374     std::cout << "\n" << std::string(70, '=') << "\n";
375     std::cout << "==== SECTION 5: Are They Alternatives to ASIO? ===\n";
376     std::cout << std::string(70, '=') << "\n\n";
377
378     std::cout << "SHORT ANSWER: NO - They serve DIFFERENT purposes!\n\n";
379
380     std::cout << "    ";
381     std::cout << "    future/promise/async (Standard Library Concurrency)
382         \n";
383     std::cout << "    ";
384     std::cout << "    PURPOSE:
385         \n";
386
387     std::cout << "    •      Task-based concurrency
388         \n";
389     std::cout << "    •      CPU-bound computations
390         \n";
391     std::cout << "    •      Running functions asynchronously
392         \n";
393     std::cout << "    •      Getting results from other threads
394         \n";
395
396     std::cout << "    ";
397
398     std::cout << "    EXAMPLES:
399         \n";

```

```
380     std::cout << " • Parallel calculations\n";
381     std::cout << " • Image processing in background\n";
382     std::cout << " • File compression\n";
383     std::cout << " • Any CPU-intensive work\n";
384     std::cout << "\n";
385     std::cout << " LIMITATIONS:\n";
386     std::cout << " • Not designed for I/O operations\n";
387     std::cout << " • No built-in event loop\n";
388     std::cout << " • No socket/network abstractions\n";
389     std::cout << " • Limited scalability for many I/O operations\n";
390     std::cout << "\n\n";
391
392     std::cout << " ASIO (Asynchronous I/O Library)\n";
393     std::cout << " PURPOSE:\n";
394     std::cout << " • Asynchronous I/O operations\n";
395     std::cout << " • Network programming (sockets, TCP/UDP)\n";
396     std::cout << " • Event-driven architecture\n";
397     std::cout << " • Timers and signals\n";
398     std::cout << " • Serial ports\n";
399
400     std::cout << "\n";
401     std::cout << " EXAMPLES:\n";
402     std::cout << " • HTTP/REST servers and clients\n";
403     std::cout << " • WebSocket servers\n";
404     std::cout << " • Chat applications\n";
405     std::cout << " • Real-time data streaming\n";
406     std::cout << " • Timers and periodic tasks\n";
407     std::cout << "\n";
```

```
409     std::cout << "    STRENGTHS:\n";
410     std::cout << "        Optimized for I/O-bound operations\n";
411     std::cout << "        Event loop / io_context\n";
412     std::cout << "        Handles thousands of connections efficiently\n";
413     std::cout << "        Cross-platform I/O abstractions\n";
414     std::cout << "        Proactor pattern\n";
415     std::cout << "                                \n";
416
417     std::cout << "                                \n";
418     std::cout << "    THEY ARE COMPLEMENTARY - Use Together!\n";
419     std::cout << "                                \n";
420     std::cout << "                                \n";
421     std::cout << "    EXAMPLE 1: ASIO for I/O + async for CPU work\n";
422     std::cout << "        • Use ASIO to handle HTTP requests\n";
423     std::cout << "        • Use std::async to process images in parallel\n";
424     std::cout << "        • Return result via ASIO response\n";
425     std::cout << "                                \n";
426     std::cout << "    EXAMPLE 2: ASIO for networking + packaged_task for jobs\n";
427     std::cout << "        • ASIO receives network messages\n";
428     std::cout << "        • Queue CPU-intensive tasks with packaged_task\n";
429     std::cout << "        • Thread pool processes tasks\n";
430     std::cout << "        • ASIO sends results back over network\n";
431     std::cout << "                                \n";
432     std::cout << "    EXAMPLE 3: ASIO timers + promise/future for results\n";
433     std::cout << "        • ASIO timer for periodic checks\n";
434     std::cout << "        • Use promise/future to coordinate between timers\n";
435     std::cout << "        • Combine I/O events with task results\n";
436     std::cout << "                                \n";
437     std::cout << "                                \n\n";
```

```

438     std::cout << "DECISION TREE:\n";
439     std::cout << "    Need async I/O (network, files, timers)?   → Use ASIO\n";
440     std::cout << "\n";
441     std::cout << "    Need CPU-bound parallel computation?      → Use std::async\n";
442     std::cout << "\n";
443     std::cout << "    Need producer-consumer pattern?          → Use promise/\n";
444     std::cout << "\n";
445     std::cout << "    Building thread pool / task queue?       → Use\n";
446     std::cout << "\n";
447     std::cout << "\n";
448     std::cout << "    Need both I/O AND computation?           → Use ASIO + future\n";
449 }
450
451 // -----
452 // SECTION 6: Practical Example - Combining Them
453 //
454 // -----
455
456 namespace combined_example {
457
458 // Simulate a web server scenario
459 class RequestProcessor {
460 public:
461     // Simulate receiving HTTP request (would use ASIO in real app)
462     static std::string receive_request() {
463         std::cout << " [ASIO would be here] Received HTTP request\n";
464         return "process_image:photo.jpg";
465     }
466
467     // CPU-intensive image processing (use std::async)
468     static std::string process_image(const std::string& filename) {
469         std::cout << " [Worker] Processing image: " << filename << "\n";
470         std::this_thread::sleep_for(1s); // Simulate heavy processing
471         return "processed_" + filename;
472     }
473
474     // Send response (would use ASIO in real app)
475     static void send_response(const std::string& result) {
476         std::cout << " [ASIO would be here] Sending response: " << result <<
477             "\n";
478     }
479 };
480
481 void demonstrate() {
482     std::cout << "\n" << std::string(70, '=') << "\n";
483     std::cout << "==== SECTION 6: Practical Example - ASIO + async ===\n";
484     std::cout << std::string(70, '=') << "\n\n";

```

```
483     std::cout << "Scenario: Web server handling image processing requests\n\n";
484     ;
485
486     // 1. ASIO would receive request (simulated)
487     std::string request = RequestProcessor::receive_request();
488
489     // 2. Parse request
490     auto pos = request.find(':');
491     std::string filename = request.substr(pos + 1);
492
493     // 3. Use std::async for CPU-intensive work (doesn't block I/O thread)
494     std::cout << "  Launching async image processing...\n";
495     auto future = std::async(std::launch::async,
496                             RequestProcessor::process_image,
497                             filename);
498
499     std::cout << "  ASIO thread is free to handle other requests!\n";
500     std::this_thread::sleep_for(200ms);
501     std::cout << "  (Handling other requests...)\n";
502     std::this_thread::sleep_for(300ms);
503
504     // 4. Get result and send response
505     std::cout << "  Waiting for processing to complete...\n";
506     std::string result = future.get();
507
508     // 5. ASIO would send response (simulated)
509     RequestProcessor::send_response(result);
510
511     std::cout << "\n This is how you combine them:\n";
512     std::cout << " • ASIO handles network I/O (non-blocking)\n";
513     std::cout << " • std::async handles CPU work (parallel)\n";
514     std::cout << " • Best of both worlds!\n";
515 }
516
517 } // namespace combined_example
518 //
519 // =====
520 // MAIN FUNCTION
521 //
522 // =====
523
524 int main() {
525     std::cout << "\n";
526     std::cout << "                               \n";
527     std::cout << "           C++ Concurrency: future, promise, async, packaged_task\n";
528     std::cout << "                               \n";
529     std::cout << "           And their relationship with ASIO\n";
530     std::cout << "                               \n";
531 }
```

```
530 // Section 1: std::async  
531 async_examples::demonstrate();  
532  
533 // Section 2: promise/future  
534 promise_future_examples::demonstrate();  
535  
536 // Section 3: packaged_task  
537 packaged_task_examples::demonstrate();  
538  
539 // Section 4: Comparison  
540 show_comparison();  
541  
542 // Section 5: ASIO relationship  
543 explain_asio_relationship();  
544  
545 // Section 6: Combined example  
546 combined_example::demonstrate();  
547  
548 std::cout << "\n" << std::string(70, '=') << "\n";  
549 std::cout << "All demonstrations completed!\n";  
550 std::cout << std::string(70, '=') << "\n\n";  
551  
552 std::cout << "KEY TAKEAWAYS:\n";  
553 std::cout << "1. future/promise/async are for TASK-BASED concurrency\n";  
554 std::cout << "2. ASIO is for ASYNCHRONOUS I/O and event-driven programming  
      \n";  
555 std::cout << "3. They are NOT alternatives - use them TOGETHER!\n";  
556 std::cout << "4. std::async: simplest for parallel tasks\n";  
557 std::cout << "5. promise/future: manual control, producer-consumer\n";  
558 std::cout << "6. packaged_task: thread pools, task queues\n";  
559 std::cout << "7. ASIO: network I/O, timers, scalable servers\n\n";  
560  
561     return 0;  
562 }
```

36 Source Code: GenericLambdas.cpp

File: src/GenericLambdas.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <algorithm>
5 #include <numeric>
6 #include <functional>
7 #include <map>
8 #include <memory>
9
10 // =====
11 // 1. BASIC GENERIC LAMBDA (C++14)
12 // =====
13 void example_basic_generic_lambda() {
14     std::cout << "\n== 1. BASIC GENERIC LAMBDA (C++14) ==" << std::endl;
15
16     // Generic lambda that works with any type
17     auto identity = [] (auto x) {
18         return x;
19     };
20
21     std::cout << "Identity int: " << identity(42) << std::endl;
22     std::cout << "Identity double: " << identity(3.14) << std::endl;
23     std::cout << "Identity string: " << identity(std::string("Hello")) << std::endl;
24     std::cout << "Identity char: " << identity('A') << std::endl;
25 }
26
27 // =====
28 // 2. GENERIC LAMBDA WITH TYPE OPERATIONS
29 // =====
30 void example_generic_lambda_operations() {
31     std::cout << "\n== 2. GENERIC LAMBDA WITH TYPE OPERATIONS ==" << std::endl;
32
33     // Generic lambda that adds two values
34     auto add = [] (auto a, auto b) {
35         return a + b;
36     };
37
38     std::cout << "Add ints: " << add(10, 20) << std::endl;
39     std::cout << "Add doubles: " << add(3.14, 2.86) << std::endl;
40     std::cout << "Add strings: " << add(std::string("Hello "), std::string("World")) << std::endl;
41
42     // Generic lambda for multiplication
43     auto multiply = [] (auto a, auto b) {
44         return a * b;
45     };
46 }
```

```
47     std::cout << "Multiply ints: " << multiply(5, 6) << std::endl;
48     std::cout << "Multiply doubles: " << multiply(2.5, 4.0) << std::endl;
49 }
50
51 // =====
52 // 3. GENERIC LAMBDA WITH CONTAINERS
53 // =====
54 void example_generic_lambda_containers() {
55     std::cout << "\n==== 3. GENERIC LAMBDA WITH CONTAINERS ===" << std::endl;
56
57     // Generic lambda to print container elements
58     auto print_container = [] (const auto& container, const std::string& name)
59     {
60         std::cout << name << ": ";
61         for (const auto& elem : container) {
62             std::cout << elem << " ";
63         }
64         std::cout << std::endl;
65     };
66
67     std::vector<int> vec = {1, 2, 3, 4, 5};
68     std::vector<std::string> vec_str = {"Hello", "World", "C++14"};
69
70     print_container(vec, "Vector<int>");
71     print_container(vec_str, "Vector<string>");
72 }
73
74 // =====
75 // 4. GENERIC LAMBDA WITH STL ALGORITHMS
76 // =====
77 void example_generic_lambda_algorithms() {
78     std::cout << "\n==== 4. GENERIC LAMBDA WITH STL ALGORITHMS ===" << std::endl;
79
80     std::vector<int> numbers = {5, 2, 8, 1, 9, 3};
81
82     // Generic lambda for comparison
83     auto greater_than = [] (auto a, auto b) {
84         return a > b;
85     };
86
87     std::sort(numbers.begin(), numbers.end(), greater_than);
88
89     std::cout << "Sorted (descending): ";
90     for (auto n : numbers) {
91         std::cout << n << " ";
92     }
93     std::cout << std::endl;
94
95     // Generic lambda for transformation
96     auto square = [] (auto x) {
97         return x * x;
98     };

```

```
99     std::vector<int> squared(numbers.size());
100    std::transform(numbers.begin(), numbers.end(), squared.begin(), square);
101
102    std::cout << "Squared: ";
103    for (auto n : squared) {
104        std::cout << n << " ";
105    }
106    std::cout << std::endl;
107}
108
109// =====
110// 5. GENERIC LAMBDA WITH MULTIPLE AUTO PARAMETERS
111// =====
112void example_multiple_auto_parameters() {
113    std::cout << "\n==== 5. GENERIC LAMBDA WITH MULTIPLE AUTO PARAMETERS ==="
114        << std::endl;
115
116    // Generic lambda with three different types
117    auto combine = [] (auto a, auto b, auto c) {
118        std::cout << "Types can differ: " << a << ", " << b << ", " << c <<
119        std::endl;
120        return true;
121    };
122
123    combine(42, 3.14, "Hello");
124    combine(std::string("World"), 100, 'X');
125}
126
127// =====
128// 6. GENERIC LAMBDA WITH VARIADIC PARAMETERS
129// =====
130void example_generic_lambda_variadic() {
131    std::cout << "\n==== 6. GENERIC LAMBDA WITH VARIADIC PARAMETERS ===" << std::
132        ::endl;
133
134    // Generic lambda that sums any number of arguments
135    auto sum_all = [] (auto... args) {
136        return (args + ...); // C++17 fold expression
137    };
138
139    std::cout << "Sum of ints: " << sum_all(1, 2, 3, 4, 5) << std::endl;
140    std::cout << "Sum of doubles: " << sum_all(1.1, 2.2, 3.3) << std::endl;
141    std::cout << "Sum mixed: " << sum_all(1, 2.5, 3) << std::endl;
142}
143
144// =====
145// 7. GENERIC LAMBDA FOR FACTORY PATTERN
146// =====
147void example_generic_lambda_factory() {
148    std::cout << "\n==== 7. GENERIC LAMBDA FOR FACTORY PATTERN ===" << std::
149        endl;
150
151    // Generic factory lambda
152    auto make_unique_ptr = [] (auto value) {
```

```
149     using T = decltype(value);
150     return std::make_unique<T>(value);
151 }
152
153 auto int_ptr = make_unique_ptr(42);
154 auto str_ptr = make_unique_ptr(std::string("Hello"));
155 auto double_ptr = make_unique_ptr(3.14);
156
157 std::cout << "Int unique_ptr: " << *int_ptr << std::endl;
158 std::cout << "String unique_ptr: " << *str_ptr << std::endl;
159 std::cout << "Double unique_ptr: " << *double_ptr << std::endl;
160 }
161
162 // =====
163 // 8. GENERIC LAMBDA WITH MAP OPERATIONS
164 // =====
165 void example_generic_lambda_map() {
166     std::cout << "\n== 8. GENERIC LAMBDA WITH MAP OPERATIONS ==" << std::endl;
167
168     std::map<std::string, int> age_map = {
169         {"Alice", 30},
170         {"Bob", 25},
171         {"Charlie", 35}
172     };
173
174     // Generic lambda to print key-value pairs
175     auto print_map = [] (const auto& map, const std::string& name) {
176         std::cout << name << ":" << std::endl;
177         for (const auto& [key, value] : map) {
178             std::cout << " " << key << " -> " << value << std::endl;
179         }
180     };
181
182     print_map(age_map, "Age Map");
183
184     // Generic lambda for filtering
185     auto filter_by_value = [] (const auto& map, auto threshold) {
186         std::vector<typename std::decay<decltype(map)>::type::key_type> result
187         ;
188         for (const auto& [key, value] : map) {
189             if (value > threshold) {
190                 result.push_back(key);
191             }
192         }
193         return result;
194     };
195
196     auto filtered = filter_by_value(age_map, 28);
197     std::cout << "People older than 28: ";
198     for (const auto& name : filtered) {
199         std::cout << name << " ";
200     }
201     std::cout << std::endl;
```

```
201 }
202
203 // =====
204 // 9. GENERIC LAMBDA AS PREDICATE
205 // =====
206 void example_generic_lambda_predicate() {
207     std::cout << "\n==== 9. GENERIC LAMBDA AS PREDICATE ===" << std::endl;
208
209     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
210
211     // Generic lambda predicate
212     auto is_even = [] (auto n) {
213         return n % 2 == 0;
214     };
215
216     auto count = std::count_if(numbers.begin(), numbers.end(), is_even);
217     std::cout << "Even numbers count: " << count << std::endl;
218
219     // Find first even number
220     auto it = std::find_if(numbers.begin(), numbers.end(), is_even);
221     if (it != numbers.end()) {
222         std::cout << "First even number: " << *it << std::endl;
223     }
224 }
225
226 // =====
227 // 10. GENERIC LAMBDA WITH RETURN TYPE DEDUCTION
228 // =====
229 void example_return_type_deduction() {
230     std::cout << "\n==== 10. GENERIC LAMBDA WITH RETURN TYPE DEDUCTION ===" <<
231         std::endl;
232
233     // Lambda with auto return type - deduced from expression
234     auto double_value = [] (auto x) {
235         return x * 2;
236     };
237
238     // Lambda with explicit return type
239     auto to_string_value = [] (auto x) -> std::string {
240         return std::to_string(x);
241     };
242
243     std::cout << "Double int: " << double_value(21) << std::endl;
244     std::cout << "Double double: " << double_value(3.14) << std::endl;
245     std::cout << "To string (int): " << to_string_value(42) << std::endl;
246     std::cout << "To string (double): " << to_string_value(3.14159) << std::
247         endl;
248 }
249
250 // =====
251 // MAIN FUNCTION
252 // =====
253 int main() {
254     std::cout << "\n======" << std::endl;
```

```
253     endl;
254     std::cout << "      C++14 GENERIC LAMBDAS EXAMPLES" << std::endl;
255     std::cout << "===== ===== ===== ===== =====" << std::
256         endl;
257
258     example_basic_generic_lambda();
259     example_generic_lambda_operations();
260     example_generic_lambda_containers();
261     example_generic_lambda_algorithms();
262     example_multiple_auto_parameters();
263     example_generic_lambda_variadic();
264     example_generic_lambda_factory();
265     example_generic_lambda_map();
266     example_generic_lambda_predicate();
267     example_return_type_deduction();
268
269     std::cout << "\n===== ===== ===== ===== =====" << std::
270         endl;
271     std::cout << "      ALL EXAMPLES COMPLETED" << std::endl;
272     std::cout << "===== ===== ===== ===== =====\n" << std::
273         endl;
274
275     return 0;
276 }
```

37 Source Code: InheritanceTypes.cpp

File: src/InheritanceTypes.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <memory>
5 #include <algorithm>
6
7 // =====
8 // PRIVATE, PROTECTED, AND PUBLIC INHERITANCE IN C++
9 // =====
10 // =====
11 // 1. PUBLIC INHERITANCE - "IS-A" RELATIONSHIP
12 // =====
13
14
15 class Animal {
16 protected:
17     std::string name;
18
19 public:
20     Animal(const std::string& n) : name(n) {}
21     virtual ~Animal() = default;
22
23     virtual void makeSound() const {
24         std::cout << name << " makes a sound" << std::endl;
25     }
26
27     void eat() const {
28         std::cout << name << " is eating" << std::endl;
29     }
30 };
31
32 // Public inheritance: Dog IS-A Animal
33 // All public members of Animal remain public in Dog
34 class Dog : public Animal {
35 public:
36     Dog(const std::string& n) : Animal(n) {}
37
38     void makeSound() const override {
39         std::cout << name << " barks: Woof!" << std::endl;
40     }
41 };
42
43 void example_public_inheritance() {
44     std::cout << "\n== 1. PUBLIC INHERITANCE (IS-A) ==" << std::endl;
45     std::cout << "Use case: Dog IS-A Animal (polymorphism, substitutability)\n"
46     " << std::endl;
47
48     Dog dog("Buddy");
49     dog.makeSound(); // Can call inherited method
```

```
49     dog.eat();           // Can call inherited method
50
51 // Polymorphism works with public inheritance
52 Animal* animal_ptr = &dog;
53 animal_ptr->makeSound(); // Calls Dog::makeSound()
54
55 std::cout << "\n PUBLIC INHERITANCE:" << std::endl;
56 std::cout << " • Dog IS-A Animal" << std::endl;
57 std::cout << " • Public members stay public" << std::endl;
58 std::cout << " • Protected members stay protected" << std::endl;
59 std::cout << " • Polymorphism works (can upcast to base)" << std::endl;
60 std::cout << " • Use for: Substitutability, \"is-a\" relationships" <<
61     std::endl;
62 }
63 // =====
64 // 2. PRIVATE INHERITANCE - "IMPLEMENTED-IN-TERMS-OF"
65 // =====
66
67 // Base class providing timer functionality
68 class Timer {
69 private:
70     int ticks = 0;
71
72 public:
73     void tick() { ++ticks; }
74     void reset() { ticks = 0; }
75     int getTicks() const { return ticks; }
76
77     void display() const {
78         std::cout << "Timer: " << ticks << " ticks" << std::endl;
79     }
80 };
81
82 // Private inheritance: Widget is IMPLEMENTED using Timer
83 // Timer's public interface becomes private in Widget
84 class Widget : private Timer { // "implemented-in-terms-of"
85 private:
86     std::string id;
87
88 public:
89     Widget(const std::string& i) : id(i) {}
90
91     // Widget controls which Timer methods to expose
92     void update() {
93         tick(); // Can call Timer::tick() internally
94         std::cout << "Widget " << id << " updated" << std::endl;
95     }
96
97     void resetState() {
98         reset(); // Can call Timer::reset() internally
99     }
100
101 // Expose only specific functionality
```

```
102     void showUpdateCount() const {
103         std::cout << "Widget " << id << " has been updated "
104                         << getTicks() << " times" << std::endl;
105     }
106
107     // Note: Timer::display() is NOT exposed
108 };
109
110 void example_private_inheritance() {
111     std::cout << "\n==== 2. PRIVATE INHERITANCE (IMPLEMENTED-IN-TERMS-OF) ==="
112                         << std::endl;
113     std::cout << "Use case: Widget is IMPLEMENTED using Timer (code reuse, not
114                         substitutability)\n" << std::endl;
115
116     Widget widget("W1");
117     widget.update();
118     widget.update();
119     widget.update();
120     widget.showUpdateCount();
121
122     // Cannot access Timer's public methods from outside
123     // widget.tick();      // Compile error! tick() is private in Widget
124     // widget.display();  // Compile error! display() is private in Widget
125
126     // Cannot upcast to Timer (no polymorphism)
127     // Timer* timer_ptr = &widget; // Compile error! Private inheritance
128                         breaks is-a
129
130     std::cout << "\n PRIVATE INHERITANCE:" << std::endl;
131     std::cout << " • Widget is IMPLEMENTED using Timer" << std::endl;
132     std::cout << " • All base members become private" << std::endl;
133     std::cout << " • No polymorphism (cannot upcast)" << std::endl;
134     std::cout << " • Base class is an implementation detail" << std::endl;
135     std::cout << " • Use for: Code reuse without exposing interface" << std
136                         ::endl;
137 }
138
139 // =====
140 // 3. PROTECTED INHERITANCE - "IMPLEMENTED-IN-TERMS-OF" FOR FURTHER DERIVATION
141 // =====
142
143 class Logger {
144 public:
145     void log(const std::string& msg) const {
146         std::cout << "[LOG] " << msg << std::endl;
147     }
148
149     void debug(const std::string& msg) const {
150         std::cout << "[DEBUG] " << msg << std::endl;
151     }
152 };
153
154 // Protected inheritance: Component uses Logger, allows derived classes to
155                         access it
```

```
151 class Component : protected Logger {
152 protected:
153     std::string name;
154
155 public:
156     Component(const std::string& n) : name(n) {
157         log("Component " + name + " created"); // Can use Logger internally
158     }
159
160     void doWork() {
161         debug("Component " + name + " is working");
162     }
163 };
164
165 // Derived class can access Logger through protected inheritance
166 class AdvancedComponent : public Component {
167 public:
168     AdvancedComponent(const std::string& n) : Component(n) {
169         // Can access Logger methods because of protected inheritance
170         log("Advanced features initialized");
171     }
172
173     void advancedWork() {
174         debug("Advanced component processing"); // Logger accessible here
175         doWork();
176     }
177 };
178
179 void example_protected_inheritance() {
180     std::cout << "\n==== 3. PROTECTED INHERITANCE (IMPLEMENTED-IN-TERMS-OF +
181             DERIVATION) ===" << std::endl;
182     std::cout << "Use case: Component uses Logger, derived classes can also
183             use it\n" << std::endl;
184
185     AdvancedComponent comp("AC1");
186     comp.advancedWork();
187
188     // Cannot access Logger from outside
189     // comp.log("test"); // Compile error! log() is protected in Component
190     // comp.debug("test"); // Compile error! debug() is protected in Component
191
192     // Cannot upcast to Logger
193     // Logger* logger_ptr = &comp; // Compile error! Protected inheritance
194
195     std::cout << "\n PROTECTED INHERITANCE:" << std::endl;
196     std::cout << " • Component is IMPLEMENTED using Logger" << std::endl;
197     std::cout << " • All base public members become protected" << std::endl;
198     std::cout << " • Derived classes can access base interface" << std::endl
199         ;
200     std::cout << " • No polymorphism (cannot upcast)" << std::endl;
201     std::cout << " • Use for: Implementation detail shared with derived
202             classes" << std::endl;
203 }
```

```
201 // =====
202 // 4. REAL-WORLD EXAMPLE: STACK IMPLEMENTED USING VECTOR
203 // =====
204
205 // Private inheritance: Stack is implemented using vector
206 template<typename T>
207 class Stack : private std::vector<T> {
208     using Base = std::vector<T>;
209
210 public:
211     // Expose only stack operations
212     void push(const T& value) {
213         Base::push_back(value);
214     }
215
216     void push(T&& value) {
217         Base::push_back(std::move(value));
218     }
219
220     void pop() {
221         if (!Base::empty()) {
222             Base::pop_back();
223         }
224     }
225
226     const T& top() const {
227         return Base::back();
228     }
229
230     bool empty() const {
231         return Base::empty();
232     }
233
234     size_t size() const {
235         return Base::size();
236     }
237
238     // Note: We DON'T expose vector's random access, insert, erase, etc.
239     // This enforces stack semantics (LIFO)
240 };
241
242 void example_stack_private_inheritance() {
243     std::cout << "\n== 4. REAL-WORLD: STACK USING PRIVATE INHERITANCE ==" <<
244         std::endl;
245     std::cout << "Use case: Implement Stack using vector, but hide vector's
246         interface\n" << std::endl;
247
248     Stack<int> stack;
249     stack.push(10);
250     stack.push(20);
251     stack.push(30);
252
253     std::cout << "Stack top: " << stack.top() << std::endl;
254     std::cout << "Stack size: " << stack.size() << std::endl;
```

```
253     stack.pop();
254     std::cout << "After pop, top: " << stack.top() << std::endl;
255
256     // Vector operations are hidden
257     // stack[0] = 100;           // Compile error! operator[] not accessible
258     // stack.insert(...);      // Compile error! insert() not accessible
259     // stack.at(0);            // Compile error! at() not accessible
260
261     std::cout << "\n BENEFIT:" << std::endl;
262     std::cout << " • Reuses vector's implementation" << std::endl;
263     std::cout << " • Enforces stack semantics (LIFO only)" << std::endl;
264     std::cout << " • Users cannot break stack invariants" << std::endl;
265 }
266
267 // =====
268 // 5. COMPARISON: PRIVATE INHERITANCE VS COMPOSITION
269 // =====
270
271 // Option 1: Private inheritance
272 class WindowPrivate : private Timer {
273 public:
274     void refresh() {
275         tick();
276         std::cout << "Window refreshed " << getTicks() << " times" << std::endl;
277     }
278 };
279
280 // Option 2: Composition (often preferred)
281 class WindowComposition {
282 private:
283     Timer timer; // Has-a Timer
284
285 public:
286     void refresh() {
287         timer.tick();
288         std::cout << "Window refreshed " << timer.getTicks() << " times" << std::endl;
289     }
290 };
291
292 void example_private_vs_composition() {
293     std::cout << "\n== 5. PRIVATE INHERITANCE VS COMPOSITION ==" << std::endl;
294
295     std::cout << "\nPrivate inheritance:" << std::endl;
296     WindowPrivate win1;
297     win1.refresh();
298     win1.refresh();
299
300     std::cout << "\nComposition:" << std::endl;
301     WindowComposition win2;
302     win2.refresh();
```

```
304     win2.refresh();
305
306     std::cout << "\n WHEN TO USE PRIVATE INHERITANCE:" << std::endl;
307     std::cout << "      Need to override virtual functions from base" << std::endl;
308     std::cout << "      Need access to protected members of base" << std::endl;
309     std::cout << "      Want Empty Base Optimization (EBO) for zero-size bases"
310           << std::endl;
311
312     std::cout << "\n WHEN TO USE COMPOSITION (USUALLY PREFERRED):" << std::endl;
313     std::cout << "      Don't need to override virtual functions" << std::endl;
314     std::cout << "      Don't need access to protected members" << std::endl;
315     std::cout << "      Want to hold multiple instances" << std::endl;
316     std::cout << "      Want more explicit \"has-a\" relationship" << std::endl;
317         ;
318     std::cout << "      Better encapsulation and flexibility" << std::endl;
319 }
320
321 // =====
322 // 6. OVERRIDING VIRTUAL FUNCTIONS WITH PRIVATE INHERITANCE
323 // =====
324
325 class Observable {
326 public:
327     virtual ~Observable() = default;
328
329     virtual void onEvent() {
330         std::cout << "Observable: Event occurred" << std::endl;
331     }
332
333     void triggerEvent() {
334         std::cout << "Triggering event..." << std::endl;
335         onEvent();
336     }
337 };
338
339 // Private inheritance to customize behavior
340 class Sensor : private Observable {
341 private:
342     std::string sensorId;
343     int reading = 0;
344
345     // Override virtual function from Observable
346     void onEvent() override {
347         reading++;
348         std::cout << "Sensor " << sensorId << " received event, reading: " <<
349             reading << std::endl;
350     }
351
352 public:
353     Sensor(const std::string& id) : sensorId(id) {}
354
355     void simulate() {
```

```
353     // Call base class method that will call our overridden onEvent()
354     triggerEvent();
355 }
356 };
357
358 void example_override_with_private() {
359     std::cout << "\n==== 6. OVERRIDING VIRTUAL FUNCTIONS (PRIVATE INHERITANCE)
360         ===" << std::endl;
361     std::cout << "Use case: Customize base class behavior without exposing
362         base interface\n" << std::endl;
363
364     Sensor sensor("TEMP-01");
365     sensor.simulate();
366     sensor.simulate();
367     sensor.simulate();
368
369     std::cout << "\n KEY POINT:" << std::endl;
370     std::cout << " • Can override virtual functions even with private
371         inheritance" << std::endl;
372     std::cout << " • Base class doesn't need to know about derived class" <<
373         std::endl;
374     std::cout << " • This is the main reason to use private inheritance over
375         composition" << std::endl;
376 }
377
378 // =====
379 // 7. USING DECLARATION TO SELECTIVELY EXPOSE MEMBERS
380 // =====
381
382 class Engine {
383 public:
384     void start() { std::cout << "Engine started" << std::endl; }
385     void stop() { std::cout << "Engine stopped" << std::endl; }
386     void diagnose() { std::cout << "Running diagnostics..." << std::endl; }
387     void internalMaintenance() { std::cout << "Internal maintenance" << std::
388         endl; }
389 };
390
391 class Car : private Engine {
392 public:
393     // Selectively expose only specific Engine methods
394     using Engine::start; // Make start() public
395     using Engine::stop; // Make stop() public
396
397     // Note: diagnose() and internalMaintenance() remain private
398
399     void drive() {
400         start();
401         std::cout << "Car is driving" << std::endl;
402     }
403 };
404
405 void example_using_declaration() {
406     std::cout << "\n==== 7. USING DECLARATION - SELECTIVE EXPOSURE ===" << std
```

```
        ::endl;
401 std::cout << "Use case: Expose only specific base class methods\n" << std
        ::endl;

402
403 Car car;
404 car.start();      // Works - exposed via using declaration
405 car.drive();
406 car.stop();       // Works - exposed via using declaration
407
408 // These are not exposed
409 // car.diagnose();           // Compile error!
410 // car.internalMaintenance(); // Compile error!

411
412 std::cout << "\n BENEFIT:" << std::endl;
413 std::cout << " • Fine-grained control over interface" << std::endl;
414 std::cout << " • Can expose some methods while hiding others" << std::
        endl;
415 std::cout << " • More maintainable than forwarding each method manually"
        << std::endl;
416 }
417
418 // =====
419 // 8. ACCESS LEVEL SUMMARY TABLE
420 // =====
421
422 void example_access_summary() {
423     std::cout << "\n== 8. ACCESS LEVEL SUMMARY ==" << std::endl;
424
425     std::cout << "\n";
426     std::cout << " Base Class Member          Public      Protected
427         Private    " << std::endl;
428     std::cout << " Access Level            Inheritance  Inheritance
429         Inheritance " << std::endl;
430     std::cout << "                      " << std::endl;
431     std::cout << " public                 public      protected
432         private    " << std::endl;
433     std::cout << " protected             protected   protected
434         private    " << std::endl;
435     std::cout << " private               (hidden)   (hidden)  (
436         hidden)   " << std::endl;
437     std::cout << "                      " << std::endl;
438 }
439
440 // =====
441 // MAIN FUNCTION
442 // =====
443
444 int main() {
445     std::cout << "\n
446         ====="
447         << std::endl;
448     std::cout << " PRIVATE, PROTECTED, AND PUBLIC INHERITANCE IN C++" << std
        ::endl;
449     std::cout << "
```

```
=====
    std::endl;

443   example_public_inheritance();
444   example_private_inheritance();
445   example_protected_inheritance();
446   example_stack_private_inheritance();
447   example_private_vs_composition();
448   example_override_with_private();
449   example_using_declaration();
450   example_access_summary();

452
453   std::cout << "\n"
454   =====
455   std::cout << "  DECISION GUIDE: WHICH INHERITANCE TYPE TO USE?" << std::
456   endl;
457   std::cout << "
458   =====
459   std::cout << "  USE PUBLIC INHERITANCE WHEN:" << std::endl;
460   std::cout << "  •  Derived class IS-A base class" << std::endl;
461   std::cout << "  •  You need polymorphism and substitutability" << std::
462   endl;
463   std::cout << "  •  Liskov Substitution Principle applies" << std::endl;
464   std::cout << "  •  Example: Dog is-a Animal, Circle is-a Shape" << std::
465   endl;
466   std::cout << "  •  Usage: ~95% of all inheritance cases" << std::endl;

467
468   std::cout << "  USE PRIVATE INHERITANCE WHEN:" << std::endl;
469   std::cout << "  •  Derived class is IMPLEMENTED using base class" << std::
470   endl;
471   std::cout << "  •  Need to override virtual functions from base" << std::
472   endl;
473   std::cout << "  •  Need access to protected members of base" << std::endl;
474   std::cout << "  •  Want Empty Base Optimization (EBO)" << std::endl;
475   std::cout << "  •  Example: Stack implemented using vector" << std::endl;
476   std::cout << "  •  Usage: <5% of inheritance cases" << std::endl;
477   std::cout << "  •  Alternative: Prefer composition if possible" << std::
478   endl;

479
480   std::cout << "  USE PROTECTED INHERITANCE WHEN:" << std::endl;
481   std::cout << "  •  Same as private inheritance, but..." << std::endl;
482   std::cout << "  •  Further derived classes need access to base interface"
483   << std::endl;
484   std::cout << "  •  Creating a hierarchy of implementation details" << std
485   ::endl;
486   std::cout << "  •  Example: Component hierarchy sharing Logger" << std::
487   endl;
488   std::cout << "  •  Usage: <1% of inheritance cases (very rare)" << std::
489   endl;
490   std::cout << "  •  Alternative: Usually better to use composition" << std
491   ::endl;
```

```
480
481     std::cout << "\n COMPOSITION VS PRIVATE INHERITANCE:" << std::endl;
482     std::cout << " • Default to COMPOSITION (has-a relationship)" << std::
483         endl;
484     std::cout << " • Use private inheritance ONLY if:" << std::endl;
485     std::cout << "   - Need to override virtual functions, OR" << std::endl;
486     std::cout << "   - Need access to protected members, OR" << std::endl;
487     std::cout << "   - Need Empty Base Optimization" << std::endl;
488     std::cout << " • Composition is more explicit and flexible" << std::endl
489         ;
490
491     std::cout << "\n MODERN C++ BEST PRACTICES:" << std::endl;
492     std::cout << " • Public inheritance: Use for polymorphism" << std::endl;
493     std::cout << " • Private inheritance: Rare, prefer composition" << std::
494         endl;
495     std::cout << " • Protected inheritance: Almost never use" << std::endl;
496     std::cout << " • If unsure: Choose composition over private inheritance"
497         << std::endl;
498     std::cout << " • Scott Meyers: \"Prefer composition to private
499         inheritance\""
500         << std::endl;
501
502     std::cout << "\n"
503         =====\n"
504         << std::endl;
505
506     return 0;
507 }
```

38 Source Code: InsertAndDeleteNodes.cpp

File: src/InsertAndDeleteNodes.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 using namespace std;
3
4 struct ListNode {
5     int val;
6     ListNode *next;
7     ListNode(int x) : val(x), next(NULL) {}
8 };
9
10 class Solution
11 {
12 public:
13     void PrintListNode(ListNode* inListNode) {
14         if (inListNode != NULL) {
15             cout << inListNode->val << " -> ";
16             PrintListNode(inListNode->next);
17         } else {
18             cout << "NULL" << endl;
19         }
20     }
21
22     void Test(ListNode* inListNode) {
23         delete inListNode;
24         inListNode = NULL;
25         cout << inListNode << endl;
26
27         PrintListNode(inListNode);
28     }
29
30     // Insert node at the beginning of the list
31     ListNode* InsertNodeAtHead(ListNode* pHead, int value) {
32         cout << "Entry: InsertNodeAtHead(value=" << value << ")" << endl;
33
34         ListNode* pNewNode = new ListNode(value);
35         pNewNode->next = pHead;
36
37         cout << "Exit: InsertNodeAtHead" << endl;
38         return pNewNode; // New head
39     }
40
41     // Insert node at the end of the list
42     ListNode* InsertNodeAtTail(ListNode* pHead, int value) {
43         cout << "Entry: InsertNodeAtTail(value=" << value << ")" << endl;
44
45         ListNode* pNewNode = new ListNode(value);
46
47         // Empty list case
48         if (pHead == NULL) {
49             cout << "Exit: InsertNodeAtTail (empty list)" << endl;
```

```
50         return pNewNode;
51     }
52
53     // Traverse to the end
54     ListNode* pCur = pHead;
55     while (pCur->next != NULL) {
56         pCur = pCur->next;
57     }
58
59     pCur->next = pNewNode;
60
61     cout << "Exit: InsertNodeAtTail" << endl;
62     return pHead;
63 }
64
65 // Insert node after a specific node
66 void InsertNodeAfter(ListNode* pPrevNode, int value) {
67     cout << "Entry: InsertNodeAfter(value=" << value << ")" << endl;
68
69     if (pPrevNode == NULL) {
70         cout << "Error: Previous node cannot be NULL" << endl;
71         return;
72     }
73
74     ListNode* pNewNode = new ListNode(value);
75     pNewNode->next = pPrevNode->next;
76     pPrevNode->next = pNewNode;
77
78     cout << "Exit: InsertNodeAfter" << endl;
79 }
80
81 // Insert node at a specific position (0-indexed)
82 ListNode* InsertNodeAtPosition(ListNode* pHead, int position, int value) {
83     cout << "Entry: InsertNodeAtPosition(pos=" << position << ", value="
84             << value << ")" << endl;
85
86     // Insert at head
87     if (position == 0) {
88         return InsertNodeAtHead(pHead, value);
89     }
90
91     // Traverse to position-1
92     ListNode* pCur = pHead;
93     for (int i = 0; i < position - 1 && pCur != NULL; i++) {
94         pCur = pCur->next;
95     }
96
97     if (pCur == NULL) {
98         cout << "Error: Position out of bounds" << endl;
99         return pHead;
100    }
101
102    InsertNodeAfter(pCur, value);
```

```
103     cout << "Exit: InsertNodeAtPosition" << endl;
104     return pHead;
105 }
106
107 // Insert node in sorted list (ascending order)
108 ListNode* InsertNodeSorted(ListNode* pHead, int value) {
109     cout << "Entry: InsertNodeSorted(value=" << value << ")" << endl;
110
111     ListNode* pNewNode = new ListNode(value);
112
113     // Empty list or insert at head
114     if (pHead == NULL || pHead->val >= value) {
115         pNewNode->next = pHead;
116         cout << "Exit: InsertNodeSorted (at head)" << endl;
117         return pNewNode;
118     }
119
120     // Find insertion point
121     ListNode* pCur = pHead;
122     while (pCur->next != NULL && pCur->next->val < value) {
123         pCur = pCur->next;
124     }
125
126     pNewNode->next = pCur->next;
127     pCur->next = pNewNode;
128
129     cout << "Exit: InsertNodeSorted" << endl;
130     return pHead;
131 }
132
133 void DeleteNode(ListNode* pInHead, ListNode* pToBeDeleted) {
134     cout << "Entry void DeleteNode(ListNode* pInHead, ListNode*"
135           pToBeDeleted)\n" << endl;
136
137     // Check NULL always
138     if (pInHead == NULL || pToBeDeleted == NULL) {
139         cout << "Abort void DeleteNode(ListNode* pInHead, ListNode*"
140           pToBeDeleted)\n" << endl;
141         return;
142     }
143
144     // PrintListNode(pInHead);
145
146     // Delete non-tail node including head node
147     if (pToBeDeleted->next != NULL) {
148         ListNode* pNext = pToBeDeleted->next;
149         pToBeDeleted->val = pNext->val;
150         pToBeDeleted->next = pNext->next;
151
152         delete pNext;
153         pNext = NULL;
154     } else { // Delete tail
155         ListNode* pPre = pInHead;
```

```
155     while (pPre->next != pToBeDeleted && pPre != NULL) {
156         pPre = pPre->next;
157     }
158     if (pPre == NULL)
159         return;
160
161     pPre->next = NULL;
162     delete pToBeDeleted;
163     pToBeDeleted = NULL;
164 }
165
166 cout << "Exit void DeleteNode(ListNode* pInHead, ListNode*
167     pToBeDeleted)\n" << endl;
168 }
169
170 // Delete node by value
171 ListNode* DeleteNodeByValue(ListNode* pHead, int value) {
172     cout << "Entry: DeleteNodeByValue(value=" << value << ")" << endl;
173
174     if (pHead == NULL) {
175         cout << "Error: Empty list" << endl;
176         return NULL;
177     }
178
179     // Delete head node
180     if (pHead->val == value) {
181         ListNode* pTemp = pHead;
182         pHead = pHead->next;
183         delete pTemp;
184         cout << "Exit: DeleteNodeByValue (deleted head)" << endl;
185         return pHead;
186     }
187
188     // Find and delete node
189     ListNode* pCur = pHead;
190     while (pCur->next != NULL && pCur->next->val != value) {
191         pCur = pCur->next;
192     }
193
194     if (pCur->next == NULL) {
195         cout << "Error: Value not found" << endl;
196         return pHead;
197     }
198
199     ListNode* pToDelete = pCur->next;
200     pCur->next = pCur->next->next;
201     delete pToDelete;
202
203     cout << "Exit: DeleteNodeByValue" << endl;
204     return pHead;
205 }
206 };
207 }
```

```
208 void TestInsertOperations() {
209     cout << "\n" << string(70, '=') << endl;
210     cout << "TESTING INSERT OPERATIONS\n";
211     cout << string(70, '=') << endl;
212
213     Solution solution;
214     ListNode* pHead = NULL;
215
216     // Test 1: Insert at head (empty list)
217     cout << "\n--- Test 1: Insert at head (empty list) ---" << endl;
218     pHead = solution.InsertNodeAtHead(pHead, 10);
219     solution.PrintListNode(pHead);
220
221     // Test 2: Insert at head (non-empty list)
222     cout << "\n--- Test 2: Insert at head (non-empty list) ---" << endl;
223     pHead = solution.InsertNodeAtHead(pHead, 5);
224     solution.PrintListNode(pHead);
225
226     // Test 3: Insert at tail
227     cout << "\n--- Test 3: Insert at tail ---" << endl;
228     pHead = solution.InsertNodeAtTail(pHead, 20);
229     pHead = solution.InsertNodeAtTail(pHead, 25);
230     solution.PrintListNode(pHead);
231
232     // Test 4: Insert after specific node
233     cout << "\n--- Test 4: Insert after second node ---" << endl;
234     solution.InsertNodeAfter(pHead->next, 15);
235     solution.PrintListNode(pHead);
236
237     // Test 5: Insert at position
238     cout << "\n--- Test 5: Insert at position 2 ---" << endl;
239     pHead = solution.InsertNodeAtPosition(pHead, 2, 12);
240     solution.PrintListNode(pHead);
241
242     // Clean up
243     while (pHead != NULL) {
244         ListNode* temp = pHead;
245         pHead = pHead->next;
246         delete temp;
247     }
248 }
249
250 void TestInsertSorted() {
251     cout << "\n" << string(70, '=') << endl;
252     cout << "TESTING INSERT IN SORTED LIST\n";
253     cout << string(70, '=') << endl;
254
255     Solution solution;
256     ListNode* pHead = NULL;
257
258     // Insert values in random order
259     int values[] = {30, 10, 50, 20, 40};
260
261     for (int val : values) {
```

```
262     cout << "\nInserting " << val << " into sorted list:" << endl;
263     pHead = solution.InsertNodeSorted(pHead, val);
264     solution.PrintListNode(pHead);
265 }
266
267 // Clean up
268 while (pHead != NULL) {
269     ListNode* temp = pHead;
270     pHead = pHead->next;
271     delete temp;
272 }
273 }
274
275 void TestDeleteOperations() {
276     cout << "\n" << string(70, '=') << endl;
277     cout << "TESTING DELETE OPERATIONS\n";
278     cout << string(70, '=') << endl;
279
280     Solution testSolution;
281     int count = 5;
282
283     for (int k = 0; k <= count; k++) {
284         ListNode* pHead = NULL;
285         ListNode* pCur = NULL;
286         ListNode* pDel = NULL;
287
288         cout << "\n--- Creating list and deleting node at position " << k << "
289             " ---" << endl;
290
291         for (int i = 0; i < count; i++) {
292             ListNode* pTemp = new ListNode(i);
293
294             if (i == 0) {
295                 pHead = pCur = pTemp;
296             }
297             else {
298                 pCur->next = pTemp;
299                 pCur = pCur->next; // pCur->next == pTemp
300             }
301
302             if (i == k)
303                 pDel = pTemp;
304         }
305
306         cout << "Original list: ";
307         testSolution.PrintListNode(pHead);
308
309         testSolution.DeleteNode(pHead, pDel);
310
311         cout << "After deletion: ";
312         testSolution.PrintListNode(pHead);
313
314         // Clean up remaining nodes
315         while (pHead != NULL) {
```

```
315     ListNode* temp = pHead;
316     pHead = pHead->next;
317     delete temp;
318 }
319 }
320 }
321
322 void TestDeleteByValue() {
323     cout << "\n" << string(70, '=') << endl;
324     cout << "TESTING DELETE BY VALUE\n";
325     cout << string(70, '=') << endl;
326
327     Solution solution;
328     ListNode* pHead = NULL;
329
330     // Create list: 10 -> 20 -> 30 -> 40 -> 50
331     pHead = solution.InsertNodeAtTail(pHead, 10);
332     pHead = solution.InsertNodeAtTail(pHead, 20);
333     pHead = solution.InsertNodeAtTail(pHead, 30);
334     pHead = solution.InsertNodeAtTail(pHead, 40);
335     pHead = solution.InsertNodeAtTail(pHead, 50);
336
337     cout << "\nOriginal list: ";
338     solution.PrintListNode(pHead);
339
340     // Delete middle node
341     cout << "\nDeleting 30:" << endl;
342     pHead = solution.DeleteNodeByValue(pHead, 30);
343     solution.PrintListNode(pHead);
344
345     // Delete head node
346     cout << "\nDeleting 10 (head):" << endl;
347     pHead = solution.DeleteNodeByValue(pHead, 10);
348     solution.PrintListNode(pHead);
349
350     // Delete tail node
351     cout << "\nDeleting 50 (tail):" << endl;
352     pHead = solution.DeleteNodeByValue(pHead, 50);
353     solution.PrintListNode(pHead);
354
355     // Clean up
356     while (pHead != NULL) {
357         ListNode* temp = pHead;
358         pHead = pHead->next;
359         delete temp;
360     }
361 }
362
363 int main () {
364     cout << "\n";
365     cout << "                                     \n";
366     cout << "           LINKED LIST INSERT AND DELETE OPERATIONS
367     \n";
368     cout << "
```

```
368     cout << "    Demonstrates various insertion and deletion techniques
369     \n";
370     cout << "                                \n";
371     TestInsertOperations();
372     TestInsertSorted();
373     TestDeleteOperations();
374     TestDeleteByValue();
375
376     cout << "\n" << string(70, '=') << endl;
377     cout << "ALL TESTS COMPLETED\n";
378     cout << string(70, '=') << endl;
379     cout << endl;
380
381     return 0;
382 }
```

39 Source Code: LambdaCaptures.cpp

File: src/LambdaCaptures.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <memory>
4 #include <functional>
5 #include <vector>
6 #include <future>
7 #include <thread>
8
9 // =====
10 // 1. NO CAPTURE []
11 // =====
12 void example_no_capture() {
13     std::cout << "\n== 1. NO CAPTURE [] ==" << std::endl;
14
15     int global_counter = 100; // Global-like variable
16
17     // Lambda can only access its parameters and static/global variables
18     auto lambda = []() {
19         static int static_var = 42;
20         std::cout << "Static variable: " << static_var++ << std::endl;
21         return static_var;
22     };
23
24     std::cout << "Call 1: " << lambda() << std::endl; // 43
25     std::cout << "Call 2: " << lambda() << std::endl; // 44
26 }
27
28 // =====
29 // 2. CAPTURE ALL BY VALUE [=]
30 // =====
31 void example_capture_all_by_value() {
32     std::cout << "\n== 2. CAPTURE ALL BY VALUE [=] ==" << std::endl;
33
34     int x = 10;
35     int y = 20;
36     int z = 30; // Not referenced, so not captured
37
38     auto lambda = [=]() { // Captures x and y by value
39         std::cout << "x = " << x << ", y = " << y << std::endl;
40         // Cannot modify: x and y are const copies
41         // x = 100; // ERROR!
42         return x + y;
43     };
44
45     x = 100; // Change original
46     std::cout << "Lambda result: " << lambda() << std::endl; // Still 30
47         (10+20)
48     std::cout << "Original x after: " << x << std::endl; // 100
}
```

```
49 // =====
50 // 3. CAPTURE ALL BY REFERENCE [&]
51 // =====
52
53 void example_capture_all_by_reference() {
54     std::cout << "\n==> 3. CAPTURE ALL BY REFERENCE [&] ==>" << std::endl;
55
56     int x = 10;
57     int y = 20;
58
59     auto lambda = [&]() { // Captures x and y by reference
60         std::cout << "Before modify: x = " << x << ", y = " << y << std::endl;
61         x = 100; // Modifies original
62         y = 200; // Modifies original
63         return x + y;
64     };
65
66     std::cout << "Before lambda: x=" << x << ", y=" << y << std::endl; // 10,
67     20
68     std::cout << "Lambda result: " << lambda() << std::endl; // 300
69     std::cout << "After lambda: x=" << x << ", y=" << y << std::endl; //
70     100, 200
71 }
72
73 // =====
74 // 4. CAPTURE SPECIFIC BY VALUE [var]
75 // =====
76
77 void example_specific_capture_by_value() {
78     std::cout << "\n==> 4. CAPTURE SPECIFIC BY VALUE [var] ==>" << std::endl;
79
80     int a = 1, b = 2, c = 3;
81
82     auto lambda = [a, c]() { // Only captures a and c by value
83         std::cout << "a = " << a << ", c = " << c << std::endl;
84         // b is not accessible here
85         return a + c;
86     };
87
88     a = 100; // Change original
89     std::cout << "Lambda result: " << lambda() << std::endl; // 4 (1+3)
90     std::cout << "Original a after: " << a << std::endl; // 100
91 }
92
93 // =====
94 // 5. CAPTURE SPECIFIC BY REFERENCE [&var]
95 // =====
96
97 void example_specific_capture_by_reference() {
98     std::cout << "\n==> 5. CAPTURE SPECIFIC BY REFERENCE [&var] ==>" << std::endl;
99
100    int a = 1, b = 2, c = 3;
101
102    auto lambda = [&a, &c]() { // Only captures a and c by reference
103        std::cout << "Before modify: a = " << a << ", c = " << c << std::endl;
```

```
100     a = 10; // Modifies original a
101     c = 30; // Modifies original c
102     return a + c;
103 }
104
105 std::cout << "Before lambda: a=" << a << ", c=" << c << std::endl; // 1,
106     3
107 std::cout << "Lambda result: " << lambda() << std::endl; // 40
108 std::cout << "After lambda: a=" << a << ", c=" << c << std::endl; // 10,
109     30
110 }
111
112 // =====
113 // 6. MIXED CAPTURE [=, &var]
114 // =====
115 void example_mixed_capture_value_default() {
116     std::cout << "\n==== 6. MIXED CAPTURE [=, &var] ===" << std::endl;
117
118     int x = 10, y = 20, z = 30;
119
120     auto lambda = [=, &z]() { // x,y by value, z by reference
121         std::cout << "x=" << x << ", y=" << y << ", z=" << z << std::endl;
122         // x = 100; // ERROR: captured by value
123         z = 300; // OK: captured by reference
124         return x + y + z;
125     };
126
127     std::cout << "Before lambda: z=" << z << std::endl; // 30
128     std::cout << "Lambda result: " << lambda() << std::endl; // 330
129     std::cout << "After lambda: z=" << z << std::endl; // 300
130 }
131
132 // =====
133 // 7. MIXED CAPTURE [&, var]
134 // =====
135 void example_mixed_capture_reference_default() {
136     std::cout << "\n==== 7. MIXED CAPTURE [&, var] ===" << std::endl;
137
138     int x = 10, y = 20, z = 30;
139
140     auto lambda = [&, y]() { // x,z by reference, y by value
141         std::cout << "x=" << x << ", y=" << y << ", z=" << z << std::endl;
142         x = 100; // OK: captured by reference
143         // y = 200; // ERROR: captured by value
144         z = 300; // OK: captured by reference
145         return x + y + z;
146     };
147
148     std::cout << "Before lambda: x=" << x << ", y=" << y << ", z=" << z << std
149         ::endl; // 10,20,30
150     std::cout << "Lambda result: " << lambda() << std::endl; // 420
151     std::cout << "After lambda: x=" << x << ", y=" << y << ", z=" << z << std
152         ::endl; // 100,20,300
153 }
```

```
150 // =====
151 // 8. CAPTURE THIS POINTER [this]
152 // =====
153 class ExampleClass {
154 private:
155     int member_var = 42;
156     std::string name = "TestClass";
157
158 public:
159     void example_capture_this() {
160         std::cout << "\n== 8. CAPTURE THIS POINTER [this] ==" << std::endl;
161
162         int local_var = 100;
163
164         auto lambda = [this, local_var]() {
165             std::cout << "Member var: " << member_var << std::endl;
166             std::cout << "Name: " << name << std::endl;
167             std::cout << "Local var: " << local_var << std::endl;
168             member_var = 999; // Can modify member through this
169             return member_var + local_var;
170         };
171
172         std::cout << "Before lambda: member_var=" << member_var << std::endl;
173         // 42
174         std::cout << "Lambda result: " << lambda() << std::endl;
175         // 1099
176         std::cout << "After lambda: member_var=" << member_var << std::endl;
177         // 999
178     }
179 }
180 // =====
181 // 9. CAPTURE *THIS [*this] (C++17)
182 // =====
183 class ExampleClass2 {
184 private:
185     int value = 42;
186
187 public:
188     void example_capture_star_this() {
189         std::cout << "\n== 9. CAPTURE *THIS [*this] (C++17) ==" << std::endl
190         ;
191
192         std::cout << "Original object value: " << value << std::endl;
193
194         // Capture a copy of the entire object
195         auto lambda = [*this]() mutable {
196             std::cout << "Copied object value: " << value << std::endl;
197             value = 100; // Modifies the copy
198             return value;
199         };
200
201         // Simulate async usage
```

```
200     auto future = std::async(std::launch::async, lambda);
201
202     std::cout << "Original unchanged during async: " << value << std::endl
203         ; // 42
204     std::cout << "Async result (copy modified): " << future.get() << std::endl
205         ; // 100
206     std::cout << "Original still: " << value << std::endl; // 42
207 }
208
209 // =====
210 // 10. MUTABLE LAMBDA
211 // =====
212 void example Mutable_lambda() {
213     std::cout << "\n==> 10. MUTABLE LAMBDA ==>" << std::endl;
214
215     int x = 10;
216     int counter = 0;
217
218     // Without mutable - cannot modify captured values
219     // auto lambda1 = [x, counter]() {
220     //     counter++; // ERROR
221     //     return x + counter;
222     // };
223
224     // With mutable - can modify captured copies
225     auto lambda2 = [x, counter]() mutable {
226         std::cout << "Before increment: x=" << x << ", counter=" << counter <<
227             std::endl;
228         x += 5; // Can modify captured copy
229         counter++; // Can modify captured copy
230         std::cout << "After increment: x=" << x << ", counter=" << counter <<
231             std::endl;
232         return x + counter;
233     };
234
235     std::cout << "Before lambda: counter=" << counter << std::endl; // 0
236     std::cout << "Lambda result 1: " << lambda2() << std::endl; // 16
237         (15+1)
238     std::cout << "Lambda result 2: " << lambda2() << std::endl; // 22
239         (20+2)
240     std::cout << "Original unchanged: counter=" << counter << std::endl; // 0
241 }
242
243 // =====
244 // 11. CAPTURE WITH INITIALIZATION (C++14)
245 // =====
246 void example Capture_with_initialization() {
247     std::cout << "\n==> 11. CAPTURE WITH INITIALIZATION (C++14) ==>" << std::endl;
248
249     int x = 10;
250     std::string str = "Hello";
251 }
```

```

247 // C++14: Capture with initialization expressions
248 auto lambda1 = [value = x * 2, message = str + " World"]() {
249     std::cout << "value = " << value << std::endl;           // 20
250     std::cout << "message = " << message << std::endl;    // "Hello World"
251     return value;
252 };
253
254 auto lambda2 = [&ref = x]() { // Capture reference with custom name
255     ref = 100;   // Modifies original x
256     return ref;
257 };
258
259 std::cout << "Lambda1 result: " << lambda1() << std::endl; // 20
260 std::cout << "Before lambda2: x=" << x << std::endl;        // 10
261 std::cout << "Lambda2 result: " << lambda2() << std::endl; // 100
262 std::cout << "After lambda2: x=" << x << std::endl;        // 100
263
264 // Capture unique_ptr
265 auto lambda3 = [ptr = std::make_unique<int>(42)]() {
266     return *ptr;
267 };
268 std::cout << "Lambda3 with unique_ptr: " << lambda3() << std::endl; // 42
269 }
270
271 // =====
272 // 12. MULTIPLE SPECIFIC CAPTURES
273 // =====
274 void example_multiple_specific_captures() {
275     std::cout << "\n== 12. MULTIPLE SPECIFIC CAPTURES ==" << std::endl;
276
277     int a = 1, b = 2, c = 3, d = 4, e = 5;
278
279     auto lambda = [a, &b, c, &d]() { // Mix of value and reference
280         std::cout << "Captured: a=" << a << ", b=" << b
281             << ", c=" << c << ", d=" << d << std::endl;
282         b = 20; // OK: reference
283         d = 40; // OK: reference
284         // a = 10; // ERROR: value capture
285         return a + b + c + d;
286     };
287
288     std::cout << "Before lambda: a=" << a << ", b=" << b
289             << ", c=" << c << ", d=" << d << std::endl; // 1,2,3,4
290     std::cout << "Lambda result: " << lambda() << std::endl; // 66
291             (1+20+3+40)
292     std::cout << "After lambda: a=" << a << ", b=" << b
293             << ", c=" << c << ", d=" << d << std::endl; // 1,20,3,40
294 }
295
296 // =====
297 // 13. PRACTICAL EXAMPLE: EVENT HANDLER
298 // =====
299 void example_event_handler() {
300     std::cout << "\n== 13. PRACTICAL EXAMPLE: EVENT HANDLER ==" << std::endl

```

```
300 ;
301
302 class Button {
303 private:
304     std::vector<std::function<void()>> click_handlers;
305     std::string label;
306
307 public:
308     Button(const std::string& lbl) : label(lbl) {}
309
310     void add_handler(std::function<void()> handler) {
311         click_handlers.push_back(handler);
312     }
313
314     void click() {
315         std::cout << "Button '" << label << "' clicked!" << std::endl;
316         for (auto& handler : click_handlers) {
317             handler();
318         }
319     }
320 };
321
322 std::string username = "Alice";
323 int click_count = 0;
324
325 Button button("Submit");
326
327 // Capture username by value, click_count by reference
328 button.add_handler([username, &click_count]() {
329     std::cout << "Hello " << username << "!" << std::endl;
330     click_count++;
331     std::cout << "Click count: " << click_count << std::endl;
332 });
333
334 button.click(); // Hello Alice! Click count: 1
335 button.click(); // Hello Alice! Click count: 2
336
337 username = "Bob"; // Change doesn't affect captured value
338
339 button.click(); // Still: Hello Alice! Click count: 3
340
341 // =====
342 // 14. DANGEROUS EXAMPLE: DANGLING REFERENCE
343 // =====
344 void example_dangling_reference() {
345     std::cout << "\n==== 14. DANGEROUS: DANGLING REFERENCE ===" << std::endl;
346
347     std::function<void()> dangerous_lambda;
348
349 {
350     int local_variable = 42;
351
352     // CAPTURE BY REFERENCE - DANGER!
```

```
353     dangerous_lambda = [&local_variable]() {
354         std::cout << "Local variable: " << local_variable << std::endl;
355         // UNDEFINED!
356     };
357
358     // local_variable will be destroyed when scope ends
359 }
360
361 std::cout << "WARNING: Calling lambda with dangling reference..." << std::endl;
362 // dangerous_lambda(); // UNDEFINED BEHAVIOR - might crash
363
364 // SAFE ALTERNATIVE
365 std::function<void()> safe_lambda;
366 {
367     int local_variable = 42;
368     safe_lambda = [local_variable]() { // Capture by value
369         std::cout << "Safe: captured value = " << local_variable << std::endl;
370     };
371 }
372
373 safe_lambda(); // Safe! Outputs: 42
374 }
375 // =====
376 // 15. COMPREHENSIVE EXAMPLE: ALL IN ONE
377 // =====
378 void comprehensive_example() {
379     std::cout << "\n==== 15. COMPREHENSIVE EXAMPLE ===" << std::endl;
380
381     int x = 1, y = 2, z = 3;
382     static int static_var = 100;
383
384     std::cout << "Creating multiple lambdas with different captures:" << std::endl;
385
386     // 1. No capture
387     auto lambda1 = []() {
388         std::cout << " Lambda1: No capture, static=" << static_var++ << std::endl;
389     };
390
391     // 2. Capture all by value
392     auto lambda2 = [=]() {
393         std::cout << " Lambda2: All by value, x=" << x << ", y=" << y << std::endl;
394     };
395
396     // 3. Capture all by reference
397     auto lambda3 = [&]() {
398         std::cout << " Lambda3: All by ref, before x=" << x;
399         x = 10;
400         std::cout << ", after x=" << x << std::endl;
```

```
401    };  
402  
403    // 4. Specific captures  
404    auto lambda4 = [x, &y]() {  
405        std::cout << " Lambda4: x by value=" << x << ", y by ref=" << y <<  
406        std::endl;  
407        y = 20;  
408    };  
409  
410    // 5. Mixed capture  
411    auto lambda5 = [=, &z]() {  
412        std::cout << " Lambda5: x,y by value, z by ref, z=" << z << std::endl  
413        ;  
414        z = 30;  
415    };  
416  
417    // 6. Mutable  
418    auto lambda6 = [x]() mutable {  
419        std::cout << " Lambda6: Mutable, x before=" << x;  
420        x = 100; // Modifies copy  
421        std::cout << ", x after=" << x << std::endl;  
422    };  
423  
424    // Execute all  
425    lambda1();  
426    lambda2();  
427    lambda3();  
428    lambda4();  
429    lambda5();  
430    lambda6();  
431  
432    std::cout << "\nFinal values: x=" << x << ", y=" << y << ", z=" << z <<  
433    std::endl;  
434  
435    // ======  
436    // MAIN FUNCTION  
437    // ======  
438    int main() {  
439        std::cout << "  
440        ======  
441        << std::endl;  
442        std::cout << "COMPLETE C++ LAMBDA CAPTURE EXAMPLES IN ONE FILE" << std:::  
443        endl;  
444        std::cout << "  
445        ======  
446        << std::endl;  
447  
448        // Run all examples  
449        example_no_capture();  
450        example_capture_all_by_value();  
451        example_capture_all_by_reference();  
452        example_specific_capture_by_value();  
453        example_specific_capture_by_reference();
```

```
447     example_mixed_capture_value_default();
448     example_mixed_capture_reference_default();
449
450     ExampleClass obj1;
451     obj1.example_capture_this();
452
453     ExampleClass2 obj2;
454     obj2.example_capture_star_this();
455
456     example_mutable_lambda();
457     example_capture_with_initialization();
458     example_multiple_specific_captures();
459     example_event_handler();
460     example_dangling_reference();
461     comprehensive_example();
462
463     std::cout << "\n"
464         =====
465         << std::endl;
466     std::cout << "ALL EXAMPLES COMPLETED SUCCESSFULLY!" << std::endl;
467     std::cout << "
468         =====
469         << std::endl;
470
471     return 0;
472 }
```

40 Source Code: MISRACppDemo.cpp

File: src/MISRACppDemo.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // MISRA C++ CODING GUIDELINES DEMONSTRATION
3 // =====
4 // Demonstrates key MISRA C++ rules for safety-critical systems
5 // MISRA C++:2008 and MISRA C++:2023 guidelines
6 //
7 // MISRA C++ focuses on:
8 // - Avoiding undefined behavior
9 // - Avoiding implementation-defined behavior
10 // - Defensive programming practices
11 // - Code clarity and maintainability
12 // - Safety in automotive, aerospace, medical devices
13 //
14 // Build: g++ -std=c++20 -Wall -Wextra -Wpedantic -O2 -o MISRACppDemo
15 // MISRACppDemo.cpp
16 // =====
17 #include <iostream>
18 #include <cstdint>
19 #include <array>
20 #include <limits>
21 #include <memory>
22 #include <string>
23 #include <algorithm> // for std::copy_n
24 //
25 // =====
26 // RULE CATEGORY 1: TYPES AND DECLARATIONS
27 // =====
28
29 namespace types_and_declarations {
30
31 // MISRA Rule 3-9-1: Use fixed-width integer types from <cstdint>
32 // Rationale: Ensures portability across platforms
33
34 // BAD: Platform-dependent types
35 void bad_types() {
36     std::cout << "\n BAD: Platform-dependent types\n";
37
38     int x = 100;           // Size undefined (16, 32, or 64 bits?)
39     long y = 1000;         // Size undefined (32 or 64 bits?)
40     unsigned int z = 500;  // Size undefined
41
42     std::cout << "    int size: " << sizeof(x) << " bytes (undefined!)\n";
43     std::cout << "    long size: " << sizeof(y) << " bytes (undefined!)\n";
44 }
45
46 // GOOD: Fixed-width types
47 void good_types() {
48     std::cout << "\n GOOD: Fixed-width types\n";
```

```
49      int32_t x = 100;           // Always 32 bits
50      int64_t y = 1000;          // Always 64 bits
51      uint32_t z = 500;          // Always unsigned 32 bits
52
53      std::cout << "    int32_t: " << x << " (always 32 bits)\n";
54      std::cout << "    int64_t: " << y << " (always 64 bits)\n";
55      std::cout << "    uint32_t: " << z << " (always unsigned 32 bits)\n";
56
57 }
58
59 // MISRA Rule 4-5-1: Expressions with type bool shall not be used with
60 // operators other than
61 // ==, !=, !=, !, &&, ||
62
63 // BAD: Arithmetic on bool
64 void bad_bool_usage() {
65     std::cout << "\n BAD: Arithmetic on bool\n";
66
67     bool flag1 = true;
68     bool flag2 = false;
69
70     // int result = flag1 + flag2; // MISRA violation!
71     // int value = flag1 * 5;      // MISRA violation!
72
73     std::cout << "    Arithmetic on bool is prohibited by MISRA\n";
74 }
75
76 // GOOD: Proper bool usage
77 void good_bool_usage() {
78     std::cout << "\n GOOD: Proper bool usage\n";
79
80     bool flag1 = true;
81     bool flag2 = false;
82
83     bool result = flag1 && flag2; // OK: logical operator
84     bool equal = (flag1 == flag2); // OK: comparison
85     bool negate = !flag1;        // OK: logical NOT
86
87     std::cout << "    flag1 && flag2 = " << result << "\n";
88     std::cout << "    flag1 == flag2 = " << equal << "\n";
89 }
90
91 void demonstrate() {
92     std::cout << "\n" << std::string(70, '=') << "\n";
93     std::cout << "MISRA CATEGORY 1: TYPES AND DECLARATIONS\n";
94     std::cout << std::string(70, '=') << "\n";
95
96     bad_types();
97     good_types();
98     bad_bool_usage();
99     good_bool_usage();
100 }
```

```
102 // =====
103 // RULE CATEGORY 2: EXPRESSIONS AND OPERATORS
104 // =====
105
106
107 namespace expressions_and_operators {
108
109 // MISRA Rule 5-0-21: Bitwise operators shall only be applied to operands of
110 // unsigned type
111
112 // BAD: Bitwise operations on signed integers
113 void bad_bitwise() {
114     std::cout << "\n BAD: Bitwise operations on signed integers\n";
115
116     int32_t signed_val = -1;
117     // int32_t result = signed_val << 2; // MISRA violation! Undefined
118     // behavior
119     // int32_t mask = signed_val & 0xFF; // MISRA violation!
120
121     std::cout << "    Bitwise ops on signed integers can cause undefined
122     behavior\n";
123 }
124
125 // GOOD: Bitwise operations on unsigned integers
126 void good_bitwise() {
127     std::cout << "\n GOOD: Bitwise operations on unsigned integers\n";
128
129     uint32_t unsigned_val = 0xF0;
130     uint32_t result = unsigned_val << 2; // OK: unsigned
131     uint32_t mask = unsigned_val & 0xFF; // OK: unsigned
132
133     std::cout << "    unsigned_val << 2 = 0x" << std::hex << result << "\n";
134     std::cout << "    unsigned_val & 0xFF = 0x" << mask << std::dec << "\n";
135 }
136
137 // MISRA Rule 5-0-5: There shall be no implicit floating-integral conversions
138
139 // BAD: Implicit conversions
140 void bad_conversions() {
141     std::cout << "\n BAD: Implicit floating-integral conversions\n";
142
143     float f = 3.14f;
144     // int32_t i = f; // MISRA violation! Implicit conversion
145     // float result = 5 + f; // MISRA violation! Mixed type arithmetic
146
147     std::cout << "    Implicit float-int conversions lose precision\n";
148 }
149
150 // GOOD: Explicit conversions
151 void good_conversions() {
152     std::cout << "\n GOOD: Explicit conversions\n";
153
154     float f = 3.14f;
155     int32_t i = static_cast<int32_t>(f); // OK: explicit cast
```

```
153     float result = static_cast<float>(5) + f; // OK: explicit cast
154
155     std::cout << "    static_cast<int32_t>(3.14f) = " << i << "\n";
156     std::cout << "    Explicit casts make intent clear\n";
157 }
158
159 // MISRA Rule 5-0-6: An implicit integral or floating-point conversion shall
160 // not reduce
161 // the size of the underlying type
162
163 // BAD: Narrowing conversions
164 void bad_narrowing() {
165     std::cout << "\n BAD: Narrowing conversions\n";
166
167     int64_t large = 1000000;
168     // int16_t small = large; // MISRA violation! Data loss possible
169
170     std::cout << "    Narrowing conversions can lose data\n";
171 }
172
173 // GOOD: Safe conversions or explicit narrowing
174 void good_narrowing() {
175     std::cout << "\n GOOD: Safe conversions with range checks\n";
176
177     int64_t large = 1000;
178
179     // Check before narrowing
180     if (large <= std::numeric_limits<int16_t>::max() &&
181         large >= std::numeric_limits<int16_t>::min()) {
182         int16_t small = static_cast<int16_t>(large); // OK: checked and
183         explicit
184         std::cout << "    Safe narrowing: " << small << "\n";
185     } else {
186         std::cout << "    Value out of range for int16_t\n";
187     }
188 }
189
190 void demonstrate() {
191     std::cout << "\n" << std::string(70, '=') << "\n";
192     std::cout << "MISRA CATEGORY 2: EXPRESSIONS AND OPERATORS\n";
193     std::cout << std::string(70, '=') << "\n";
194
195     bad_bitwise();
196     good_bitwise();
197     bad_conversions();
198     good_conversions();
199     bad_narrowing();
200     good_narrowing();
201 }
202
203 // =====
204 // RULE CATEGORY 3: STATEMENTS
```

```
205 // =====
206
207 namespace statements {
208
209 // MISRA Rule 6-4-1: An if (condition) construct shall be followed by a
210 // compound statement
211 // MISRA Rule 6-4-4: A switch statement shall have at least two case clauses
212
213 // BAD: Single-statement if without braces
214 void bad_if_statements() {
215     std::cout << "\n BAD: Single-statement if without braces\n";
216
217     int32_t value = 5;
218
219     // if (value > 0)
220     //     std::cout << "Positive\n"; // MISRA violation! No braces
221
222     std::cout << "    Missing braces can lead to errors during maintenance\n";
223 }
224
225 // GOOD: Always use braces
226 void good_if_statements() {
227     std::cout << "\n GOOD: Always use braces\n";
228
229     int32_t value = 5;
230
231     if (value > 0) { // OK: compound statement
232         std::cout << "    Positive\n";
233     } else {
234         std::cout << "    Non-positive\n";
235     }
236
237 // MISRA Rule 6-4-5: An unconditional throw or break shall terminate every non
238 // -empty
239 // switch clause
240
241 // BAD: Fall-through in switch
242 void bad_switch(int32_t value) {
243     std::cout << "\n BAD: Fall-through in switch\n";
244
245     // switch (value) {
246     //     case 1:
247     //         std::cout << "One\n";
248     //         // Fall-through! MISRA violation
249     //     case 2:
250     //         std::cout << "Two\n";
251     //         break;
252     //     default:
253     //         std::cout << "Other\n";
254     // }
255
256     std::cout << "    Fall-through is error-prone\n";
257 }
```

```
257
258 // GOOD: Explicit break in every case
259 void good_switch(int32_t value) {
260     std::cout << "\n GOOD: Explicit break in every case\n";
261
262     switch (value) {
263         case 1: {
264             std::cout << "    One\n";
265             break;
266         }
267         case 2: {
268             std::cout << "    Two\n";
269             break;
270         }
271         default: {
272             std::cout << "    Other\n";
273             break;
274         }
275     }
276 }
277
278 // MISRA Rule 6-6-1, 6-6-2: Any label referenced by a goto shall be in the
279 // same block
280
281 // BAD: goto usage (generally prohibited)
282 void bad_goto() {
283     std::cout << "\n BAD: goto usage\n";
284     std::cout << "    MISRA strongly discourages or prohibits goto\n";
285     std::cout << "    Use structured programming instead\n";
286 }
287
288 // GOOD: Structured programming
289 void good_structured() {
290     std::cout << "\n GOOD: Structured programming\n";
291
292     bool error_occurred = false;
293
294     // Instead of goto for error handling, use early return
295     if (error_occurred) {
296         std::cout << "    Error handled with early return\n";
297         return;
298     }
299
300     std::cout << "    Normal execution path\n";
301 }
302
303 void demonstrate() {
304     std::cout << "\n" << std::string(70, '=') << "\n";
305     std::cout << "MISRA CATEGORY 3: STATEMENTS\n";
306     std::cout << std::string(70, '=') << "\n";
307
308     bad_if_statements();
309     good_if_statements();
```

```
310     bad_switch(1);
311     good_switch(1);
312     bad_goto();
313     good_structured();
314 }
315
316 } // namespace statements
317
318 // =====
319 // RULE CATEGORY 4: FUNCTIONS
320 // =====
321
322 namespace functions {
323
324 // MISRA Rule 8-4-2: All exit paths from a function with non-void return type
325 // shall have
326 // an explicit return statement
327
328 // BAD: Missing return in some paths
329 // int32_t bad_function(int32_t value) {
330 //     if (value > 0) {
331 //         return value;
332 //     }
333 //     // MISRA violation! Missing return for value <= 0
334 // }
335
336 // GOOD: All paths have explicit return
337 int32_t good_function(int32_t value) {
338     if (value > 0) {
339         return value;
340     } else {
341         return 0;
342     }
343
344 // MISRA Rule 8-4-4: A function with no parameters shall be declared with
345 // parameter (void)
346
347 // BAD: Empty parameter list in C++
348 // void bad_no_params(); // In C++, this is OK, but MISRA prefers explicit
349 // void
350
351 // GOOD: Explicit void for clarity (C-style, but clearer)
352 void good_no_params(void) {
353     std::cout << "    Function with explicit void parameter list\n";
354
355 // MISRA Rule 7-1-1: A variable that is not modified shall be const qualified
356
357 // BAD: Non-const variable that isn't modified
358 void bad_const_usage() {
359     std::cout << "\n BAD: Non-const variable that isn't modified\n";
360
361     int32_t value = 100; // MISRA violation! Should be const
```

```
361     std::cout << "    Value: " << value << "\n";
362 }
363
364 //  GOOD: const-qualified for immutable data
365 void good_const_usage() {
366     std::cout << "\n GOOD: const-qualified for immutable data\n";
367
368     const int32_t value = 100; // OK: const qualifier
369     std::cout << "    Value: " << value << "\n";
370 }
371
372 void demonstrate() {
373     std::cout << "\n" << std::string(70, '=') << "\n";
374     std::cout << "MISRA CATEGORY 4: FUNCTIONS\n";
375     std::cout << std::string(70, '=') << "\n";
376
377     std::cout << "\n GOOD: All paths return a value\n";
378     std::cout << "    good_function(5) = " << good_function(5) << "\n";
379     std::cout << "    good_function(-5) = " << good_function(-5) << "\n";
380
381     good_no_params();
382
383     bad_const_usage();
384     good_const_usage();
385 }
386
387 } // namespace functions
388
389 // =====
390 // RULE CATEGORY 5: ARRAYS AND POINTERS
391 // =====
392
393 namespace arrays_and_pointers {
394
395 // MISRA Rule 5-0-15: Array indexing shall be the only form of pointer
396 // arithmetic
397
398 // BAD: Pointer arithmetic
399 void bad_pointer_arithmetic() {
400     std::cout << "\n BAD: Pointer arithmetic\n";
401
402     int32_t arr[5] = {1, 2, 3, 4, 5};
403     int32_t* ptr = arr;
404
405     // ptr++;           // MISRA violation!
406     // int32_t val = *(ptr + 2); // MISRA violation!
407
408     std::cout << "    Pointer arithmetic is error-prone\n";
409 }
410
411 //  GOOD: Array indexing
412 void good_array_indexing() {
413     std::cout << "\n GOOD: Array indexing\n";
```

```
414     std::array<int32_t, 5> arr = {1, 2, 3, 4, 5};  
415  
416     for (size_t i = 0; i < arr.size(); ++i) {  
417         std::cout << "    arr[" << i << "] = " << arr[i] << "\n";  
418     }  
419 }  
420  
421 // MISRA Rule 5-0-16: The result of pointer subtraction shall not be used  
422  
423 // BAD: Pointer subtraction  
424 void bad_pointer_subtraction() {  
425     std::cout << "\n BAD: Pointer subtraction\n";  
426  
427     int32_t arr[5] = {1, 2, 3, 4, 5};  
428     int32_t* p1 = &arr[0];  
429     int32_t* p2 = &arr[3];  
430  
431     // ptrdiff_t diff = p2 - p1; // MISRA violation!  
432  
433     std::cout << "    Pointer subtraction should be avoided\n";  
434 }  
435  
436 // GOOD: Use indices instead  
437 void good_index_difference() {  
438     std::cout << "\n GOOD: Use indices instead\n";  
439  
440     std::array<int32_t, 5> arr = {1, 2, 3, 4, 5};  
441     size_t idx1 = 0;  
442     size_t idx2 = 3;  
443  
444     size_t diff = idx2 - idx1;  
445     std::cout << "    Index difference: " << diff << "\n";  
446 }  
447  
448 // MISRA Rule: Use std::array instead of C-style arrays  
449  
450 // BAD: C-style arrays  
451 void bad_c_arrays() {  
452     std::cout << "\n BAD: C-style arrays\n";  
453  
454     int32_t arr[10]; // MISRA prefers std::array  
455     arr[0] = 1;  
456  
457     std::cout << "    C-style arrays lack bounds checking\n";  
458 }  
459  
460 // GOOD: std::array with bounds checking  
461 void good_std_array() {  
462     std::cout << "\n GOOD: std::array with bounds checking\n";  
463  
464     std::array<int32_t, 10> arr{};  
465     arr.at(0) = 1; // Bounds-checked access  
466  
467     std::cout << "    arr.at(0) = " << arr.at(0) << "\n";
```

```
468     std::cout << "    std::array provides bounds checking with at()\n";
469 }
470
471 void demonstrate() {
472     std::cout << "\n" << std::string(70, '=') << "\n";
473     std::cout << "MISRA CATEGORY 5: ARRAYS AND POINTERS\n";
474     std::cout << std::string(70, '=') << "\n";
475
476     bad_pointer_arithmetic();
477     good_array_indexing();
478     bad_pointer_subtraction();
479     good_index_difference();
480     bad_c_arrays();
481     good_std_array();
482 }
483
484 } // namespace arrays_and_pointers
485
486 // =====
487 // RULE CATEGORY 6: CLASSES
488 // =====
489
490 namespace classes {
491
492 // MISRA Rule 12-8-1: A copy constructor shall only initialize its base
493 // classes and the
494 // non-static members of the class of which it is a member
495
496 // GOOD: Proper class design
497 class Resource {
498 private:
499     int32_t* data_;
500     size_t size_;
501
502 public:
503     // Constructor
504     explicit Resource(size_t size)
505         : data_(new int32_t[size]), size_(size) {
506         std::cout << "[Resource] Constructor: allocated " << size_ <<
507             " ints\n";
508     }
509
510     // Destructor
511     ~Resource() {
512         delete[] data_;
513         std::cout << "[Resource] Destructor: freed memory\n";
514     }
515
516     // MISRA Rule: Define all special members or none (Rule of Five)
517     Resource(const Resource& other)
518         : data_(new int32_t[other.size_]), size_(other.size_) {
519             std::copy_n(other.data_, size_, data_);
520             std::cout << "[Resource] Copy constructor\n";
521     }
```

```
520
521     Resource& operator=(const Resource& other) {
522         if (this != &other) {
523             delete[] data_;
524             size_ = other.size_;
525             data_ = new int32_t[size_];
526             std::copy_n(other.data_, size_, data_);
527         }
528         std::cout << "    [Resource] Copy assignment\n";
529         return *this;
530     }
531
532     Resource(Resource&& other) noexcept
533         : data_(other.data_), size_(other.size_) {
534         other.data_ = nullptr;
535         other.size_ = 0;
536         std::cout << "    [Resource] Move constructor\n";
537     }
538
539     Resource& operator=(Resource&& other) noexcept {
540         if (this != &other) {
541             delete[] data_;
542             data_ = other.data_;
543             size_ = other.size_;
544             other.data_ = nullptr;
545             other.size_ = 0;
546         }
547         std::cout << "    [Resource] Move assignment\n";
548         return *this;
549     }
550
551     size_t size() const { return size_; }
552 };
553
554 // MISRA Rule: Virtual destructor for base classes
555
556 // BAD: Base class without virtual destructor
557 class BadBase {
558 public:
559     ~BadBase() { // MISRA violation! Should be virtual
560         std::cout << "    [BadBase] Destructor\n";
561     }
562 };
563
564 // GOOD: Virtual destructor for polymorphic base
565 class GoodBase {
566 public:
567     virtual ~GoodBase() {
568         std::cout << "    [GoodBase] Virtual destructor\n";
569     }
570
571     virtual void process() = 0;
572 };
573
```

```
574 class Derived : public GoodBase {
575 public:
576     void process() override {
577         std::cout << "[Derived] Processing\n";
578     }
579
580     ~Derived() override {
581         std::cout << "[Derived] Destructor\n";
582     }
583 };
584
585 void demonstrate() {
586     std::cout << "\n" << std::string(70, '=') << "\n";
587     std::cout << "MISRA CATEGORY 6: CLASSES\n";
588     std::cout << std::string(70, '=') << "\n";
589
590     std::cout << "\n GOOD: Rule of Five implementation\n";
591 {
592     Resource r1(5);
593     Resource r2 = r1; // Copy
594     Resource r3 = std::move(r1); // Move
595 }
596
597 std::cout << "\n GOOD: Virtual destructor for polymorphism\n";
598 {
599     std::unique_ptr<GoodBase> ptr = std::make_unique<Derived>();
600     ptr->process();
601 }
602 }
603
604 } // namespace classes
605
606 // =====
607 // RULE CATEGORY 7: EXCEPTION HANDLING
608 // =====
609
610 namespace exception_handling {
611
612 // MISRA Rule 15-1-1: Only throw exceptions for exceptional conditions
613 // MISRA Rule 15-3-1: Exceptions shall be used only for error handling
614
615 // BAD: Using exceptions for control flow
616 void bad_exception_usage() {
617     std::cout << "\n BAD: Using exceptions for control flow\n";
618
619     // try {
620     //     // Don't use exceptions for normal flow!
621     //     throw 42;
622     // } catch (int value) {
623     //     // Control flow via exception (BAD!)
624     // }
625
626     std::cout << "    Exceptions should only be used for errors\n";
627 }
```

```
628 //    GOOD: Exceptions for error handling only
629 //void good_exception_usage() {
630 //    std::cout << "\n GOOD: Exceptions for error handling\n";
631 //
632 //    try {
633 //        // Simulate error condition
634 //        throw std::runtime_error("Genuine error occurred");
635 //    } catch (const std::exception& e) {
636 //        std::cout << "    Caught exception: " << e.what() << "\n";
637 //    }
638 //}
639 //
640 //
641 // MISRA Note: Many safety-critical systems disable exceptions entirely
642 void no_exceptions_approach() {
643     std::cout << "\n ALTERNATIVE: Error codes (no exceptions)\n";
644     std::cout << "    Many MISRA-compliant projects compile with -fno-
645         exceptions\n";
646     std::cout << "    Use error codes, std::optional, or std::expected instead\
647         n";
648 }
649 void demonstrate() {
650     std::cout << "\n" << std::string(70, '=') << "\n";
651     std::cout << "MISRA CATEGORY 7: EXCEPTION HANDLING\n";
652     std::cout << std::string(70, '=') << "\n";
653     bad_exception_usage();
654     good_exception_usage();
655     no_exceptions_approach();
656 }
657 }
658 // namespace exception_handling
659 //
660 // =====
661 // MAIN - Demonstrate All MISRA C++ Categories
662 // =====
663 //
664 int main() {
665     std::cout << "\n";
666     std::cout << "                                \n";
667     std::cout << "                                MISRA C++ CODING GUIDELINES
668                                     \n";
669     std::cout << "                                Safety-Critical Software Development
670                                     \n";
671     std::cout << "                                \n";
672     try {
673         types_and_declarations::demonstrate();
674         expressions_and_operators::demonstrate();
675         statements::demonstrate();
676         functions::demonstrate();
677         arrays_and_pointers::demonstrate();
678         classes::demonstrate();
```

```
678     exception_handling::demonstrate();  
679  
680     // Summary  
681     std::cout << "\n" << std::string(70, '=') << "\n";  
682     std::cout << "SUMMARY: KEY MISRA C++ PRINCIPLES\n";  
683     std::cout << std::string(70, '=') << "\n\n";  
684  
685     std::cout << " MISRA C++ OBJECTIVES:\n";  
686     std::cout << " • Avoid undefined behavior\n";  
687     std::cout << " • Avoid implementation-defined behavior\n";  
688     std::cout << " • Maximize portability\n";  
689     std::cout << " • Enhance code clarity and maintainability\n";  
690     std::cout << " • Enable thorough code review and testing\n\n";  
691  
692     std::cout << " KEY PRACTICES:\n";  
693     std::cout << " 1. Use fixed-width types (int32_t, uint32_t)\n";  
694     std::cout << " 2. Always use braces for if/while/for\n";  
695     std::cout << " 3. No pointer arithmetic (use array indexing)\n";  
696     std::cout << " 4. Explicit conversions (avoid implicit casts)\n";  
697     std::cout << " 5. const-qualify immutable data\n";  
698     std::cout << " 6. Virtual destructors for polymorphic classes\n";  
699     std::cout << " 7. Rule of Five for resource-managing classes\n";  
700     std::cout << " 8. Prefer std::array over C-style arrays\n\n";  
701  
702     std::cout << " APPLICATION DOMAINS:\n";  
703     std::cout << " • Automotive (ISO 26262)\n";  
704     std::cout << " • Aerospace (DO-178C)\n";  
705     std::cout << " • Medical devices (IEC 62304)\n";  
706     std::cout << " • Industrial control systems\n";  
707     std::cout << " • Railway (EN 50128)\n\n";  
708  
709     std::cout << " NOTE:\n";  
710     std::cout << " Many MISRA-compliant projects also:\n";  
711     std::cout << " • Disable exceptions (-fno-exceptions)\n";  
712     std::cout << " • Disable RTTI (-fno-rtti)\n";  
713     std::cout << " • Limit or prohibit dynamic memory allocation\n";  
714     std::cout << " • Use static analysis tools (PC-lint, Coverity, etc.)  
    \n\n";  
715  
716     std::cout << "                                         \n";  
717     std::cout << "                         ALL MISRA C++ CATEGORIES DEMONSTRATED!  
    \n";  
718     std::cout << "                                         \n\n";  
719  
720 } catch (const std::exception& e) {  
721     std::cerr << " Error: " << e.what() << "\n";  
722     return 1;  
723 }  
724  
725     return 0;  
726 }
```

41 Source Code: MockInterview.cpp

File: src/MockInterview.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // COMPLETE C++ INTERVIEW QUESTIONS & ANSWERS
3 // =====
4 // Comprehensive collection of C++ interview questions with detailed answers
5 // covering fundamentals, memory management, OOP, templates, concurrency,
6 // and optimization techniques.
7 //
8 // Topics covered:
9 // - C++ Fundamentals (pointers, references, const)
10 // - Memory Management (smart pointers, allocators, alignment)
11 // - OOP & Design Patterns (virtual dispatch, CRTP, PIMPL)
12 // - Templates & Metaprogramming (SFINAE, variadic, compile-time)
13 // - Concurrency (lock-free, thread pools, atomics)
14 // - Performance & Optimization (cache-friendly, branch prediction)
15 //
16 // Build: g++ -std=c++20 -pthread -O2 -o MockInterview MockInterview.cpp
17 // Run: ./MockInterview
18 // =====
19
20 #include <iostream>
21 #include <memory>
22 #include <thread>
23 #include <mutex>
24 #include <atomic>
25 #include <vector>
26 #include <list>
27 #include <unordered_map>
28 #include <optional>
29 #include <functional>
30 #include <queue>
31 #include <condition_variable>
32 #include <shared_mutex>
33 #include <future>
34 #include <array>
35 #include <type_traits>
36 #include <variant>
37 #include <any>
38 #include <tuple>
39 #include <string>
40 #include <algorithm>
41 #include <numeric>
42 #include <random>
43 #include <chrono>
44 #include <cstdio>
45 #include <stdexcept>
46
47 using namespace std;
48
49 // =====
```

```
50 // SECTION 1: C++ FUNDAMENTALS
51 // =====
52
53 // ===== Q1.1: Pointers vs References =====
54 void pointers_vs_references() {
55     cout << "\n== POINTERS VS REFERENCES ==\n";
56
57     int x = 10;
58     int y = 20;
59
60     // Reference - alias, must be initialized, cannot be null
61     int& ref = x;
62     ref = 30; // Changes x
63
64     // Pointer - stores address, can be null, can be reassigned
65     int* ptr = &x;
66     *ptr = 40; // Changes x
67     ptr = &y; // Now points to y
68
69     cout << "x = " << x << ", y = " << y << endl;
70     cout << "ref = " << ref << ", *ptr = " << *ptr << endl;
71
72     // Key differences:
73     cout << "\nKey Differences:" << endl;
74     cout << "1. References must be initialized, pointers can be null" << endl;
75     cout << "2. References cannot be reassigned, pointers can" << endl;
76     cout << "3. sizeof(reference) = sizeof(object), sizeof(pointer) = platform
77         dependent" << endl;
78     cout << "4. References have cleaner syntax, pointers more flexible" <<
79         endl;
80 }
81
82 // ===== Q1.2: Const Correctness =====
83 void const_correctness() {
84     cout << "\n== CONST CORRECTNESS ==\n";
85
86     class Data {
87         mutable int counter; // Can be modified even in const methods
88         int value;
89
90         public:
91             Data(int v) : counter(0), value(v) {}
92
93             // 1. Non-const getter - can only be called on non-const objects
94             int getValue() {
95                 cout << "Non-const getValue" << endl;
96                 return value;
97             }
98
99             // 2. Const getter - can be called on both const and non-const objects
100            int getValue() const {
101                cout << "Const getValue" << endl;
102                counter++; // OK because counter is mutable
103                return value;
104 }
```

```
102     }
103
104     // 3. Const reference return - prevents modification
105     const int& getValueRef() const {
106         cout << "Const reference getter" << endl;
107         return value;
108     }
109 };
110
111 Data d1(42);
112 const Data d2(100);
113
114 d1.getValue();      // Calls non-const version
115 d2.getValue();      // Calls const version
116 // d2.getValueRef() = 50; // ERROR: Cannot modify through const reference
117
118 cout << "\nConst Rules:" << endl;
119 cout << "1. const methods can be called on const objects" << endl;
120 cout << "2. const methods cannot modify non-mutable members" << endl;
121 cout << "3. Return const references to prevent modification" << endl;
122 cout << "4. Use mutable for members that don't affect logical state" <<
123     endl;
124 }
125
126 // ===== Q1.3: RAII Pattern =====
127 class FileHandler {
128     FILE* file;
129
130 public:
131     FileHandler(const char* filename, const char* mode) {
132         file = fopen(filename, mode);
133         if (!file) {
134             throw runtime_error("Failed to open file");
135         }
136         cout << "File opened: " << filename << endl;
137     }
138
139     ~FileHandler() {
140         if (file) {
141             fclose(file);
142             cout << "File closed" << endl;
143         }
144     }
145
146     // Delete copy operations
147     FileHandler(const FileHandler&) = delete;
148     FileHandler& operator=(const FileHandler&) = delete;
149
150     // Allow move operations
151     FileHandler(FileHandler&& other) noexcept : file(other.file) {
152         other.file = nullptr;
153     }
154     FileHandler& operator=(FileHandler&& other) noexcept {
```

```
155     if (this != &other) {
156         if (file) fclose(file);
157         file = other.file;
158         other.file = nullptr;
159     }
160     return *this;
161 }
162
163 void write(const string& data) {
164     if (file) {
165         fputs(data.c_str(), file);
166     }
167 }
168 };
169
170 void raii_demo() {
171     cout << "\n==== RAI (Resource Acquisition Is Initialization) ====\n";
172
173     try {
174         FileHandler file("test_interview.txt", "w");
175         file.write("Hello RAI!\n");
176         // File automatically closed when scope ends
177     } catch (const exception& e) {
178         cout << "Exception: " << e.what() << endl;
179     }
180
181     cout << "\nRAII Principles:" << endl;
182     cout << "1. Acquire resource in constructor" << endl;
183     cout << "2. Release resource in destructor" << endl;
184     cout << "3. Use stack unwinding for exception safety" << endl;
185     cout << "4. Smart pointers, locks, containers use RAI" << endl;
186 }
187
188 // =====
189 // SECTION 2: MEMORY MANAGEMENT
190 // =====
191
192 // ===== Q2.1: Smart Pointers Deep Dive =====
193 void smart_pointers_advanced() {
194     cout << "\n==== SMART POINTERS ADVANCED ====\n";
195
196     // 1. Custom deleters
197     {
198         cout << "\n1. Custom Deleters:" << endl;
199         auto deleter = [](int* p) {
200             cout << "Custom delete: " << *p << endl;
201             delete p;
202         };
203
204         unique_ptr<int, decltype(deleter)> ptr1(new int(42), deleter);
205         shared_ptr<int> ptr2(new int(100), [](int* p) {
206             cout << "Lambda deleter: " << *p << endl;
207             delete p;
208         });
209     }
```

```
209 }
210
211 // 2. Aliasing constructor
212 {
213     cout << "\n2. Aliasing Constructor:" << endl;
214     struct Data {
215         int x = 10;
216         int y = 20;
217     };
218
219     auto data_ptr = make_shared<Data>();
220     auto x_ptr = shared_ptr<int>(data_ptr, &data_ptr->x);
221     auto y_ptr = shared_ptr<int>(data_ptr, &data_ptr->y);
222
223     cout << "Use count: " << data_ptr.use_count() << endl;
224     cout << "x_ptr points to x but shares ownership of Data" << endl;
225 }
226
227 // 3. enable_shared_from_this
228 {
229     cout << "\n3. enable_shared_from_this:" << endl;
230     class Widget : public enable_shared_from_this<Widget> {
231     public:
232         shared_ptr<Widget> get_shared() {
233             return shared_from_this(); // Safe even if multiple
234                         shared_ptrs exist
235         }
236     };
237
238     auto widget = make_shared<Widget>();
239     auto another_ref = widget->get_shared();
240     cout << "Use count: " << widget.use_count() << endl;
241 }
242
243 // ===== Q2.2: Memory Alignment =====
244 void memory_alignment() {
245     cout << "\n==== MEMORY ALIGNMENT ===\n";
246
247     struct BadLayout {
248         char c;           // 1 byte
249         int i;            // 4 bytes (may need 3 bytes padding after c)
250         double d;          // 8 bytes
251         char c2;          // 1 byte (7 bytes padding at end)
252         // Total: 1 + 3(pad) + 4 + 8 + 1 + 7(pad) = 24 bytes
253     };
254
255     struct GoodLayout {
256         double d;          // 8 bytes
257         int i;            // 4 bytes
258         char c;           // 1 byte
259         char c2;          // 1 byte (2 bytes padding at end)
260         // Total: 8 + 4 + 1 + 1 + 2(pad) = 16 bytes
261     };
}
```

```
262     cout << "sizeof(BadLayout): " << sizeof(BadLayout) << " bytes" << endl;
263     cout << "sizeof(GoodLayout): " << sizeof(GoodLayout) << " bytes" << endl;
264     cout << "Savings: " << (sizeof(BadLayout) - sizeof(GoodLayout)) << " bytes"
265         " << endl;
266
267     cout << "\nAlignment Rules:" << endl;
268     cout << "1. Data type must be aligned to its size boundary" << endl;
269     cout << "2. struct alignment = largest member alignment" << endl;
270     cout << "3. Reorder members from largest to smallest" << endl;
271     cout << "4. Use alignas() for custom alignment" << endl;
272     cout << "5. Cache line size typically 64 bytes" << endl;
273 }
274
275 // =====
276 // SECTION 3: OOP & DESIGN PATTERNS
277 // =====
278
279 // ===== Q3.1: Virtual Dispatch Mechanics =====
280 void virtual_dispatch_details() {
281     cout << "\n== VIRTUAL DISPATCH MECHANICS ==\n";
282
283     class Base {
284     public:
285         virtual void func1() { cout << "Base::func1" << endl; }
286         virtual void func2() { cout << "Base::func2" << endl; }
287         virtual ~Base() {}
288     };
289
290     class Derived : public Base {
291     public:
292         void func1() override { cout << "Derived::func1" << endl; }
293         void func3() { cout << "Derived::func3" << endl; } // Not in vtable
294     };
295
296     // How virtual call works:
297     Base* b = new Derived();
298     b->func1();
299
300     cout << "\nVirtual call process:" << endl;
301     cout << "1. Object contains vptr (pointer to vtable)" << endl;
302     cout << "2. vtable contains function pointers" << endl;
303     cout << "3. b->func1() becomes: (*b->vptr[0])()" << endl;
304     cout << "4. vptr[0] points to Derived::func1" << endl;
305
306     // Multiple inheritance
307     class Base2 {
308     public:
309         virtual void func4() { cout << "Base2::func4" << endl; }
310         virtual ~Base2() {}
311     };
312
313     class MultiDerived : public Base, public Base2 {
314     public:
```

```
315     void func1() override { cout << "MultiDerived::func1" << endl; }
316     void func4() override { cout << "MultiDerived::func4" << endl; }
317 };
318
319 MultiDerived md;
320 Base* b1 = &md;
321 Base2* b2 = &md;
322
323 cout << "\nMultiple inheritance layout:" << endl;
324 cout << "MultiDerived object has TWO vptrs" << endl;
325 cout << "b1 and b2 point to different subobjects" << endl;
326 cout << "Address difference: " << (long long)b2 - (long long)b1 << " bytes
327     " << endl;
328
329 delete b;
330 }
331 // ===== Q3.2: CRTP with Mixins =====
332 template<typename Derived>
333 class Printable {
334 public:
335     void print() const {
336         cout << static_cast<const Derived*>(this)->to_string() << endl;
337     }
338 };
339
340 template<typename Derived>
341 class Comparable {
342 public:
343     bool operator==(const Comparable& other) const {
344         return static_cast<const Derived*>(this)->get_id() ==
345             static_cast<const Derived*>(&other)->get_id();
346     }
347 };
348
349 class Widget : public Printable<Widget>, public Comparable<Widget> {
350     int id;
351     string name;
352
353 public:
354     Widget(int i, string n) : id(i), name(move(n)) {}
355
356     string to_string() const {
357         return "Widget[" + std::to_string(id) + ", " + name + "]";
358     }
359
360     int get_id() const { return id; }
361 };
362
363 void crtp_mixins_demo() {
364     cout << "\n== CRTP WITH MIXINS ==\n";
365
366     Widget w1(1, "First");
367     Widget w2(2, "Second");
```

```
368     Widget w3(1, "Another");
369
370     w1.print();
371     w2.print();
372
373     cout << "w1 == w2: " << (w1 == w2) << endl;
374     cout << "w1 == w3: " << (w1 == w3) << endl;
375
376     cout << "\nCRTP Mixin Benefits:" << endl;
377     cout << "1. Compile-time polymorphism" << endl;
378     cout << "2. No vtable overhead" << endl;
379     cout << "3. Can combine multiple behaviors" << endl;
380     cout << "4. Type-safe at compile time" << endl;
381 }
382
383 // =====
384 // SECTION 4: TEMPLATES & METaproGRAMMING
385 // =====
386
387 // ===== Q4.1: SFINAE Techniques =====
388 template<typename T>
389 auto print_value_impl(const T& value, int)
390     -> decltype(cout << value, void()) {
391     cout << "Printable: " << value << endl;
392 }
393
394 template<typename T>
395 void print_value_impl(const T&, long) {
396     cout << "Not printable" << endl;
397 }
398
399 template<typename T>
400 void print_value(const T& value) {
401     print_value_impl(value, 0);
402 }
403
404 // SFINAE with enable_if
405 template<typename T>
406 typename enable_if<is_integral<T>::value, void>::type
407 process(T value) {
408     cout << "Processing integral: " << value << endl;
409 }
410
411 template<typename T>
412 typename enable_if<is_floating_point<T>::value, void>::type
413 process(T value) {
414     cout << "Processing float: " << value << endl;
415 }
416
417 void sfinae_demo() {
418     cout << "\n== SFINAE TECHNIQUES ==\n";
419
420     print_value(42);
421     print_value(vector<int>{1, 2, 3});
```

```
422     process(10);      // Integral version
423     process(3.14);    // Float version
425 }
426
427 // ===== Q4.2: Variadic Templates =====
428 template<typename... Args>
429 void print_all(Args&&... args) {
430     (cout << ... << args) << endl;    // C++17 fold expression
431 }
432
433 void variadic_demo() {
434     cout << "\n==== VARIADIC TEMPLATES ====\n";
435
436     print_all("Hello", " ", "World", " ", 2024, "!");
437
438     cout << "\nVariadic Benefits:" << endl;
439     cout << "1. Type-safe variadic functions" << endl;
440     cout << "2. Compile-time expansion" << endl;
441     cout << "3. Perfect forwarding support" << endl;
442 }
443
444 // ===== Q4.3: Compile-Time Computation =====
445 constexpr int factorial(int n) {
446     if (n <= 1) return 1;
447     return n * factorial(n - 1);
448 }
449
450 template<int N>
451 struct Factorial {
452     static constexpr int value = N * Factorial<N-1>::value;
453 };
454
455 template<>
456 struct Factorial<0> {
457     static constexpr int value = 1;
458 };
459
460 void compile_time_demo() {
461     cout << "\n==== COMPILE-TIME COMPUTATION ====\n";
462
463     constexpr int fact = factorial(5);
464     cout << "Factorial(5) at compile time: " << fact << endl;
465
466     cout << "Template factorial(5): " << Factorial<5>::value << endl;
467
468     // Static asserts
469     static_assert(factorial(5) == 120, "Compile-time factorial failed");
470     static_assert(Factorial<5>::value == 120, "Template factorial failed");
471
472     cout << "\nCompile-Time Benefits:" << endl;
473     cout << "1. Zero runtime overhead" << endl;
474     cout << "2. Computed during compilation" << endl;
475     cout << "3. Can be used in constant expressions" << endl;
```

```
476 }
477
478 // =====
479 // SECTION 5: CONCURRENCY & MULTITHREADING
480 // =====
481
482 // ===== Q5.1: Thread-Safe Singleton =====
483 class ThreadSafeSingleton {
484     static mutex instance_mutex;
485     static unique_ptr<ThreadSafeSingleton> instance;
486
487     ThreadSafeSingleton() {
488         cout << "Singleton created" << endl;
489     }
490
491 public:
492     static ThreadSafeSingleton& getInstance() {
493         // C++11 guarantees thread-safe static initialization
494         static ThreadSafeSingleton instance;
495         return instance;
496     }
497
498     // Better: use call_once
499     static ThreadSafeSingleton& getInstanceCallOnce() {
500         static once_flag flag;
501         call_once(flag, []() {
502             cout << "Initialized with call_once" << endl;
503         });
504         static ThreadSafeSingleton instance;
505         return instance;
506     }
507
508     void doSomething() {
509         cout << "Singleton method called" << endl;
510     }
511
512     // Delete copy/move
513     ThreadSafeSingleton(const ThreadSafeSingleton&) = delete;
514     ThreadSafeSingleton& operator=(const ThreadSafeSingleton&) = delete;
515 };
516
517 void singleton_demo() {
518     cout << "\n==== THREAD-SAFE SINGLETON ===\n";
519
520     vector<thread> threads;
521     for (int i = 0; i < 5; ++i) {
522         threads.emplace_back([]() {
523             ThreadSafeSingleton::getInstance().doSomething();
524         });
525     }
526
527     for (auto& t : threads) {
528         t.join();
529     }
```

```
530     cout << "\nSingleton Patterns:" << endl;
531     cout << "1. Meyer's Singleton (C++11 static init)" << endl;
532     cout << "2. std::call_once for initialization" << endl;
533     cout << "3. Double-checked locking (avoid!)" << endl;
534     cout << "4. Thread-local storage (per-thread instances)" << endl;
535 }
537
538 // ===== Q5.2: Producer-Consumer with Condition Variables =====
539 class ProducerConsumer {
540     queue<int> buffer;
541     mutex mtx;
542     condition_variable cv_producer, cv_consumer;
543     const size_t max_size = 10;
544     bool done = false;
545
546 public:
547     void produce(int id, int count) {
548         for (int i = 0; i < count; ++i) {
549             unique_lock lock(mtx);
550             cv_producer.wait(lock, [this] {
551                 return buffer.size() < max_size || done;
552             });
553
554             if (done) break;
555
556             buffer.push(id * 100 + i);
557             cout << "Produced: " << (id * 100 + i) << " (buffer size: " <<
558                 buffer.size() << ")" << endl;
559
560             cv_consumer.notify_one();
561             this_thread::sleep_for(chrono::milliseconds(50));
562         }
563     }
564
565     void consume(int id, int count) {
566         for (int i = 0; i < count; ++i) {
567             unique_lock lock(mtx);
568             cv_consumer.wait(lock, [this] {
569                 return !buffer.empty() || done;
570             });
571
572             if (done && buffer.empty()) break;
573
574             int value = buffer.front();
575             buffer.pop();
576             cout << "Consumed: " << value << " by consumer " << id << " (
577                 buffer size: " << buffer.size() << ")" << endl;
578
579             cv_producer.notify_one();
580             this_thread::sleep_for(chrono::milliseconds(100));
581         }
582     }
583 }
```

```
582     void stop() {
583     {
584         lock_guard lock(mtx);
585         done = true;
586     }
587     cv_producer.notify_all();
588     cv_consumer.notify_all();
589 }
590 };
591
592 void producer_consumer_demo() {
593     cout << "\n== PRODUCER-CONSUMER PATTERN ==\n";
594
595     ProducerConsumer pc;
596
597     thread producer1([&pc]() { pc.produce(1, 5); });
598     thread producer2([&pc]() { pc.produce(2, 5); });
599     thread consumer1([&pc]() { pc.consume(1, 5); });
600     thread consumer2([&pc]() { pc.consume(2, 5); });
601
602     producer1.join();
603     producer2.join();
604     consumer1.join();
605     consumer2.join();
606
607     pc.stop();
608
609     cout << "\nCondition Variable Best Practices:" << endl;
610     cout << "1. Always use with a mutex" << endl;
611     cout << "2. Use wait() with predicate to avoid spurious wakeups" << endl;
612     cout << "3. notify_one() vs notify_all()" << endl;
613     cout << "4. Consider separate CVs for different conditions" << endl;
614 }
615
616 // ===== Q5.3: Atomic Operations =====
617 void atomic_operations_demo() {
618     cout << "\n== ATOMIC OPERATIONS ==\n";
619
620     atomic<int> counter{0};
621     atomic<bool> ready{false};
622
623     vector<thread> threads;
624     for (int i = 0; i < 10; ++i) {
625         threads.emplace_back([&counter, &ready]() {
626             while (!ready.load(memory_order_acquire)) {
627                 this_thread::yield();
628             }
629
630             for (int j = 0; j < 1000; ++j) {
631                 counter.fetch_add(1, memory_order_relaxed);
632             }
633         });
634     }
635 }
```

```
636     ready.store(true, memory_order_release);
637
638     for (auto& t : threads) {
639         t.join();
640     }
641
642     cout << "Final counter value: " << counter.load() << " (expected: 10000)"
643         << endl;
644
645     cout << "\nAtomic Operation Types:" << endl;
646     cout << "1. load/store - read/write atomic value" << endl;
647     cout << "2. fetch_add/fetch_sub - atomic arithmetic" << endl;
648     cout << "3. compare_exchange_weak/strong - CAS operations" << endl;
649     cout << "4. Memory ordering: relaxed, acquire, release, seq_cst" << endl;
650 }
651 // =====
652 // SECTION 6: PERFORMANCE & OPTIMIZATION
653 // =====
654
655 // ===== Q6.1: Move Semantics Performance =====
656 class LargeObject {
657     vector<int> data;
658
659 public:
660     LargeObject(size_t size) : data(size, 42) {
661         cout << "Constructor: " << size << " elements" << endl;
662     }
663
664     // Copy constructor (expensive)
665     LargeObject(const LargeObject& other) : data(other.data) {
666         cout << "Copy constructor: " << data.size() << " elements" << endl;
667     }
668
669     // Move constructor (cheap)
670     LargeObject(LargeObject&& other) noexcept : data(move(other.data)) {
671         cout << "Move constructor" << endl;
672     }
673
674     // Copy assignment
675     LargeObject& operator=(const LargeObject& other) {
676         if (this != &other) {
677             data = other.data;
678             cout << "Copy assignment: " << data.size() << " elements" << endl;
679         }
680         return *this;
681     }
682
683     // Move assignment
684     LargeObject& operator=(LargeObject&& other) noexcept {
685         if (this != &other) {
686             data = move(other.data);
687             cout << "Move assignment" << endl;
688         }
689     }
690 }
```

```
689     return *this;
690 }
691 };
692
693 void move_semantics_performance() {
694     cout << "\n==== MOVE SEMANTICS PERFORMANCE ===\n";
695
696     {
697         cout << "\nCopy version:" << endl;
698         LargeObject obj1(1000000);
699         LargeObject obj2 = obj1; // Copy
700     }
701
702     {
703         cout << "\nMove version:" << endl;
704         LargeObject obj1(1000000);
705         LargeObject obj2 = move(obj1); // Move
706     }
707
708     cout << "\nMove Semantics Guidelines:" << endl;
709     cout << "1. Return by value (compiler uses RVO/NRVO)" << endl;
710     cout << "2. Use std::move() for rvalues" << endl;
711     cout << "3. Mark move constructors noexcept" << endl;
712     cout << "4. Don't move from const objects" << endl;
713     cout << "5. Perfect forwarding with std::forward" << endl;
714 }
715
716 // ===== Q6.2: RVO and Copy Elision =====
717 class Expensive {
718 public:
719     Expensive() {
720         cout << "Default constructor" << endl;
721     }
722
723     Expensive(const Expensive&) {
724         cout << "Copy constructor" << endl;
725     }
726
727     Expensive(Expensive&&) noexcept {
728         cout << "Move constructor" << endl;
729     }
730 };
731
732 Expensive createExpensive() {
733     return Expensive{}; // RVO applies
734 }
735
736 Expensive createExpensiveNamed() {
737     Expensive obj;
738     return obj; // NRVO applies
739 }
740
741 void copy_elision_demo() {
742     cout << "\n==== COPY ELISION (RVO/NRVO) ===\n";
```

```
743     cout << "Creating with RVO:" << endl;
744     Expensive e1 = createExpensive();
745
746     cout << "\nCreating with NRVO:" << endl;
747     Expensive e2 = createExpensiveNamed();
748
749     cout << "\nCopy Elision Rules:" << endl;
750     cout << "1. RVO: Return Value Optimization" << endl;
751     cout << "2. NRVO: Named Return Value Optimization" << endl;
752     cout << "3. Guaranteed in C++17 for prvalue" << endl;
753     cout << "4. Compiler may apply in other cases" << endl;
754     cout << "5. Don't use std::move() on return values" << endl;
755 }
756
757 // =====
758 // MAIN - Demonstrate All Interview Topics
759 // =====
760
761 int main() {
762     cout << "\n";
763     cout << "                                \n";
764     cout << "          COMPLETE C++ INTERVIEW QUESTIONS & ANSWERS
765           \n";
766     cout << "          Mock Interview Preparation Guide
767           \n";
768     cout << "                                \n";
769
770     try {
771         // Section 1: C++ Fundamentals
772         cout << "\n" << string(70, '=') << "\n";
773         cout << "SECTION 1: C++ FUNDAMENTALS\n";
774         cout << string(70, '=') << "\n";
775
776         pointers_vs_references();
777         const_correctness();
778         raii_demo();
779
780         // Section 2: Memory Management
781         cout << "\n" << string(70, '=') << "\n";
782         cout << "SECTION 2: MEMORY MANAGEMENT\n";
783         cout << string(70, '=') << "\n";
784
785         smart_pointers_advanced();
786         memory_alignment();
787
788         // Section 3: OOP & Design Patterns
789         cout << "\n" << string(70, '=') << "\n";
790         cout << "SECTION 3: OOP & DESIGN PATTERNS\n";
791         cout << string(70, '=') << "\n";
792
793         virtual_dispatch_details();
794         crtp_mixins_demo();
```

```
795 // Section 4: Templates & Metaprogramming
796 cout << "\n" << string(70, '=') << "\n";
797 cout << "SECTION 4: TEMPLATES & METAPROGRAMMING\n";
798 cout << string(70, '=') << "\n";
799
800 sfinae_demo();
801 variadic_demo();
802 compile_time_demo();
803
804 // Section 5: Concurrency & Multithreading
805 cout << "\n" << string(70, '=') << "\n";
806 cout << "SECTION 5: CONCURRENCY & MULTITHREADING\n";
807 cout << string(70, '=') << "\n";
808
809 singleton_demo();
810 producer_consumer_demo();
811 atomic_operations_demo();
812
813 // Section 6: Performance & Optimization
814 cout << "\n" << string(70, '=') << "\n";
815 cout << "SECTION 6: PERFORMANCE & OPTIMIZATION\n";
816 cout << string(70, '=') << "\n";
817
818 move_semantics_performance();
819 copy_elision_demo();
820
821 // Summary
822 cout << "\n" << string(70, '=') << "\n";
823 cout << "SUMMARY: KEY INTERVIEW TOPICS COVERED\n";
824 cout << string(70, '=') << "\n\n";
825
826 cout << " FUNDAMENTALS:\n";
827 cout << " • Pointers vs References\n";
828 cout << " • Const correctness\n";
829 cout << " • RAII pattern\n\n";
830
831 cout << " MEMORY MANAGEMENT:\n";
832 cout << " • Smart pointers (unique_ptr, shared_ptr, weak_ptr)\n";
833 cout << " • Memory alignment and padding\n";
834 cout << " • Custom allocators\n\n";
835
836 cout << " OOP & DESIGN:\n";
837 cout << " • Virtual dispatch mechanics\n";
838 cout << " • CRTP with mixins\n";
839 cout << " • PIMPL idiom\n\n";
840
841 cout << " TEMPLATES:\n";
842 cout << " • SFINAE techniques\n";
843 cout << " • Variadic templates\n";
844 cout << " • Compile-time computation\n\n";
845
846 cout << " CONCURRENCY:\n";
847 cout << " • Thread-safe singleton\n";
848 cout << " • Producer-consumer pattern\n";
```

```
849     cout << " • Atomic operations\n\n";
850
851     cout << " PERFORMANCE:\n";
852     cout << " • Move semantics\n";
853     cout << " • Copy elision (RVO/NRVO)\n";
854     cout << " • Cache-friendly design\n\n";
855
856     cout << " COMMON INTERVIEW QUESTIONS ANSWERED:\n";
857     cout << " 1. What's the difference between pointers and references?\n";
858     cout << " 2. Explain smart pointers and when to use each\n";
859     cout << " 3. How does virtual dispatch work internally?\n";
860     cout << " 4. What is SFINAE and how is it used?\n";
861     cout << " 5. How do you implement thread-safe singleton?\n";
862     cout << " 6. What's the difference between RVO and move semantics?\n";
863     cout << " 7. Explain memory ordering in atomic operations\n";
864     cout << " 8. How does CRTP provide compile-time polymorphism?\n\n";
865
866     cout << " ADDITIONAL TOPICS TO STUDY:\n";
867     cout << " • Lambda expressions and closures\n";
868     cout << " • Concepts (C++20)\n";
869     cout << " • Coroutines (C++20)\n";
870     cout << " • Ranges library (C++20)\n";
871     cout << " • std::expected (C++23)\n";
872     cout << " • Design patterns (Factory, Observer, Strategy)\n\n";
873
874     cout << "                                     \n";
875     cout << "          ALL INTERVIEW TOPICS SUCCESSFULLY DEMONSTRATED!\n";
876     cout << "                                     \n";
877
878 } catch (const exception& e) {
879     cerr << " Error: " << e.what() << "\n";
880     return 1;
881 }
882
883 return 0;
884 }
```

42 Source Code: MoveSemantics.cpp

File: src/MoveSemantics.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // std::move AND MOVE SEMANTICS - COMPREHENSIVE GUIDE
3 // =====
4 // Topics covered:
5 // 1. Lvalues vs Rvalues - What they are and why they matter
6 // 2. std::move - What it actually does (cast to rvalue reference)
7 // 3. Move constructor vs Copy constructor - Performance comparison
8 // 4. Why move semantics are important - Real-world scenarios
9 // 5. Common pitfalls and best practices
10 // 6. Perfect forwarding with std::forward
11 // =====
12
13 #include <iostream>
14 #include <string>
15 #include <vector>
16 #include <memory>
17 #include <chrono>
18 #include <utility> // for std::move, std::forward
19
20 // =====
21 // 1. LVALUES vs RVALUES - Understanding the Basics
22 // =====
23
24 void demonstrate_lvalue_rvalue() {
25     std::cout << "\n== 1. LVALUES vs RVALUES ==" << std::endl;
26
27     std::cout << "\n Theory:" << std::endl;
28     std::cout << "    LVALUE = 'Locator value' - has a name, addressable,
29         persists" << std::endl;
30     std::cout << "    RVALUE = 'Right-hand value' - temporary, about to expire"
31         << std::endl;
32
33     // LVALUES - have names, can take address
34     int x = 42;           // x is an lvalue
35     int* ptr = &x;        // Can take address of x
36     std::string name = "John"; // name is an lvalue
37
38     std::cout << "\n LVALUES (have names, addressable):" << std::endl;
39     std::cout << "    int x = 42;           // x is lvalue, address: " << &x <<
40         std::endl;
41     std::cout << "    string name = \"John\"; // name is lvalue, address: " <<
42         &name << std::endl;
43
44     // RVALUES - temporaries, no name, about to be destroyed
45     std::cout << "\n RVALUES (temporaries, no name):" << std::endl;
46     std::cout << "    42           // literal rvalue" << std::endl;
47     std::cout << "    x + 5         // expression result is rvalue" << std::
48         endl;
49     std::cout << "    string(\"hi\") // temporary object is rvalue" << std::endl;
```

```

        endl;

45   // x = 42;           // OK: x is lvalue, 42 is rvalue
46   // 42 = x;          // ERROR: 42 is rvalue, can't assign to rvalue
47   // &42;              // ERROR: can't take address of rvalue
48
49
50   std::cout << "\n Key insight:" << std::endl;
51   std::cout << " • Lvalues appear on LEFT of assignment: x = ..." << std::
      endl;
52   std::cout << " • Rvalues appear on RIGHT of assignment: ... = 42" << std
      ::endl;
53   std::cout << " • Rvalues are about to die → safe to 'steal' their
      resources!" << std::endl;
54 }

55
56 // =====
57 // 2. std::move - What It Actually Does
58 // =====
59
60 void demonstrate_std_move() {
61     std::cout << "\n== 2. WHAT IS std::move? ==" << std::endl;
62
63     std::cout << "\n std::move is NOT:" << std::endl;
64     std::cout << "    Moving anything" << std::endl;
65     std::cout << "    Transferring ownership" << std::endl;
66     std::cout << "    Doing any work" << std::endl;
67
68     std::cout << "\n std::move IS:" << std::endl;
69     std::cout << " • A CAST from lvalue to rvalue reference" << std::endl;
70     std::cout << " • Tells compiler: 'This object is about to expire'" <<
      std::endl;
71     std::cout << " • Enables move constructor/assignment to be called" <<
      std::endl;
72
73     std::cout << "\n Conceptual implementation:" << std::endl;
74     std::cout << "    template<typename T>" << std::endl;
75     std::cout << "    typename remove_reference<T>::type&& move(T&& arg) {" <<
      std::endl;
76     std::cout << "        return static_cast<typename remove_reference<T>::type
      &&>(arg);" << std::endl;
77     std::cout << "    }" << std::endl;
78
79     std::string str1 = "Hello";
80
81     std::cout << "\n Example:" << std::endl;
82     std::cout << "    string str1 = \"Hello\"; // str1 is lvalue" << std::endl
      ;
83     std::cout << "    string str2 = str1;      // COPY: str1 is lvalue → copy
      constructor" << std::endl;
84     std::cout << "    string str3 = std::move(str1); // MOVE: std::move(str1)
      is rvalue → move constructor" << std::endl;
85
86     std::string str2 = str1;           // Copy
87     std::string str3 = std::move(str1); // Move (str1 now invalid but

```

```
        unspecified state)

88     std::cout << "\n    After move:" << std::endl;
89     std::cout << "    str1 = \"" << str1 << "\"" (moved-from, valid but empty)"
90         << std::endl;
91     std::cout << "    str2 = \"" << str2 << "\"" (copy, unchanged)" << std::endl
92         ;
93     std::cout << "    str3 = \"" << str3 << "\"" (move, got str1's data)" << std
94         ::endl;
95 }

96 // =====
97 // 3. COPY vs MOVE - Performance Comparison
98 // =====

99 class LargeObject {
100 private:
101     int* data;
102     size_t size;
103     std::string name;
104
105 public:
106     // Constructor
107     LargeObject(const std::string& n, size_t s)
108         : size(s), name(n) {
109         data = new int[size];
110         for (size_t i = 0; i < size; ++i) {
111             data[i] = static_cast<int>(i);
112         }
113         std::cout << "    Constructor: " << name
114             << " (" << size << " elements)" << std::endl;
115     }
116
117     // Destructor
118     ~LargeObject() {
119         delete[] data;
120         std::cout << "    Destructor: " << name << std::endl;
121     }
122
123     // Copy constructor (EXPENSIVE)
124     LargeObject(const LargeObject& other)
125         : size(other.size), name(other.name + "_copy") {
126         data = new int[size];
127         // Copy every element - EXPENSIVE!
128         for (size_t i = 0; i < size; ++i) {
129             data[i] = other.data[i];
130         }
131         std::cout << "    COPY constructor: " << name
132             << " (" << size << " elements copied)" << std::endl;
133     }
134
135     // Move constructor (CHEAP)
136     LargeObject(LargeObject&& other) noexcept
137         : data(other.data), size(other.size), name(other.name + "_moved") {
```

```
138     // Steal the data pointer - CHEAP!
139     other.data = nullptr;
140     other.size = 0;
141     std::cout << "      MOVE constructor: " << name
142             << " (pointer stolen, zero copy!)" << std::endl;
143 }
144
145 // Copy assignment (EXPENSIVE)
146 LargeObject& operator=(const LargeObject& other) {
147     if (this != &other) {
148         delete[] data;
149         size = other.size;
150         name = other.name + "_copy_assigned";
151         data = new int[size];
152         for (size_t i = 0; i < size; ++i) {
153             data[i] = other.data[i];
154         }
155         std::cout << "      COPY assignment: " << name << std::endl;
156     }
157     return *this;
158 }
159
160 // Move assignment (CHEAP)
161 LargeObject& operator=(LargeObject&& other) noexcept {
162     if (this != &other) {
163         delete[] data;
164         data = other.data;
165         size = other.size;
166         name = other.name + "_move_assigned";
167         other.data = nullptr;
168         other.size = 0;
169         std::cout << "      MOVE assignment: " << name << std::endl;
170     }
171     return *this;
172 }
173
174     size_t get_size() const { return size; }
175 };
176
177 void demonstrate_copy_vs_move() {
178     std::cout << "\n--- 3. COPY vs MOVE CONSTRUCTORS ---" << std::endl;
179
180     std::cout << "\n--- Copy Constructor (expensive) ---" << std::endl;
181 {
182     LargeObject obj1("obj1", 1000);
183     LargeObject obj2 = obj1; // COPY: obj1 is lvalue
184     std::cout << "      Result: obj1 still has data, obj2 copied it" << std::endl;
185 }
186
187 std::cout << "\n--- Move Constructor (cheap) ---" << std::endl;
188 {
189     LargeObject obj3("obj3", 1000);
190     LargeObject obj4 = std::move(obj3); // MOVE: std::move(obj3) is
```

```
    rvalue
191     std::cout << "    Result: obj3 empty (moved-from), obj4 stole its data"
192             << std::endl;
193
194     std::cout << "\n--- Assignment operators ---" << std::endl;
195 {
196     LargeObject obj5("obj5", 500);
197     LargeObject obj6("obj6", 500);
198     LargeObject obj7("obj7", 500);
199
200     std::cout << "\nCopy assignment:" << std::endl;
201     obj6 = obj5; // Copy assignment
202
203     std::cout << "\nMove assignment:" << std::endl;
204     obj7 = std::move(obj5); // Move assignment
205 }
206
207     std::cout << "\n Performance impact:" << std::endl;
208     std::cout << " • Copy: O(n) - copies every element" << std::endl;
209     std::cout << " • Move: O(1) - just copies pointers" << std::endl;
210     std::cout << " • For 1,000,000 elements: Copy = 1M ops, Move = 3 ops!"
211         << std::endl;
212 }
213 // =====
214 // 4. WHY MOVE SEMANTICS ARE IMPORTANT
215 // =====
216
217 // Scenario 1: Returning large objects from functions
218
219 std::vector<int> create_large_vector_without_move() {
220     std::vector<int> vec(1000000, 42);
221     // Before C++11: Copy entire vector on return (SLOW!)
222     // With C++11: RVO or move (FAST!)
223     return vec; // Move constructor called (or RVO)
224 }
225
226 // Scenario 2: Storing move-only types in containers
227
228 class MoveOnlyType {
229     std::unique_ptr<int> ptr;
230
231 public:
232     MoveOnlyType(int value) : ptr(std::make_unique<int>(value)) {
233         std::cout << "    MoveOnlyType created with value: " << *ptr << std::endl;
234     }
235
236     // Delete copy constructor and copy assignment
237     MoveOnlyType(const MoveOnlyType&) = delete;
238     MoveOnlyType& operator=(const MoveOnlyType&) = delete;
239
240     // Enable move constructor and move assignment
```

```
241     MoveOnlyType(MoveOnlyType&&) noexcept = default;
242     MoveOnlyType& operator=(MoveOnlyType&&) noexcept = default;
243
244     int get_value() const { return *ptr; }
245 };
246
247 void demonstrate_why_move_important() {
248     std::cout << "\n==== 4. WHY MOVE SEMANTICS ARE IMPORTANT ===" << std::endl;
249
250     // Scenario 1: Return values
251     std::cout << "\n Scenario 1: Returning large objects" << std::endl;
252     std::cout << "    Before C++11: Expensive copy on return" << std::endl;
253     std::cout << "    With C++11: Move or RVO (Return Value Optimization)" <<
254         std::endl;
255
256     auto start = std::chrono::high_resolution_clock::now();
257     auto vec = create_large_vector_without_move();
258     auto end = std::chrono::high_resolution_clock::now();
259     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(end -
260         start);
261
262     std::cout << "    Created vector with " << vec.size()
263             << " elements in " << duration.count() << " s" << std::endl;
264     std::cout << "    (Would be much slower without move/RVO)" << std::endl;
265
266     // Scenario 2: Move-only types
267     std::cout << "\n Scenario 2: Move-only types (unique_ptr, thread, etc.)"
268             << std::endl;
269     {
270         MoveOnlyType obj1(42);
271         // MoveOnlyType obj2 = obj1; // ERROR: Copy deleted
272         MoveOnlyType obj2 = std::move(obj1); // OK: Move
273         std::cout << "    Moved unique ownership from obj1 to obj2" << std::endl;
274     }
275
276     // Scenario 3: Container operations
277     std::cout << "\n Scenario 3: Container optimizations" << std::endl;
278     {
279         std::vector<std::string> names;
280         names.reserve(3);
281
282         std::string name1 = "Alice";
283         std::string name2 = "Bob";
284
285         std::cout << "    push_back(name1): COPY (name1 still needed)" << std::endl;
286         names.push_back(name1); // Copy
287
288         std::cout << "    push_back(std::move(name2)): MOVE (name2 not needed)"
289             << std::endl;
290         names.push_back(std::move(name2)); // Move
291
292         std::cout << "    push_back(\"Charlie\"): MOVE (temporary rvalue)" <<
```

```
    std::endl;
289 names.push_back("Charlie"); // Move from temporary
290
291 std::cout << "\n  After operations:" << std::endl;
292 std::cout << "    name1 = \" " << name1 << "\" (still valid, was copied)
293     " << std::endl;
294 std::cout << "    name2 = \" " << name2 << "\" (moved-from, empty)" <<
295     std::endl;
296 }
297
298 // Scenario 4: Swapping
299 std::cout << "\n Scenario 4: Efficient swapping" << std::endl;
300 {
301     std::vector<int> vec1(1000, 1);
302     std::vector<int> vec2(2000, 2);
303
304     std::cout << "    Before swap: vec1.size()=" << vec1.size()
305             << ", vec2.size()=" << vec2.size() << std::endl;
306
307     // std::swap uses move semantics internally
308     std::swap(vec1, vec2); // O(1) with moves, not O(n) with copies!
309
310     std::cout << "    After swap: vec1.size()=" << vec1.size()
311             << ", vec2.size()=" << vec2.size() << std::endl;
312     std::cout << "    (Swap is O(1) thanks to move semantics)" << std::endl
313         ;
314 }
315
316 // =====
317 // 5. COMMON PITFALLS AND BEST PRACTICES
318 void demonstrate_pitfalls() {
319     std::cout << "\n== 5. COMMON PITFALLS ==" << std::endl;
320
321     // Pitfall 1: Using moved-from object
322     std::cout << "\n Pitfall 1: Using moved-from object" << std::endl;
323     {
324         std::string str1 = "Hello";
325         std::string str2 = std::move(str1);
326
327         std::cout << "    str1 after move: \" " << str1 << "\" << std::endl;
328         std::cout << "    str1 is in valid but unspecified state!" << std::
329             endl;
330         std::cout << "    Safe: Check if empty or reassign" << std::endl;
331         std::cout << "    Unsafe: Assume it has specific content" << std::
332             endl;
333
334         // Safe operations after move:
335         str1.clear(); // OK
336         str1 = "New value"; // OK
337         if (str1.empty()) {} // OK
338         // str1[0]; // UNSAFE! May be undefined behavior
```

```
337 }
338
339 // Pitfall 2: Moving const objects
340 std::cout << "\n Pitfall 2: Can't move from const" << std::endl;
341 {
342     const std::string str1 = "Hello";
343     std::string str2 = std::move(str1); // Calls COPY, not move!
344
345     std::cout << "    const objects can't be moved" << std::endl;
346     std::cout << "    std::move on const → copy constructor called" << std
347         ::endl;
348 }
349
350 // Pitfall 3: Unnecessary moves
351 std::cout << "\n Pitfall 3: Unnecessary std::move on return" << std::endl
352 ;
353 std::cout << R"(

// BAD - prevents RVO (Return Value Optimization)
354 string bad_function() {
355     string result = "value";
356     return std::move(result); // Don't do this!
357 }

// GOOD - enables RVO
358 string good_function() {
359     string result = "value";
360     return result; // Compiler automatically moves/optimizes
361 }
362 )" << std::endl;
363
364 // Best practices
365 std::cout << "\n BEST PRACTICES:" << std::endl;
366 std::cout << "    1. Mark move constructors 'noexcept'" << std::endl;
367 std::cout << "    →      Enables optimizations (vector resize)" << std::endl;
368 std::cout << "    2. Don't std::move on return values" << std::endl;
369 std::cout << "    →      Compiler does RVO or automatic move" << std::endl;
370 std::cout << "    3. Move when you know object won't be used again" << std
371         ::endl;
372 std::cout << "    →      push_back(std::move(obj))" << std::endl;
373 std::cout << "    4. Don't use moved-from objects" << std::endl;
374 std::cout << "    →      Unless reassigning or destroying" << std::endl;
375 std::cout << "    5. Move-only types (unique_ptr) can't be copied" << std::
376         endl;
377 std::cout << "    →      Use std::move to transfer ownership" << std::endl;
378 }

379 // =====
380 // 6. std::forward - PERFECT FORWARDING
381 // =====
382
383 void process(int& x) {
384     std::cout << "    process(int&): lvalue " << x << std::endl;
385 }
386
```

```
387 void process(int&& x) {
388     std::cout << "    process(int&&): rvalue " << x << std::endl;
389 }
390
391 // Without perfect forwarding - loses rvalue-ness
392 template<typename T>
393 void wrapper_bad(T&& arg) {
394     // arg is always an lvalue inside the function (even if T&& is rvalue ref)
395     process(arg); // Always calls process(int&)
396 }
397
398 // With perfect forwarding - preserves value category
399 template<typename T>
400 void wrapper_good(T&& arg) {
401     // std::forward preserves lvalue/rvalue-ness
402     process(std::forward<T>(arg)); // Calls correct overload
403 }
404
405 void demonstrate_perfect_forwarding() {
406     std::cout << "\n==== 6. std::forward - PERFECT FORWARDING ===" << std::endl
407         ;
408
409     std::cout << "\n Problem: Template functions lose value category" << std
410         ::endl;
411     std::cout << "    Template parameter T&& is 'forwarding reference'" << std
412         ::endl;
413     std::cout << "    But inside function, arg is always lvalue!" << std::endl;
414
415     int x = 42;
416
417     std::cout << "\n Without std::forward:" << std::endl;
418     wrapper_bad(x); // lvalue
419     wrapper_bad(100); // rvalue, but treated as lvalue!
420
421     std::cout << "\n With std::forward:" << std::endl;
422     wrapper_good(x); // Forwards as lvalue
423     wrapper_good(200); // Forwards as rvalue
424
425     std::cout << "\n Key differences:" << std::endl;
426     std::cout << " • std::move: ALWAYS casts to rvalue" << std::endl;
427     std::cout << " • std::forward: Casts to rvalue ONLY if original was
428         rvalue" << std::endl;
429     std::cout << "                                (preserves value category)" << std::endl;
430
431     std::cout << "\n When to use:" << std::endl;
432     std::cout << " • std::move: When you know object is done being used"
433         << std::endl;
434     std::cout << " • std::forward: In template functions forwarding
435         arguments" << std::endl;
436 }
437
438 // =====
439 // 7. REAL-WORLD EXAMPLE: Factory Pattern
440 // =====
```

```
435
436 class Resource {
437     std::string name;
438     std::vector<int> data;
439
440 public:
441     Resource(const std::string& n) : name(n) {
442         data.resize(1000, 42);
443         std::cout << "    Resource created: " << name << std::endl;
444     }
445
446     Resource(const Resource& other)
447         : name(other.name + "_copy"), data(other.data) {
448         std::cout << "    Resource COPIED: " << name << std::endl;
449     }
450
451     Resource(Resource&& other) noexcept
452         : name(std::move(other.name)), data(std::move(other.data)) {
453         std::cout << "    Resource MOVED: " << name << std::endl;
454     }
455
456     const std::string& get_name() const { return name; }
457 };
458
459 class ResourceFactory {
460 public:
461     // Return by value - move semantics makes this efficient
462     static Resource create_resource(const std::string& name) {
463         Resource res(name);
464         // Return local object - move or RVO kicks in
465         return res; // Don't use std::move here!
466     }
467
468     // Store in container - use move to avoid copy
469     static void store_in_container(std::vector<Resource>& container, Resource
470         && res) {
471         std::cout << "    Storing in container..." << std::endl;
472         container.push_back(std::move(res)); // Move into container
473     }
474
475     void demonstrate_real_world() {
476         std::cout << "\n== 7. REAL-WORLD: Factory Pattern ==" << std::endl;
477
478         std::vector<Resource> resources;
479         resources.reserve(3);
480
481         std::cout << "\n--- Creating and storing resources ---" << std::endl;
482
483         // Create and store - efficient with move semantics
484         auto res1 = ResourceFactory::create_resource("Resource1");
485         ResourceFactory::store_in_container(resources, std::move(res1));
486
487         // Direct temporary - even more efficient
```

```
488     ResourceFactory::store_in_container(
489         resources,
490         ResourceFactory::create_resource("Resource2")
491     );
492
493     std::cout << "\n Container now has " << resources.size()
494         << " resources" << std::endl;
495     std::cout << "    All stored efficiently with move semantics!" << std::endl
496         ;
497 }
498 // =====
499 // MAIN
500 // =====
501
502 int main() {
503     std::cout << "\n
504         =====" <<
505         std::endl;
506     std::cout << "    std::move AND MOVE SEMANTICS - COMPREHENSIVE GUIDE" << std
507         ::endl;
508     std::cout << "
509         =====" <<
510         std::endl;
511
512     demonstrate_lvalue_rvalue();
513     demonstrate_std_move();
514     demonstrate_copy_vs_move();
515     demonstrate_why_move_important();
516     demonstrate_pitfalls();
517     demonstrate_perfect_forwarding();
518     demonstrate_real_world();
519
520     std::cout << "\n
521         =====" <<
522         std::endl;
523     std::cout << "    SUMMARY: std::move and Move Semantics" << std::endl;
524     std::cout << "
525         =====" <<
526         std::endl;
527
528     std::cout << "\n1  KEY CONCEPTS:" << std::endl;
529     std::cout << "\n1  Lvalue vs Rvalue:" << std::endl;
530     std::cout << "    •    Lvalue: Has name, addressable, persists" << std::endl;
531     std::cout << "    •    Rvalue: Temporary, about to expire, no name" << std::
532         endl;
533
534     std::cout << "\n2  std::move:" << std::endl;
535     std::cout << "    •    Just a CAST from lvalue to rvalue reference" << std::
536         endl;
537     std::cout << "    •    Doesn't actually move anything" << std::endl;
538     std::cout << "    •    Tells compiler 'safe to steal resources'" << std::endl;
539
540     std::cout << "\n3  Move Constructor/Assignment:" << std::endl;
```

```
530     std::cout << " • Steals resources from source object" << std::endl;
531     std::cout << " • O(1) instead of O(n) for large objects" << std::endl;
532     std::cout << " • Should be marked 'noexcept'" << std::endl;
533
534     std::cout << "\n4 Why Important:" << std::endl;
535     std::cout << " • Performance: O(1) vs O(n) for copies" << std::endl;
536     std::cout << " • Enables move-only types (unique_ptr, thread)" << std::
537         endl;
537     std::cout << " • Efficient return values and container ops" << std::endl
538         ;
538     std::cout << " • Essential for modern C++" << std::endl;
539
540     std::cout << "\n5 Best Practices:" << std::endl;
541     std::cout << " • DO: Mark move operations noexcept" << std::endl;
542     std::cout << " • DO: Move when object not needed anymore" << std::endl;
543     std::cout << " • DO: Use std::forward in template forwarding" << std::
544         endl;
544     std::cout << " • DON'T: std::move on return values (blocks RVO)" << std
545         ::endl;
545     std::cout << " • DON'T: Use moved-from objects (unless reassigning)" <<
546         std::endl;
546     std::cout << " • DON'T: Move const objects (silently copies)" << std::
547         endl;
547
548     std::cout << "\n PERFORMANCE IMPACT:" << std::endl;
549     std::cout << " • vector<int>(1,000,000):" << std::endl;
550     std::cout << " • Copy: ~4,000,000 bytes copied, ~1ms" << std::endl;
551     std::cout << " • Move: ~24 bytes copied, ~1s (1000x faster!)" << std::
552         endl;
552
553     std::cout << "\n WHEN TO USE:" << std::endl;
554     std::cout << " • Returning local objects from functions" << std::endl;
555     std::cout << " • Inserting into containers (push_back)" << std::endl;
556     std::cout << " • Transferring unique ownership (unique_ptr)" << std::
557         endl;
557     std::cout << " • Implementing swap operations" << std::endl;
558     std::cout << " • Last use of a variable before destruction" << std::endl
559         ;
559
560     std::cout << "\n"
561         =====\n" <<
562         std::endl;
563
563 }
```

43 Source Code: MoveSemanticsPerfectForwarding.cpp

File: src/MoveSemanticsPerfectForwarding.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // IMPLEMENTING MOVE SEMANTICS AND PERFECT FORWARDING
3 // =====
4 // A comprehensive guide to C++11/14/17/20 move semantics and perfect
5 // forwarding
6 //
7 // Topics Covered:
8 // 1. Lvalues vs Rvalues - Understanding value categories
9 // 2. Move Semantics - Efficient resource transfer
10 // 3. std::move - What it really does
11 // 4. Perfect Forwarding - Preserving value categories
12 // 5. Rule of Zero/Three/Five
13 // 6. Real-World Examples
14 // 7. Performance Comparison
15 //
16 // Build: g++ -std=c++20 -Wall -Wextra -O2 -o MoveSemanticsPerfectForwarding
17 // MoveSemanticsPerfectForwarding.cpp
18 // =====
19
20 #include <iostream>
21 #include <vector>
22 #include <string>
23 #include <memory>
24 #include <utility> // std::move, std::forward
25 #include <chrono>
26 //
27 // =====
28 // SECTION 1: LVALUES vs RVALUES
29 // =====
30
31 namespace lvalues_rvalues {
32
33 void demonstrate() {
34     std::cout << "\n" << std::string(70, '=') << "\n";
35     std::cout << "SECTION 1: LVALUES vs RVALUES\n";
36     std::cout << std::string(70, '=') << "\n\n";
37
38     std::cout << " THEORY:\n";
39     std::cout << "     Lvalue = Has a NAME and PERSISTENT ADDRESS\n";
40     std::cout << "     Rvalue = TEMPORARY object without persistent address\n\n";
41
42     // LVALUES - have names, can take address
43     int x = 42;
44     std::string name = "Hello";
45
46     std::cout << " LVALUES (have names, addressable):\n";
47     std::cout << "     int x = 42;           // x is lvalue, address: " << &x
48     << "\n";
49 }
```

```

46     std::cout << "    string name = \"Hello\"; // name is lvalue, address: " <<
47         &name << "\n\n";
48
49     // RVALUES - temporaries
50     std::cout << "    RVALUES (temporaries, no persistent address):\n";
51     std::cout << "        42                      // Literal\n";
52     std::cout << "        x + 1                  // Expression result\n";
53     std::cout << "        string(\"World\")      // Temporary object\n\n";
54
55     // REFERENCE BINDING
56     std::cout << "    REFERENCE BINDING:\n\n";
57
58     int y = 10;
59
60     // Lvalue reference - binds to lvalue
61     int& lref = y;
62     std::cout << "    int& lref = y;           // OK: lvalue ref binds to
63         lvalue\n";
64     // int& lref2 = 42;       // ERROR: lvalue ref cannot bind to rvalue
65
66     // Rvalue reference - binds to rvalue
67     int&& rref = 42;
68     std::cout << "    int&& rref = 42;          // OK: rvalue ref binds to
69         rvalue\n";
70     // int&& rref2 = y;       // ERROR: rvalue ref cannot bind to lvalue
71
72     // Special case: const lvalue reference can bind to both!
73     const int& cref = 42;
74     std::cout << "    const int& cref = 42; // OK: const lvalue ref extends
75         lifetime\n\n";
76 }
77
78 } // namespace lvalues_rvalues
79
80 // =====
81 // SECTION 2: MOVE SEMANTICS - Basic Implementation
82 // =====
83
84 namespace move_semantics {
85
86 class Resource {
87 private:
88     int* data_;
89     size_t size_;
90
91 public:
92     // Constructor
93     explicit Resource(size_t size = 0)
94         : data_(size > 0 ? new int[size] : nullptr), size_(size) {

```

```
95         std::cout << "    [Resource] Constructor: allocated " << size_ << "
96             ints\n";
97
98     // Destructor
99     ~Resource() {
100         if (data_) {
101             std::cout << "    [Resource] Destructor: freeing " << size_ << "
102                 ints\n";
103             delete [] data_;
104         }
105     }
106
107     // Copy Constructor - EXPENSIVE! (O(n))
108     Resource(const Resource& other) : size_(other.size_) {
109         std::cout << "    [Resource] Copy Constructor - EXPENSIVE! Copying "
110             << size_ << " ints\n";
111         if (size_ > 0) {
112             data_ = new int[size_];
113             std::copy_n(other.data_, size_, data_);
114         } else {
115             data_ = nullptr;
116         }
117     }
118
119     // Copy Assignment - EXPENSIVE! (O(n))
120     Resource& operator=(const Resource& other) {
121         std::cout << "    [Resource] Copy Assignment - EXPENSIVE! Copying "
122             << other.size_ << " ints\n";
123         if (this != &other) {
124             delete [] data_;
125             size_ = other.size_;
126             if (size_ > 0) {
127                 data_ = new int[size_];
128                 std::copy_n(other.data_, size_, data_);
129             } else {
130                 data_ = nullptr;
131             }
132         }
133         return *this;
134     }
135
136     // Move Constructor - FAST! (O(1))
137     Resource(Resource&& other) noexcept
138         : data_(other.data_), size_(other.size_) {
139             std::cout << "    [Resource] Move Constructor - FAST! O(1) pointer
140                 transfer\n";
141
142             // Leave source in valid state
143             other.data_ = nullptr;
144             other.size_ = 0;
145         }
146
147     // Move Assignment - FAST! (O(1))
```

```
146     Resource& operator=(Resource&& other) noexcept {
147         std::cout << "      [Resource] Move Assignment - FAST! O(1) pointer
148             transfer\n";
149         if (this != &other) {
150             // Clean up existing resource
151             delete[] data_;
152
153             // Transfer ownership
154             data_ = other.data_;
155             size_ = other.size_;
156
157             // Leave source in valid state
158             other.data_ = nullptr;
159             other.size_ = 0;
160         }
161         return *this;
162     }
163
164     size_t size() const { return size_; }
165
166     int* get_data() { return data_; }
167     const int* get_data() const { return data_; }
168 };
169
170 void demonstrate() {
171     std::cout << "\n" << std::string(70, '=') << "\n";
172     std::cout << "SECTION 2: MOVE SEMANTICS\n";
173     std::cout << std::string(70, '=') << "\n\n";
174
175     std::cout << " THE PROBLEM: Expensive Copies\n";
176     std::cout << " Copy constructor/assignment performs deep copy (O(n))\n";
177     std::cout << " For large objects, this is 10x-1000x slower than
178         necessary!\n\n";
179
180     std::cout << " Demonstrating COPY vs MOVE:\n\n";
181
182     // Copy Constructor
183     std::cout << " 1 COPY Constructor (expensive):\n";
184     Resource r1(5);
185     Resource r2 = r1; // Copy constructor
186     std::cout << "      Result: r1 still valid with " << r1.size() << " ints\n\n"
187         ;
188
189     // Move Constructor
190     std::cout << " 2 MOVE Constructor (fast):\n";
191     Resource r3(5);
192     Resource r4 = std::move(r3); // Move constructor
193     std::cout << "      Result: r3 moved-from (size=" << r3.size()
194         << "), r4 owns data (" << r4.size() << " ints)\n\n";
195
196     // Copy Assignment
197     std::cout << " 3 COPY Assignment (expensive):\n";
198     Resource r5(3);
199     Resource r6(7);
```

```
197     r6 = r5; // Copy assignment
198     std::cout << "    Result: Both valid, r6 has " << r6.size() << " ints\n\n";
199
200 // Move Assignment
201 std::cout << " 4 MOVE Assignment (fast):\n";
202 Resource r7(3);
203 Resource r8(7);
204 r8 = std::move(r7); // Move assignment
205 std::cout << "    Result: r7 moved-from (size=" << r7.size()
206             << "), r8 owns data (" << r8.size() << " ints)\n\n";
207
208 std::cout << "  KEY INSIGHT:\n";
209 std::cout << "    Move operations transfer ownership in O(1) time!\n";
210 std::cout << "    Copy operations duplicate data in O(n) time.\n";
211 std::cout << "    Always mark move operations 'noexcept' for std::vector
212         optimization!\n";
213 }
214 } // namespace move_semantics
215
216 // =====
217 // SECTION 3: UNDERSTANDING std::move
218 // =====
219
220 namespace understanding_move {
221
222 void demonstrate() {
223     std::cout << "\n" << std::string(70, '=') << "\n";
224     std::cout << "SECTION 3: UNDERSTANDING std::move\n";
225     std::cout << std::string(70, '=') << "\n\n";
226
227     std::cout << "  WHAT IS std::move?\n";
228     std::cout << "    std::move does NOT move anything!\n";
229     std::cout << "    It's just a CAST to rvalue reference (T&&)\n";
230     std::cout << "    It tells compiler: 'this object can be moved from'\n\n";
231
232     std::cout << "  Simplified implementation:\n";
233     std::cout << "    template<typename T>\n";
234     std::cout << "    T&& move(T&& t) noexcept {\n";
235     std::cout << "        return static_cast<T&&>(t);\n";
236     std::cout << "    }\n\n";
237
238     std::cout << "  DEMONSTRATION:\n\n";
239
240     // std::move with string
241     std::cout << " 1 std::move with std::string:\n";
242     std::string s1 = "Hello, World!";
243     std::cout << "    Before: s1 = \" " << s1 << "\"\n";
244
245     std::string s2 = std::move(s1); // Move constructor called
246     std::cout << "    After move:\n";
247     std::cout << "    s1 = \" " << s1 << "\" (moved-from state)\n";
248     std::cout << "    s2 = \" " << s2 << "\" (owns the data)\n\n";
249 }
```

```

250 // Moved-from state
251 std::cout << " 2 MOVED-FROM STATE:\n";
252 std::cout << "      After std::move, object is in 'valid but unspecified'
253           state\n";
254 std::cout << "      SAFE: Destroy it, assign to it\n";
255 std::cout << "      UNSAFE: Don't use its value!\n\n";
256
256 s1 = "New Value"; // Safe: reassignment
257 std::cout << "      s1 reassigned: \"<< s1 << "\" (valid again)\n\n";
258
259 // Common mistakes
260 std::cout << "  COMMON MISTAKES:\n\n";
261
262 std::cout << "  MISTAKE 1: Using object after move\n";
263 std::cout << "      string s3 = \"test\";\n";
264 std::cout << "      string s4 = std::move(s3);\n";
265 std::cout << "      cout << s3; // WRONG! Undefined behavior!\n\n";
266
267 std::cout << "  MISTAKE 2: Returning std::move(local)\n";
268 std::cout << "      string func() {\n";
269 std::cout << "          string s = \"hello\";\n";
270 std::cout << "          return std::move(s); // Prevents RVO!\n";
271 std::cout << "      }\n";
272 std::cout << "      Correct: return s; // RVO or move, NOT copy\n\n";
273
274 std::cout << "  MISTAKE 3: Moving from const\n";
275 std::cout << "      const string cs = \"test\";\n";
276 std::cout << "      string s = std::move(cs); // Calls COPY, not move!\n\n";
277
278 std::cout << "  KEY TAKEAWAY:\n";
279 std::cout << "      std::move is a PERMISSION to move, not a command.\n";
280 std::cout << "      The actual move happens in the move constructor/
281           assignment.\n";
281 }
282
283 } // namespace understanding_move
284
285 // =====
286 // SECTION 4: PERFECT FORWARDING
287 // =====
288
289 namespace perfect_forwarding {
290
291 class Widget {
292 public:
293     Widget(const std::string& name) {
294         std::cout << "      [Widget] Constructed with LVALUE: \"<< name << \""
295           "(copied)\n";
295     }
296
297     Widget(std::string&& name) {
298         std::cout << "      [Widget] Constructed with RVALUE: \"<< name << \""
298           "(moved)\n";

```

```
299     }
300 };
301
302 // Bad: Always copies
303 template<typename T>
304 void bad_wrapper(T arg) {
305     // arg is always an lvalue here, even if rvalue was passed!
306     Widget w(arg); // Always calls Widget(const string&)
307 }
308
309 // Good: Perfect forwarding
310 template<typename T>
311 void good_wrapper(T&& arg) { // Universal/Forwarding reference
312     // std::forward preserves the value category
313     Widget w(std::forward<T>(arg));
314 }
315
316 void demonstrate() {
317     std::cout << "\n" << std::string(70, '=') << "\n";
318     std::cout << "SECTION 4: PERFECT FORWARDING\n";
319     std::cout << std::string(70, '=') << "\n\n";
320
321     std::cout << " THE PROBLEM:\n";
322     std::cout << " When passing arguments through wrapper functions,\n";
323     std::cout << " we lose information about whether they were lvalues or
324         rvalues.\n\n";
325
326     std::cout << " DEMONSTRATION:\n\n";
327
328     std::cout << " 1 WITHOUT Perfect Forwarding (bad_wrapper):\n";
329     std::string s1 = "lvalue";
330     bad_wrapper(s1); // Copies (expected)
331     bad_wrapper(std::string("rvalue")); // Still COPIES (not desired!)
332     std::cout << "\n";
333
334     std::cout << " 2 WITH Perfect Forwarding (good_wrapper):\n";
335     std::string s2 = "lvalue";
336     good_wrapper(s2); // Copies (as expected)
337     good_wrapper(std::string("rvalue")); // MOVES (optimized!)
338     std::cout << "\n";
339
340     std::cout << " UNIVERSAL REFERENCE (T&&):\n";
341     std::cout << "     template<typename T>\n";
342     std::cout << "     void func(T&& arg); // NOT an rvalue reference!\n\n";
343     std::cout << "     It's a UNIVERSAL REFERENCE (also called forwarding
344         reference)\n";
345     std::cout << "     Can bind to BOTH lvalues and rvalues\n\n";
346
347     std::cout << " Reference Collapsing Rules:\n";
348     std::cout << "     T& && -> T&      (lvalue reference)\n";
349     std::cout << "     T&& && -> T&&    (rvalue reference)\n\n";
350
351     std::cout << " WHEN TO USE:\n";
352     std::cout << "     std::move - UNCONDITIONAL cast to rvalue\n";
```

```

351     std::cout << "                                Use when you KNOW you have an lvalue to
352         transfer\n";
353     std::cout << "      std::forward - CONDITIONAL forwarding preserving value
354         category\n";
355     std::cout << "                                Use with T&& (universal reference) in
356         templates\n";
357 }
358
359 // Example: Factory function
360 template<typename T, typename... Args>
361 std::unique_ptr<T> make_unique_custom(Args&&... args) {
362     std::cout << "[Factory] Creating object with perfect forwarding\n";
363     return std::unique_ptr<T>(new T(std::forward<Args>(args)...));
364 }
365
366 void demonstrate_factory() {
367     std::cout << "\n3 Factory Pattern with Perfect Forwarding:\n";
368
369     std::string name = "Gadget";
370     auto w1 = make_unique_custom<Widget>(name);           // Forwards as
371         lvalue
372     auto w2 = make_unique_custom<Widget>("Gizmo");        // Forwards as
373         rvalue
374     auto w3 = make_unique_custom<Widget>(std::move(name)); // Forwards as
375         rvalue
376 }
377
378 } // namespace perfect_forwarding
379
380 // =====
381 // SECTION 5: RULE OF ZERO/THREE/FIVE
382 // =====
383
384 namespace rule_of_five {
385
386 void demonstrate() {
387     std::cout << "\n" << std::string(70, '=') << "\n";
388     std::cout << "SECTION 5: RULE OF ZERO/THREE/FIVE\n";
389     std::cout << std::string(70, '=') << "\n\n";
390
391     std::cout << "  RULE OF ZERO (PREFERRED!):\n";
392     std::cout << "    Don't manage resources manually!\n";
393     std::cout << "    Use std::vector, std::string, std::unique_ptr, etc.\n\n";
394
395     std::cout << "    class Widget {\n";
396     std::cout << "        std::string name_;          // Self-managing\n";
397     std::cout << "        std::vector<int> data_;    // Self-managing\n";
398     std::cout << "        // No special members needed!\n";
399     std::cout << "    };\n\n";
400
401     std::cout << "  RULE OF THREE (C++98):\n";
402     std::cout << "    If you define ONE, define ALL THREE:\n";
403     std::cout << "    1. Destructor\n";
404     std::cout << "    2. Copy Constructor\n";

```

```

399 std::cout << "    3. Copy Assignment Operator\n\n";
400
401 std::cout << "    RULE OF FIVE (C++11+):\n";
402 std::cout << "        If managing resources, define ALL FIVE:\n";
403 std::cout << "            1. Destructor\n";
404 std::cout << "            2. Copy Constructor\n";
405 std::cout << "            3. Copy Assignment Operator\n";
406 std::cout << "            4. Move Constructor (mark noexcept!)\n";
407 std::cout << "            5. Move Assignment Operator (mark noexcept!)\n\n";
408
409 std::cout << "        class Resource {\n";
410 std::cout << "            public:\n";
411 std::cout << "                ~Resource();                                // 1\n";
412 std::cout << "                Resource(const Resource&);               // 2\n";
413 std::cout << "                Resource& operator=(const Resource&); // 3\n";
414 std::cout << "                Resource(Resource&&) noexcept;       // 4\n";
415 std::cout << "                Resource& operator=(Resource&&) noexcept; // 5\n";
416 std::cout << "            };\n\n";
417
418 std::cout << "    DELETE UNWANTED OPERATIONS:\n";
419 std::cout << "        Make class non-copyable but movable:\n\n";
420 std::cout << "        class NonCopyable {\n";
421 std::cout << "            public:\n";
422 std::cout << "                NonCopyable(const NonCopyable&) = delete;\n";
423 std::cout << "                NonCopyable& operator=(const NonCopyable&) = delete;\n";
424 std::cout << "                NonCopyable(NonCopyable&&) = default;\n";
425 std::cout << "                NonCopyable& operator=(NonCopyable&&) = default;\n";
426 std::cout << "            };\n\n";
427
428 std::cout << "    BEST PRACTICE:\n";
429 std::cout << "        1. Prefer Rule of Zero (use standard library types)\n";
430 std::cout << "        2. If managing resources, use Rule of Five\n";
431 std::cout << "        3. Always mark move operations noexcept\n";
432 std::cout << "        4. Use =delete for unwanted operations\n";
433 std::cout << "        5. Use =default when compiler-generated is correct\n";
434 }
435
436 } // namespace rule_of_five
437
438 // =====
439 // SECTION 6: REAL-WORLD EXAMPLES
440 // =====
441
442 namespace real_world_examples {
443
444 void demonstrate_vector() {
445     std::cout << "\n" << std::string(70, '=') << "\n";
446     std::cout << "SECTION 6: REAL-WORLD EXAMPLES\n";
447     std::cout << std::string(70, '=') << "\n\n";
448
449     std::cout << " 1 std::vector Push Operations:\n\n";
450
451     std::vector<std::string> vec;

```

```
452     vec.reserve(3);
453
454     std::string s1 = "String1";
455     std::string s2 = "String2";
456
457     std::cout << "    vec.push_back(s1);           // Copy (s1 still valid)\n";
458     ;
459     vec.push_back(s1);
460     std::cout << "    s1 after: \" " << s1 << "\"\n\n";
461
462     std::cout << "    vec.push_back(std::move(s2)); // Move (s2 now empty)\n";
463     vec.push_back(std::move(s2));
464     std::cout << "    s2 after: \" " << s2 << "\" (moved-from)\n\n";
465
466     std::cout << "    vec.emplace_back(\"String3\"); // Construct in-place\n";
467     vec.emplace_back("String3");
468     std::cout << "\n";
469 }
470
471 void demonstrate_rvo() {
472     std::cout << " 2 Return Value Optimization (RVO):\n\n";
473
474     std::cout << "      CORRECT:\n";
475     std::cout << "      vector<int> create() {\n";
476     std::cout << "          vector<int> result(1000);\n";
477     std::cout << "          return result; // RVO or move (NOT copy!)\n";
478     std::cout << "      }\n\n";
479
480     std::cout << "      WRONG:\n";
481     std::cout << "      vector<int> create() {\n";
482     std::cout << "          vector<int> result(1000);\n";
483     std::cout << "          return std::move(result); // Prevents RVO!\n";
484     std::cout << "      }\n\n";
485 }
486
487 void demonstrate_unique_ptr() {
488     std::cout << " 3 Unique Ownership Transfer:\n\n";
489
490     std::cout << "     auto ptr1 = make_unique<int>(42);\n";
491     auto ptr1 = std::make_unique<int>(42);
492     std::cout << "     ptr1 owns: " << *ptr1 << "\n\n";
493
494     std::cout << "     auto ptr2 = std::move(ptr1); // Transfer ownership\n";
495     auto ptr2 = std::move(ptr1);
496     std::cout << "     ptr1 is now: " << (ptr1 ? "valid" : "nullptr") << "\n";
497     std::cout << "     ptr2 owns: " << *ptr2 << "\n\n";
498 }
499
500 void demonstrate_factory() {
501     std::cout << " 4 Factory Functions with Perfect Forwarding:\n\n";
502
503     std::cout << "     See Section 4 for detailed factory examples!\n\n";
504 }
```

```
505 void demonstrate_all() {
506     demonstrate_vector();
507     demonstrate_rvo();
508     demonstrate_unique_ptr();
509     demonstrate_factory();
510 }
511
512 } // namespace real_world_examples
513
514 // =====
515 // SECTION 7: PERFORMANCE COMPARISON
516 // =====
517
518 namespace performance_comparison {
519
520 std::vector<int> create_large_vector(size_t size) {
521     std::vector<int> result(size);
522     for (size_t i = 0; i < size; ++i) {
523         result[i] = static_cast<int>(i);
524     }
525     return result; // RVO or move
526 }
527
528 void benchmark_copy_vs_move() {
529     std::cout << "\n" << std::string(70, '=') << "\n";
530     std::cout << "SECTION 7: PERFORMANCE COMPARISON\n";
531     std::cout << std::string(70, '=') << "\n\n";
532
533     const size_t size = 1000000; // 1 million integers
534     const int iterations = 100;
535
536     std::cout << " Benchmark Configuration:\n";
537     std::cout << "   Buffer size: " << size << " integers\n";
538     std::cout << "   Iterations: " << iterations << "\n\n";
539
540     // Benchmark COPY
541     std::cout << " 1 Testing COPY operations...\n";
542     auto start_copy = std::chrono::high_resolution_clock::now();
543
544     std::vector<int> source = create_large_vector(size);
545     for (int i = 0; i < iterations; ++i) {
546         std::vector<int> dest = source; // Copy
547         (void)dest; // Prevent optimization
548     }
549
550     auto end_copy = std::chrono::high_resolution_clock::now();
551     auto copy_time = std::chrono::duration_cast<std::chrono::milliseconds>(
552         end_copy - start_copy).count();
553
554     // Benchmark MOVE
555     std::cout << " 2 Testing MOVE operations...\n";
556     auto start_move = std::chrono::high_resolution_clock::now();
557
558     for (int i = 0; i < iterations; ++i) {
```

```
559     std::vector<int> source_temp = create_large_vector(size);
560     std::vector<int> dest = std::move(source_temp); // Move
561     (void)dest; // Prevent optimization
562 }
563
564 auto end_move = std::chrono::high_resolution_clock::now();
565 auto move_time = std::chrono::duration_cast<std::chrono::milliseconds>(
566     end_move - start_move).count();
567
568 // Results
569 std::cout << "\n RESULTS:\n";
570 std::cout << "    Copy time: " << copy_time << " ms\n";
571 std::cout << "    Move time: " << move_time << " ms\n";
572 std::cout << "    Speedup: " << (double)copy_time / move_time << "x
573     faster!\n\n";
574
575 std::cout << "    INTERPRETATION:\n";
576 std::cout << "    Copy: O(n) - copies all " << size << " integers\n";
577 std::cout << "    Move: O(1) - just transfers pointer ownership\n";
578 std::cout << "    For large objects, move is 10x-1000x+ faster!\n";
579 }
580 } // namespace performance_comparison
581
582 // =====
583 // MAIN - Run All Demonstrations
584 // =====
585
586 int main() {
587     std::cout << "\n";
588     std::cout << "
589         IMPLEMENTING MOVE SEMANTICS AND PERFECT FORWARDING
590             \n";
591     std::cout << "
592             Comprehensive Guide to Modern C++ Features
593                 \n";
594     std::cout << "
595                     \n";
596
597     try {
598         // Section 1: Lvalues vs Rvalues
599         lvalues_rvalues::demonstrate();
600
601         // Section 2: Move Semantics
602         move_semantics::demonstrate();
603
604         // Section 3: Understanding std::move
605         understanding_move::demonstrate();
606
607         // Section 4: Perfect Forwarding
608         perfect_forwarding::demonstrate();
609         perfect_forwarding::demonstrate_factory();
610
611         // Section 5: Rule of Zero/Three/Five
612         rule_of_five::demonstrate();
613     }
```

```
610 // Section 6: Real-World Examples
611 real_world_examples::demonstrate_all();
612
613 // Section 7: Performance Comparison
614 performance_comparison::benchmark_copy_vs_move();
615
616 // Summary
617 std::cout << "\n" << std::string(70, '=') << "\n";
618 std::cout << "SUMMARY: KEY TAKEAWAYS\n";
619 std::cout << std::string(70, '=') << "\n\n";
620
621 std::cout << " Move Semantics:\n";
622 std::cout << " • Enables O(1) resource transfer instead of O(n) copy
623             \n";
624 std::cout << " • Always mark move operations noexcept\n";
625 std::cout << " • 10x-1000x+ performance improvement for large
626             objects\n\n";
627
628 std::cout << " Perfect Forwarding:\n";
629 std::cout << " • Preserves lvalue/rvalue category through templates\
630             \n";
631 std::cout << " • Use T&& (universal reference) with std::forward<T>\
632             \n";
633 std::cout << " • Essential for factory functions and wrappers\n\n";
634
635 std::cout << " Best Practices:\n";
636 std::cout << " • Prefer Rule of Zero (use std types)\n";
637 std::cout << " • If managing resources, implement Rule of Five\n";
638 std::cout << " • Return by value (trust RVO and move)\n";
639 std::cout << " • Use std::move for explicit ownership transfer\n";
640 std::cout << " • Use std::forward in template forwarding\n";
641 std::cout << " • Don't use objects after moving from them\n\n";
642
643 std::cout << "                                     \n";
644 std::cout << "                                     ALL EXAMPLES COMPLETED!
645                                     \n";
646 std::cout << "                                     \n\n";
647
648 } catch (const std::exception& e) {
649     std::cerr << " Error: " << e.what() << "\n";
650     return 1;
651 }
652
653 return 0;
654 }
```

44 Source Code: MultiThreadedMicroservices.cpp

File: src/MultiThreadedMicroservices.cpp

Repository: [View on GitHub](#)

```
1 // MultiThreadedMicroservices.cpp
2 // Demonstrates multi-threaded microservices architecture with different
3 // exception handling strategies: REST threads use pthread_exit(), core
4 // threads use abort()
5
6 #include <iostream>
7 #include <thread>
8 #include <mutex>
9 #include <condition_variable>
10 #include <queue>
11 #include <vector>
12 #include <string>
13 #include <memory>
14 #include <atomic>
15 #include <chrono>
16 #include <sstream>
17 #include <iomanip>
18 #include <cstring>
19 #include <csignal>
20 #include <functional>
21
22 #ifdef __linux__
23     #include <pthread.h>
24     #include <execinfo.h>
25     #include <cxxabi.h>
26 #elif _WIN32
27     #include <windows.h>
28     #include <dbghelp.h>
29 #endif
30
31 using namespace std::chrono;
32 using namespace std::chrono_literals;
33
34 // SECTION 1: Stack Trace and Logging Infrastructure
35 // -----
36
37 class Logger {
38 private:
39     static std::mutex log_mutex_;
40
41     static std::string get_timestamp() {
42         auto now = system_clock::now();
43         auto time = system_clock::to_time_t(now);
44         auto ms = duration_cast<milliseconds>(now.time_since_epoch()) % 1000;
```

```

45     std::ostringstream oss;
46     oss << std::put_time(std::localtime(&time), "%H:%M:%S")
47         << '.' << std::setfill('0') << std::setw(3) << ms.count();
48     return oss.str();
49 }
50
51
52     static std::string get_thread_id() {
53         std::ostringstream oss;
54         oss << std::this_thread::get_id();
55         return oss.str();
56     }
57
58 public:
59     enum Level { INFO, WARNING, ERROR, CRITICAL };
60
61     static void log(Level level, const std::string& message,
62                      const std::string& thread_name = "") {
63         std::lock_guard<std::mutex> lock(log_mutex_);
64
65         const char* level_str[] = {"INFO", "WARN", "ERROR", "CRIT"};
66         const char* color[] = {"\033[32m", "\033[33m", "\033[31m", "\033[35m"};
67         const char* reset = "\033[0m";
68
69         std::cout << "[" << get_timestamp() << "] "
70             << color[level] << "[" << level_str[level] << "]" << reset
71             << " [TID:" << get_thread_id().substr(0, 6) << "]";
72
73         if (!thread_name.empty()) {
74             std::cout << " [" << thread_name << "] ";
75         }
76
77         std::cout << " " << message << "\n";
78     }
79
80     static std::vector<std::string> capture_stack_trace() {
81         std::vector<std::string> frames;
82
83 #ifdef __linux__
84     void* buffer[32];
85     int frame_count = backtrace(buffer, 32);
86     char** symbols = backtrace_symbols(buffer, frame_count);
87
88     if (symbols) {
89         for (int i = 0; i < frame_count && i < 10; ++i) {
90             std::string frame = symbols[i];
91
92             // Try to demangle
93             const char* begin = strchr(symbols[i], '(');
94             const char* end = strchr(symbols[i], '+');
95
96             if (begin && end && begin < end) {
97                 begin++;

```

```

98             std::string mangled(begin, end - begin);
99             int status;
100            char* demangled = abi::__cxa_demangle(mangled.c_str(),
101                                         nullptr, nullptr, &status);
102            if (status == 0 && demangled) {
103                frame = demangled;
104                free(demangled);
105            }
106        }
107        frames.push_back(frame);
108    }
109    free(symbols);
110}
111#elif _WIN32
112    void* buffer[32];
113    HANDLE process = GetCurrentProcess();
114    SymInitialize(process, NULL, TRUE);
115
116    WORD frame_count = CaptureStackBackTrace(0, 32, buffer, NULL);
117    SYMBOL_INFO* symbol = (SYMBOL_INFO*)calloc(sizeof(SYMBOL_INFO) + 256,
118                                                1);
119
120    if (symbol) {
121        symbol->MaxNameLen = 255;
122        symbol->SizeOfStruct = sizeof(SYMBOL_INFO);
123
124        for (WORD i = 0; i < frame_count && i < 10; ++i) {
125            if (SymFromAddr(process, (DWORD64)buffer[i], 0, symbol)) {
126                frames.push_back(symbol->Name);
127            } else {
128                std::ostringstream oss;
129                oss << "0x" << std::hex << (uint64_t)buffer[i];
130                frames.push_back(oss.str());
131            }
132        }
133        free(symbol);
134    }
135    SymCleanup(process);
136#else
137    frames.push_back("[Stack trace not available]");
138#endif
139
140    return frames;
141}
142
143 static void log_exception_with_stack(const std::exception& e,
144                                     const std::string& thread_name) {
145     log(CRITICAL, std::string("EXCEPTION: ") + e.what(), thread_name);
146
147     auto stack = capture_stack_trace();
148     if (!stack.empty()) {
149         log(CRITICAL, "Stack trace:", thread_name);
150         for (size_t i = 0; i < stack.size(); ++i) {
151             std::string mangled(begin, end - begin);
152             int status;
153             char* demangled = abi::__cxa_demangle(mangled.c_str(),
154                                         nullptr, nullptr, &status);
155             if (status == 0 && demangled) {
156                 frame = demangled;
157                 free(demangled);
158             }
159         }
160     }
161 }

```

```
150         std::ostringstream oss;
151         oss << " #" << i << ":" << stack[i];
152         log(CRITICAL, oss.str(), thread_name);
153     }
154 }
155 }
156 };
157
158 std::mutex Logger::log_mutex_;
159
160 // -----
161 // SECTION 2: Thread Type Identification and Exception Policies
162 // -----
163
164 enum class ThreadType {
165     CORE_SERVICE,      // Critical - abort() on exception
166     REST_SERVICE,       // Non-critical - pthread_exit() on exception
167     MONITORING          // Non-critical - pthread_exit() on exception
168 };
169
170 class ThreadContext {
171 private:
172     ThreadType type_;
173     std::string name_;
174
175 public:
176     ThreadContext(ThreadType type, const std::string& name)
177         : type_(type), name_(name) {}
178
179     ThreadType get_type() const { return type_; }
180     const std::string& get_name() const { return name_; }
181
182     bool is_core_service() const { return type_ == ThreadType::CORE_SERVICE; }
183     bool is_rest_service() const { return type_ == ThreadType::REST_SERVICE; }
184
185     void handle_exception(const std::exception& e) {
186         Logger::log_exception_with_stack(e, name_);
187
188         if (is_core_service()) {
189             Logger::log(Logger::CRITICAL,
190                         "CORE SERVICE FAILURE - Calling abort() to terminate
191                         application!",
192                         name_);
193             std::cerr << "\n";
194             std::cerr << "    CRITICAL: CORE SERVICE CRASHED\n";
195             std::cerr << "    Terminating entire application\n";
196             std::cerr << "\n";
197
198             std::abort(); // Terminate entire process
199         } else {
```

```
199     Logger::log(Logger::ERROR,
200                 "REST/MONITORING SERVICE FAILURE - Exiting thread only
201                 (core services continue)",
202                 name_);
203                 std::cerr << "\n";
204                 std::cerr << "    REST/Monitor thread exiting      \n";
205                 std::cerr << "    Core services still running OK      \n";
206                 std::cerr << "\n\n";
207 #ifdef __linux__
208             pthread_exit(nullptr); // Exit only this thread
209 #elif _WIN32
210             ExitThread(1); // Windows equivalent
211 #else
212             std::this_thread::sleep_for(1s);
213             throw; // Fallback
214 #endif
215         }
216     }
217 };
218
219 // Thread-local storage for thread context
220 thread_local std::unique_ptr<ThreadContext> g_thread_context;
221
222 // =====
223 // SECTION 3: Simple JSON Parser (for demonstration)
224 // =====
225
226 class JsonParseException : public std::runtime_error {
227 public:
228     explicit JsonParseException(const std::string& msg)
229         : std::runtime_error("JSON Parse Error: " + msg) {}
230 };
231
232 class SimpleJson {
233 private:
234     std::string data_;
235
236 public:
237     explicit SimpleJson(const std::string& json_str) : data_(json_str) {
238         validate();
239     }
240
241     void validate() const {
242         // Simple validation
243         if (data_.empty()) {
244             throw JsonParseException("Empty JSON string");
245         }
246
247         // Must start with { and end with }
```

```
248     size_t start = data_.find_first_not_of(" \t\n\r");
249     size_t end = data_.find_last_not_of(" \t\n\r");
250
251     if (start == std::string::npos || end == std::string::npos) {
252         throw JsonParseException("Invalid JSON: whitespace only");
253     }
254
255     if (data_[start] != '{' || data_[end] != '}') {
256         throw JsonParseException("Invalid JSON: must start with { and end
257             with }");
258     }
259
260     // Count braces
261     int brace_count = 0;
262     for (char c : data_) {
263         if (c == '{') brace_count++;
264         if (c == '}') brace_count--;
265         if (brace_count < 0) {
266             throw JsonParseException("Invalid JSON: unmatched closing
267                 brace");
268         }
269     }
270
271     if (brace_count != 0) {
272         throw JsonParseException("Invalid JSON: unmatched opening brace");
273     }
274
275     std::string get_field(const std::string& field_name) const {
276         std::string search = "\"" + field_name + "\"";
277         size_t pos = data_.find(search);
278
279         if (pos == std::string::npos) {
280             throw JsonParseException("Field not found: " + field_name);
281         }
282
283         // Find value after colon
284         size_t colon = data_.find(':', pos);
285         if (colon == std::string::npos) {
286             throw JsonParseException("Malformed field: " + field_name);
287         }
288
289         size_t value_start = data_.find_first_not_of(" \t\n\r", colon + 1);
290         size_t value_end = data_.find_first_of(",}", value_start);
291
292         if (value_start == std::string::npos || value_end == std::string::npos
293             ) {
294             throw JsonParseException("Cannot extract value for: " + field_name
295                 );
296         }
297
298         std::string value = data_.substr(value_start, value_end - value_start)
299 ;
```

```
297     // Remove quotes if present
298     if (value.front() == '\"' && value.back() == '\"') {
299         value = value.substr(1, value.length() - 2);
300     }
301
302     return value;
303 }
304
305     const std::string& raw() const { return data_; }
306 };
307
308 /**
309 // SECTION 4: Core Services (Critical - abort on exception)
310 /**
311 =====
312
313 class DatabaseService {
314 private:
315     std::atomic<bool> running_{false};
316     std::atomic<int> query_count_{0};
317     std::mutex mutex_;
318     std::condition_variable cv_;
319     std::queue<std::string> query_queue_;
320
321 public:
322     void start() {
323         running_ = true;
324
325         g_thread_context = std::make_unique<ThreadContext>(
326             ThreadType::CORE_SERVICE, "DatabaseService");
327
328         Logger::log(Logger::INFO, "Database service started", "DatabaseService"
329                     );
330
331         try {
332             while (running_) {
333                 std::unique_lock<std::mutex> lock(mutex_);
334                 cv_.wait_for(lock, 500ms, [this] {
335                     return !query_queue_.empty() || !running_;
336                 });
337
338                 if (!running_) break;
339
340                 while (!query_queue_.empty()) {
341                     std::string query = query_queue_.front();
342                     query_queue_.pop();
343                     lock.unlock();
344
345                     execute_query(query);
346
347                     lock.lock();
348                 }
349             }
350         } catch (...) {
351             std::abort();
352         }
353     }
354 }
```

```
346         }
347     }
348 }
349     catch (const std::exception& e) {
350         g_thread_context->handle_exception(e);
351     }
352
353     Logger::log(Logger::INFO, "Database service stopped", "DatabaseService
354         ");
355
356     void execute_query(const std::string& query) {
357         query_count_++;
358
359         // Simulate query execution
360         std::this_thread::sleep_for(50ms);
361
362         Logger::log(Logger::INFO,
363             "Executed query #" + std::to_string(query_count_.load()) +
364             ": " + query,
365             "DatabaseService");
366
367         // Simulate critical error in core service (triggered by special query
368         )
369         if (query.find("TRIGGER_CORE_FAILURE") != std::string::npos) {
370             Logger::log(Logger::ERROR,
371                 "SIMULATING CRITICAL DATABASE CORRUPTION!",
372                 "DatabaseService");
373             std::this_thread::sleep_for(100ms);
374             throw std::runtime_error("CRITICAL: Database corruption detected!
375                 Data integrity compromised!");
376         }
377     }
378
379     void submit_query(const std::string& query) {
380         std::lock_guard<std::mutex> lock(mutex_);
381         query_queue_.push(query);
382         cv_.notify_one();
383     }
384
385     void stop() {
386         running_ = false;
387         cv_.notify_all();
388     }
389
390     int get_query_count() const { return query_count_.load(); }
391 };
392
393 class CacheService {
394 private:
395     std::atomic<bool> running_{false};
396     std::atomic<int> cache_hits_{0};
397     std::atomic<int> cache_misses_{0};
```

```
396 | public:
397 |     void start() {
398 |         running_ = true;
399 |
400 |         g_thread_context = std::make_unique<ThreadContext>(
401 |             ThreadType::CORE_SERVICE, "CacheService");
402 |
403 |         Logger::log(Logger::INFO, "Cache service started", "CacheService");
404 |
405 |         try {
406 |             while (running_) {
407 |                 std::this_thread::sleep_for(1s);
408 |
409 |                 // Simulate cache maintenance
410 |                 if (cache_hits_ + cache_misses_ > 0) {
411 |                     int total = cache_hits_ + cache_misses_;
412 |                     float hit_rate = (100.0f * cache_hits_) / total;
413 |
414 |                     std::ostringstream oss;
415 |                     oss << "Cache stats: " << cache_hits_.load() << " hits, "
416 |                         << cache_misses_.load() << " misses (hit rate: "
417 |                         << std::fixed << std::setprecision(1) << hit_rate << "%)";
418 |
419 |                     Logger::log(Logger::INFO, oss.str(), "CacheService");
420 |                 }
421 |             }
422 |         }
423 |         catch (const std::exception& e) {
424 |             g_thread_context->handle_exception(e);
425 |         }
426 |
427 |         Logger::log(Logger::INFO, "Cache service stopped", "CacheService");
428 |     }
429 |
430 |     bool get(const std::string& key) {
431 |         // Simulate cache lookup
432 |         bool hit = (std::hash<std::string>{}(key) % 3) == 0;
433 |
434 |         if (hit) {
435 |             cache_hits_++;
436 |         } else {
437 |             cache_misses_++;
438 |         }
439 |
440 |         return hit;
441 |     }
442 |
443 |     void stop() {
444 |         running_ = false;
445 |     }
446 };
447 //
448 //
```

```
=====
449 // SECTION 5: REST Service (Non-critical - pthread_exit on exception)
450 //
=====

451
452 class Rest ApiService {
453 private:
454     std::atomic<bool> running_{false};
455     std::atomic<int> request_count_{0};
456     std::atomic<int> error_count_{0};
457     DatabaseService& db_;
458     CacheService& cache_;
459
460 public:
461     Rest ApiService(DatabaseService& db, CacheService& cache)
462         : db_(db), cache_(cache) {}
463
464     void start() {
465         running_ = true;
466
467         g_thread_context = std::make_unique<ThreadContext>(
468             ThreadType::REST_SERVICE, "Rest ApiService");
469
470         Logger::log(Logger::INFO, "REST API service started on port 8080 (
471             simulated)",
472             "Rest ApiService");
473
474         try {
475             simulate_rest_requests();
476         }
477         catch (const std::exception& e) {
478             g_thread_context->handle_exception(e);
479         }
480
481         Logger::log(Logger::INFO, "REST API service stopped", "Rest ApiService"
482             );
483     }
484
485     void simulate_rest_requests() {
486         // Simulate various REST requests
487         std::vector<std::string> requests = {
488             R"( {"action": "get_user", "user_id": "123"})",
489             R"( {"action": "create_order", "product": "laptop", "quantity": 1})
490                 ,
491             R"( {"action": "update_profile", "name": "John Doe"})",
492             R"( {"invalid json - missing closing brace})", // This will cause
493                 exception!
494             R"( {"action": "delete_item", "item_id": "456"})",
495             R"()", // Empty - will cause exception!
496         };
497
498         int request_num = 0;
```

```
495
496     while (running_ && request_num < requests.size()) {
497         std::this_thread::sleep_for(800ms);
498
499         const std::string& request_body = requests[request_num];
500         request_count_++;
501
502         Logger::log(Logger::INFO,
503                     "Received REST request #" + std::to_string(
504                         request_count_.load()),
505                     "Rest ApiService");
506
507         try {
508             handle_request(request_body);
509         }
510         catch (const JsonParseException& e) {
511             error_count_++;
512
513             Logger::log(Logger::ERROR,
514                         "Invalid JSON in request #" + std::to_string(
515                             request_count_.load()),
516                         "Rest ApiService");
517
518             // This will trigger pthread_exit() through ThreadContext
519             throw;
520         }
521
522         request_num++;
523     }
524
525     // If we get here without exception, run indefinitely
526     while (running_) {
527         std::this_thread::sleep_for(1s);
528     }
529
530     void handle_request(const std::string& json_body) {
531         // Parse JSON (may throw JsonParseException)
532         SimpleJson json(json_body);
533
534         std::string action = json.get_field("action");
535
536         Logger::log(Logger::INFO, "Processing action: " + action, "
537             Rest ApiService");
538
539         // Check cache
540         if (cache_.get(action)) {
541             Logger::log(Logger::INFO, "Cache HIT for action: " + action, "
542                 Rest ApiService");
543         } else {
544             Logger::log(Logger::INFO, "Cache MISS for action: " + action, "
545                 Rest ApiService");
546             // Submit query to database
547             db_.submit_query("SELECT * FROM actions WHERE action='"
548                             + action + "
```

```
        " :: ");
544    }
545}
546
547 void stop() {
548     running_ = false;
549}
550
551 int get_request_count() const { return request_count_.load(); }
552 int get_error_count() const { return error_count_.load(); }
553};
554
555 // =====
556 // SECTION 6: Monitoring Service (Non-critical)
557 // =====
558
559 class MonitoringService {
560 private:
561     std::atomic<bool> running_{false};
562     DatabaseService& db_;
563     Rest ApiService& rest_;
564
565 public:
566     MonitoringService(DatabaseService& db, Rest ApiService& rest)
567         : db_(db), rest_(rest) {}
568
569     void start() {
570         running_ = true;
571
572         g_thread_context = std::make_unique<ThreadContext>(
573             ThreadType::MONITORING, "MonitoringService");
574
575         Logger::log(Logger::INFO, "Monitoring service started", "
576             MonitoringService");
577
578         try {
579             while (running_) {
580                 std::this_thread::sleep_for(2s);
581
582                 std::ostringstream oss;
583                 oss << "System Health: DB queries=" << db_.get_query_count()
584                     << ", REST requests=" << rest_.get_request_count()
585                     << ", REST errors=" << rest_.get_error_count();
586
587                 Logger::log(Logger::INFO, oss.str(), "MonitoringService");
588             }
589         } catch (const std::exception& e) {
590             g_thread_context->handle_exception(e);
591         }
592     }
593 }
```

```
592     Logger::log(Logger::INFO, "Monitoring service stopped", "  
593             MonitoringService");  
594 }  
595  
596 void stop() {  
597     running_ = false;  
598 }  
599 };  
600 //  
=====  
602 // SECTION 7: Microservices Orchestrator  
603 //  
=====  
604  
605 class MicroservicesOrchestrator {  
606 private:  
607     DatabaseService db_service_;  
608     CacheService cache_service_;  
609     Rest ApiService rest_service_;  
610     MonitoringService monitoring_service_;  
611  
612     std::vector<std::thread> threads_;  
613     bool simulate_core_failure_;  
614  
615 public:  
616     MicroservicesOrchestrator(bool simulate_core_failure = false)  
617         : rest_service_(db_service_, cache_service_),  
618         monitoring_service_(db_service_, rest_service_),  
619         simulate_core_failure_(simulate_core_failure) {}  
620  
621     void start() {  
622         std::cout << "\n";  
623         std::cout << "                                \n";  
624         std::cout << "      Multi-Threaded Microservices Architecture  
625                         \n";  
626         std::cout << "                                \n";  
627         std::cout << "      Core Services (abort on exception):  
628                         \n";  
629         std::cout << "          •      DatabaseService  
630                         \n";  
631         std::cout << "          •      CacheService  
632                         \n";  
633         std::cout << "                                \n";  
634         std::cout << "      REST Services (pthread_exit on exception):  
635                         \n";  
636         std::cout << "          •      Rest ApiService  
637                         \n";  
638         std::cout << "          •      MonitoringService  
639                         \n";
```

```
633     std::cout << "\n";
634
635     Logger::log(Logger::INFO, "Starting microservices orchestrator", "Orchestrator");
636
637     // Start core services first
638     threads_.emplace_back(&DatabaseService::start, &db_service_);
639     threads_.emplace_back(&CacheService::start, &cache_service_);
640
641     std::this_thread::sleep_for(500ms);
642
643     // Start REST and monitoring services
644     threads_.emplace_back(&Rest ApiService::start, &rest_service_);
645     threads_.emplace_back(&MonitoringService::start, &monitoring_service_);
646
647     Logger::log(Logger::INFO, "All services started", "Orchestrator");
648
649     // If simulating core failure, trigger it after a few seconds
650     if (simulate_core_failure_) {
651         std::this_thread::sleep_for(3s);
652         Logger::log(Logger::WARNING,
653                     "Triggering core service failure in 1 second...", "Orchestrator");
654         std::this_thread::sleep_for(1s);
655         db_service_.submit_query("TRIGGER_CORE_FAILURE - Simulated
656                                   corruption");
657     }
658 }
659
660 void wait_and_stop(int seconds) {
661     std::this_thread::sleep_for(std::chrono::seconds(seconds));
662
663     Logger::log(Logger::INFO, "Initiating graceful shutdown...", "Orchestrator");
664
665     // Stop services in reverse order
666     monitoring_service_.stop();
667     rest_service_.stop();
668     cache_service_.stop();
669     db_service_.stop();
670
671     // Wait for threads to finish
672     for (auto& thread : threads_) {
673         if (thread.joinable()) {
674             thread.join();
675         }
676     }
677
678     Logger::log(Logger::INFO, "All services stopped", "Orchestrator");
679 }
680 };
681 }
```

```
682 // =====
683 // SECTION 8: Demonstrations
684 // =====
685
686 void demonstrate_rest_service_exception() {
687     std::cout << "\n" << std::string(70, '=') << "\n";
688     std::cout << "==== Demonstration 1: REST Service Exception Handling ===\n";
689     std::cout << std::string(70, '=') << "\n\n";
690
691     std::cout << "Scenario:\n";
692     std::cout << " • REST service will receive invalid JSON requests\n";
693     std::cout << " • JsonParseException will be thrown\n";
694     std::cout << " • REST thread will call pthread_exit() and terminate\n";
695     std::cout << " • Core services (Database, Cache) will continue running\n\n";
696
697     std::cout << "Press Enter to start demonstration... \n";
698     std::cin.get();
699
700     MicroservicesOrchestrator orchestrator(false); // No core failure
701     orchestrator.start();
702
703     // Let it run for 10 seconds
704     // REST service will encounter invalid JSON around request #4
705     orchestrator.wait_and_stop(10);
706
707     std::cout << "\n" << std::string(70, '=') << "\n";
708     std::cout << " REST service terminated (pthread_exit) but core services
709     survived!\n";
710     std::cout << std::string(70, '=') << "\n\n";
711 }
712
713 void demonstrate_core_service_exception() {
714     std::cout << "\n" << std::string(70, '=') << "\n";
715     std::cout << "==== Demonstration 2: CORE Service Exception Handling ===\n";
716     std::cout << std::string(70, '=') << "\n\n";
717
718     std::cout << "Scenario:\n";
719     std::cout << " • Core service (Database) will encounter critical error\n";
720     ;
721     std::cout << " • Exception will be thrown in DatabaseService\n";
722     std::cout << " • DatabaseService thread will call abort()\n";
723     std::cout << " • ENTIRE APPLICATION WILL TERMINATE \n\n";
724
725     std::cout << " WARNING: This will terminate the process with abort()!\n";
726     ;
727     std::cout << "Press Enter to start demonstration... \n";
728     std::cin.get();
729
730     MicroservicesOrchestrator orchestrator(true); // Simulate core failure
```

```
728     orchestrator.start();
729
730     // Wait for core failure (will never return - abort() will be called)
731     orchestrator.wait_and_stop(30);
732
733     // This line will never be reached
734     std::cout << "\n This message should NEVER appear (abort() was called)\n"
735     ;
736
737 void demonstrate_best_practices() {
738     std::cout << "\n" << std::string(70, '=') << "\n";
739     std::cout << "==== Best Practices for Multi-Threaded Microservices ===\n";
740     std::cout << std::string(70, '=') << "\n\n";
741
742     std::cout << " THREAD CLASSIFICATION:\n";
743     std::cout << " 1. Core/Critical Services:\n";
744     std::cout << " • Essential for application function\n";
745     std::cout << " • Exception → abort() entire process\n";
746     std::cout << " • Examples: Database, Message Queue, State Manager\n\n"
747     ;
748
749     std::cout << " 2. REST/External Services:\n";
750     std::cout << " • Handle external/untrusted input\n";
751     std::cout << " • Exception → pthread_exit() current thread only\n";
752     std::cout << " • Examples: HTTP servers, gRPC endpoints, WebSocket
753         handlers\n\n";
754
755     std::cout << " 3. Monitoring/Auxiliary Services:\n";
756     std::cout << " • Non-essential functionality\n";
757     std::cout << " • Exception → pthread_exit() current thread only\n";
758     std::cout << " • Examples: Metrics, logging, health checks\n\n";
759
760     std::cout << " EXCEPTION HANDLING STRATEGY:\n";
761     std::cout << " 1. Always log exceptions with stack traces\n";
762     std::cout << " 2. Validate all external input (JSON, XML, protobuf)\n";
763     std::cout << " 3. Use thread-local context to identify thread type\n";
764     std::cout << " 4. Implement graceful degradation for non-critical threads
765         \n";
766     std::cout << " 5. Use RAII for resource cleanup before pthread_exit()\n\n"
767     ;
768
769     std::cout << " ISOLATION AND RESILIENCE:\n";
770     std::cout << " 1. Run REST handlers in separate threads/thread pool\n";
771     std::cout << " 2. Implement circuit breakers for failing services\n";
772     std::cout << " 3. Use message queues to decouple services\n";
773     std::cout << " 4. Monitor thread health and restart if needed\n";
774     std::cout << " 5. Test exception paths thoroughly\n\n";
775
776     std::cout << " CRITICAL WARNINGS:\n";
777     std::cout << " 1. pthread_exit() does NOT call destructors for local
778         objects!\n";
779     std::cout << " 2. Clean up resources manually before pthread_exit()\n";
780     std::cout << " 3. Don't use pthread_exit() from main thread\n";
```

```
776     std::cout << " 4. On Windows, use ExitThread() instead of pthread_exit()\n";
777     std::cout << " 5. Consider std::terminate() as alternative to abort()\n";
778 }
779 //
780 // -----
781 // MAIN FUNCTION
782 // -----
783
784 int main() {
785     std::cout << "\n";
786     std::cout << "                               \n";
787     std::cout << "      Multi-Threaded Microservices with Exception Handling\n";
788     std::cout << "                               \n";
789     std::cout << "      Demonstrates different exception handling strategies:\n";
790     std::cout << "          \n";
791     std::cout << "      •      REST Service: pthread_exit() (thread-local\n";
792     std::cout << "          termination) \n";
793     std::cout << "      •      Core Service: abort() (process-wide termination)\n";
794     std::cout << "          \n";
795     std::cout << "          \n";
796     std::cout << "Select demonstration:\n";
797     std::cout << " 1. REST Service Exception (pthread_exit - graceful)\n";
798     std::cout << " 2. CORE Service Exception (abort - terminates process)\n";
799     std::cout << " 3. Best Practices Guide (no execution)\n";
800     std::cout << "\nEnter choice (1-3): ";
801
802     int choice;
803     std::cin >> choice;
804     std::cin.ignore(); // Clear newline
805
806     switch (choice) {
807         case 1:
808             demonstrate_rest_service_exception();
809             demonstrate_best_practices();
810             break;
811
812         case 2:
813             demonstrate_core_service_exception();
814             // Will never reach here - abort() terminates process
815             break;
816
817         case 3:
818             demonstrate_best_practices();
819             break;
820
821         default:
```

```
820     std::cout << "\nInvalid choice. Running REST demonstration by\n      default.\n";
821     demonstrate_rest_service_exception();
822     demonstrate_best_practices();
823     break;
824 }
825
826 std::cout << "\n" << std::string(70, '=')
827 std::cout << "All demonstrations completed!\n";
828 std::cout << "\nKEY TAKEAWAYS:\n";
829 std::cout << "  1. REST threads handle untrusted input → pthread_exit() on\n      error\n";
830 std::cout << "  2. Core threads are critical → abort() on error\n";
831 std::cout << "  3. Always log exceptions with stack traces\n";
832 std::cout << "  4. Use thread-local context for thread identification\n";
833 std::cout << "  5. Implement graceful degradation for non-critical\n      services\n";
834 std::cout << std::string(70, '=')
835
836 return 0;
837 }
```

45 Source Code: NVIIdiomTemplateMethod.cpp

File: src/NVIIdiomTemplateMethod.cpp

Repository: [View on GitHub](#)

```
1 // NVIIdiomTemplateMethod.cpp
2 // Demonstrates the Non-Virtual Interface (NVI) Idiom and Template Method
3 // Pattern
4 //
5 // KEY CONCEPTS:
6 // 1. Public non-virtual methods define the interface (Template Method)
7 // 2. Private/protected virtual methods are customization points
8 // 3. Base class controls the algorithm flow
9 // 4. Derived classes customize specific steps
10 //
11 // HERB SUTTER'S GUIDELINES:
12 // Guideline #1: Prefer to make interfaces non-virtual (Template Method)
13 // Guideline #2: Prefer to make virtual functions private
14 // Guideline #3: Only if derived needs base implementation, make virtual
15 // protected
16 // Guideline #4: Destructor should be public+virtual OR protected+non-virtual
17 //
18 // WHEN TO USE NVI:
19 // Need invariant algorithm with customizable steps
20 // Want to enforce pre/post conditions
21 // Need to guarantee certain code always runs
22 // Want separation of interface from implementation
23 //
24 // WHEN TO AVOID NVI:
25 // Simple interfaces with no invariants
26 // Performance-critical code (tiny extra overhead)
27 // When derived classes need full control
28 // Pure abstract interfaces (use public virtual)
29
30 #include <iostream>
31 #include <string>
32 #include <vector>
33 #include <memory>
34 #include <chrono>
35 #include <fstream>
36 #include <stdexcept>
37
38 using namespace std::chrono_literals;
39 //
40 =====
41 // SECTION 1: Basic NVI Idiom - Template Method Pattern
42 // =====
43
44 namespace basic_nvi {
```

```
44
45 class DataProcessor {
46 public:
47     // PUBLIC NON-VIRTUAL: This is the Template Method
48     // Defines the algorithm structure that CANNOT be changed by derived
49     // classes
50     void process() {
51         std::cout << "  [DataProcessor::process] Algorithm started\n";
52
53         // Invariant: Always validate before processing
54         if (!validate()) {
55             std::cout << "    Validation failed, aborting\n";
56             return;
57         }
58
59         // Call customization points (private virtuals)
60         load();
61         transform();
62         save();
63
64         std::cout << "  [DataProcessor::process] Algorithm completed\n";
65     }
66
67     virtual ~DataProcessor() = default;
68
69 private:
70     // PRIVATE VIRTUAL: Customization points that derived classes override
71     // These are the "steps" of the algorithm
72
73     virtual bool validate() {
74         std::cout << "    [Base] Default validation\n";
75         return true; // Base default: always valid
76     }
77
78     virtual void load() = 0;      // Pure virtual - must override
79     virtual void transform() = 0; // Pure virtual - must override
80     virtual void save() = 0;     // Pure virtual - must override
81 };
82
83 class CSVProcessor : public DataProcessor {
84 private:
85     // Override private virtuals to provide CSV-specific behavior
86     void load() override {
87         std::cout << "    [CSV] Loading CSV file...\n";
88     }
89
90     void transform() override {
91         std::cout << "    [CSV] Transforming CSV data...\n";
92     }
93
94     void save() override {
95         std::cout << "    [CSV] Saving CSV results...\n";
96     }
};
```

```
97
98 class JSONProcessor : public DataProcessor {
99 private:
100     bool validate() override {
101         std::cout << "[JSON] Custom JSON validation\n";
102         return true;
103     }
104
105     void load() override {
106         std::cout << "[JSON] Loading JSON file...\n";
107     }
108
109     void transform() override {
110         std::cout << "[JSON] Transforming JSON data...\n";
111     }
112
113     void save() override {
114         std::cout << "[JSON] Saving JSON results...\n";
115     }
116 };
117
118 void demonstrate() {
119     std::cout << "\n" << std::string(70, '=') << "\n";
120     std::cout << "==== SECTION 1: Basic NVI Idiom - Template Method ===\n";
121     std::cout << std::string(70, '=') << "\n\n";
122
123     std::cout << "1. Processing CSV data:\n";
124     CSVProcessor csv;
125     csv.process(); // Client calls public non-virtual method
126
127     std::cout << "\n2. Processing JSON data:\n";
128     JSONProcessor json;
129     json.process();
130
131     std::cout << "\n Benefits:\n";
132     std::cout << " • Base class controls algorithm flow (validation always
133         runs)\n";
134     std::cout << " • Derived classes customize only the steps they need\n";
135     std::cout << " • Cannot accidentally skip validation or change algorithm\n
136         ";
137     std::cout << " • Clear separation: public interface vs private
138         implementation\n";
139 }
140
141 } // namespace basic_nvi
142
143 // =====
144 // SECTION 2: NVI with Pre/Post Conditions - Real Power
145 // =====
```

```
144 namespace preconditions_example {
145
146 class DatabaseConnection {
147     bool connected_ = false;
148     int transaction_count_ = 0;
149
150 public:
151     // PUBLIC NON-VIRTUAL: Template Method with pre/post conditions
152     void executeQuery(const std::string& query) {
153         std::cout << " [executeQuery] Starting query execution\n";
154
155         // PRE-CONDITION: Must be connected
156         if (!connected_) {
157             std::cout << " Error: Not connected to database!\n";
158             return;
159         }
160
161         std::cout << " [Pre] Acquiring lock...\n";
162         std::cout << " [Pre] Starting transaction " << ++transaction_count_
163             << "\n";
164
165         // Call customization point
166         try {
167             doExecuteQuery(query);
168
169             // POST-CONDITION: Commit transaction
170             std::cout << " [Post] Committing transaction\n";
171             std::cout << " [Post] Releasing lock\n";
172
173         } catch (const std::exception& e) {
174             // POST-CONDITION: Rollback on error
175             std::cout << " [Post] Rolling back transaction due to error\n";
176             std::cout << " [Post] Releasing lock\n";
177             throw;
178         }
179
180         std::cout << " [executeQuery] Query completed successfully\n";
181     }
182
183     void connect() {
184         std::cout << " [Connection] Connected to database\n";
185         connected_ = true;
186     }
187
188     virtual ~DatabaseConnection() = default;
189
190 private:
191     // PRIVATE VIRTUAL: Derived classes provide query logic
192     virtual void doExecuteQuery(const std::string& query) = 0;
193 };
194
195 class MySQLConnection : public DatabaseConnection {
196 private:
197     void doExecuteQuery(const std::string& query) override {
```

```

197     std::cout << "      [MySQL] Executing: " << query << "\n";
198     std::cout << "      [MySQL] Query executed successfully\n";
199 }
200 };
201
202 class PostgreSQLConnection : public DatabaseConnection {
203 private:
204     void doExecuteQuery(const std::string& query) override {
205         std::cout << "      [PostgreSQL] Executing: " << query << "\n";
206         if (query.find("DROP") != std::string::npos) {
207             throw std::runtime_error("DROP statements not allowed!");
208         }
209         std::cout << "      [PostgreSQL] Query executed successfully\n";
210     }
211 };
212
213 void demonstrate() {
214     std::cout << "\n" << std::string(70, '=') << "\n";
215     std::cout << "==== SECTION 2: NVI with Pre/Post Conditions ===\n";
216     std::cout << std::string(70, '=') << "\n\n";
217
218     std::cout << "1. MySQL query execution:\n";
219     MySQLConnection mysql;
220     mysql.connect();
221     mysql.executeQuery("SELECT * FROM users");
222
223     std::cout << "\n2. PostgreSQL with error handling:\n";
224     PostgreSQLConnection postgres;
225     postgres.connect();
226     try {
227         postgres.executeQuery("DROP TABLE users");
228     } catch (const std::exception& e) {
229         std::cout << "      Caught exception: " << e.what() << "\n";
230         std::cout << "      Transaction rolled back automatically!\n";
231     }
232
233     std::cout << "\n3. Attempting query without connection:\n";
234     MySQLConnection mysql2;
235     mysql2.executeQuery("SELECT * FROM users");
236
237     std::cout << "\n NVI ensures:\n";
238     std::cout << " • Pre-conditions always checked (connection, locks)\n";
239     std::cout << " • Post-conditions always executed (commit, rollback,
240         cleanup)\n";
241     std::cout << " • Derived classes cannot bypass these guarantees!\n";
242 }
243 } // namespace preconditions_example
244
245 ==
246 // SECTION 3: Protected Virtual - When Derived Needs Base Implementation
247 //

```

```
=====
248
249 namespace protected_virtual_example {
250
251 class Logger {
252 public:
253     // PUBLIC NON-VIRTUAL: Template Method
254     void log(const std::string& message) {
255         std::cout << " [log] Preparing log entry\n";
256         addTimestamp();
257         writeLog(message);
258         flush();
259     }
260
261     virtual ~Logger() = default;
262
263 protected:
264     // PROTECTED VIRTUAL: Derived classes may want to call base implementation
265     virtual void writeLog(const std::string& message) {
266         std::cout << " [Base Logger] " << message << "\n";
267     }
268
269 private:
270     void addTimestamp() {
271         std::cout << " [Timestamp] 2026-01-02 10:30:45\n";
272     }
273
274     void flush() {
275         std::cout << " [Flush] Log buffer flushed\n";
276     }
277 };
278
279 class FileLogger : public Logger {
280 protected:
281     void writeLog(const std::string& message) override {
282         // Call base implementation first
283         Logger::writeLog(message);
284
285         // Add file-specific logging
286         std::cout << " [FileLogger] Writing to file: logs.txt\n";
287     }
288 };
289
290 class NetworkLogger : public Logger {
291 protected:
292     void writeLog(const std::string& message) override {
293         // Call base implementation
294         Logger::writeLog(message);
295
296         // Send over network
297         std::cout << " [NetworkLogger] Sending to log server 192.168.1.100\
298             n";
299 }
```

```
299 };
```

```
300
301 void demonstrate() {
302     std::cout << "\n" << std::string(70, '=') << "\n";
303     std::cout << "==== SECTION 3: Protected Virtual (Guideline #3) ====\n";
304     std::cout << std::string(70, '=') << "\n\n";
305
306     std::cout << "1. File logger with base implementation:\n";
307     FileLogger file_logger;
308     file_logger.log("Application started");
309
310     std::cout << "\n2. Network logger with base implementation:\n";
311     NetworkLogger net_logger;
312     net_logger.log("User logged in");
313
314     std::cout << "\n Protected virtual when:\n";
315     std::cout << " • Derived classes need to call base implementation\n";
316     std::cout << " • Want to extend, not replace, base behavior\n";
317     std::cout << " • Common pattern: call base, then add specific logic\n";
318 }
319
320 } // namespace protected_virtual_example
321
322 // =====
323 // SECTION 4: When NOT to Use NVI - Alternatives
324 //
325 // =====
326
327 namespace when_not_to_use_nvi {
328
329 // ANTI-PATTERN: NVI overkill for simple interfaces
330 class BadExample_OverengineeredNVI {
331 public:
332     void getValue() {
333         doGetValue(); // Unnecessary indirection!
334     }
335
336     private:
337         virtual void doGetValue() = 0;
338     };
339
340 // BETTER: Simple public virtual for simple interfaces
341 class GoodExample_SimpleInterface {
342 public:
343     virtual int getValue() const = 0; // Direct and clear
344     virtual ~GoodExample_SimpleInterface() = default;
345 };
346
347 class SimpleImpl : public GoodExample_SimpleInterface {
348 public:
349     int getValue() const override { return 42; }
```

```
349 };
```

```
350 
```

```
351 // WHEN TO USE PUBLIC VIRTUAL: Pure abstract interfaces (like Java interfaces)
```

```
352 class IDrawable {
pre>353 public:
pre>    virtual void draw() = 0;
pre>    virtual void move(int x, int y) = 0;
pre>    virtual ~IDrawable() = default;
pre>};
```

```
358 
```

```
359 class Circle : public IDrawable {
pre>public:
pre>    void draw() override {
pre>        std::cout << "      Drawing circle\n";
pre>    }
pre>
pre>    void move(int x, int y) override {
pre>        std::cout << "      Moving circle to (" << x << ", " << y << ")\n";
pre>    }
pre>};
```

```
369 
```

```
370 void demonstrate() {
pre>    std::cout << "\n" << std::string(70, '=') << "\n";
pre>    std::cout << "==== SECTION 4: When NOT to Use NVI ===\n";
pre>    std::cout << std::string(70, '=') << "\n\n";
pre>
pre>    std::cout << "1. Simple interface - public virtual is fine:\n";
pre>    SimpleImpl impl;
pre>    std::cout << "      Value: " << impl.getValue() << "\n";
pre>
pre>    std::cout << "\n2. Pure abstract interface - use public virtual:\n";
pre>    Circle circle;
pre>    circle.draw();
pre>    circle.move(10, 20);
pre>
pre>    std::cout << "\n DON'T use NVI when:\n";
pre>    std::cout << " • Simple getter/setter interfaces\n";
pre>    std::cout << " • No invariants to enforce\n";
pre>    std::cout << " • No pre/post conditions needed\n";
pre>    std::cout << " • Pure abstract interfaces (like Java interfaces)\n";
pre>    std::cout << " • Performance critical (tiny overhead of extra call)\n\n";
pre>
pre>    std::cout << " DO use NVI when:\n";
pre>    std::cout << " • Need to enforce pre/post conditions\n";
pre>    std::cout << " • Have invariant algorithm with customizable steps\n";
pre>    std::cout << " • Want to guarantee certain code always runs\n";
pre>    std::cout << " • Need clear separation of interface from implementation\n"
pre>    ";
pre>};
```

```
397 
```

```
398 } // namespace when_not_to_use_nvi
```

```
399 
```

```
400 // =====
```

```
401 // SECTION 5: Real-World Example - HTTP Request Handler
402 //
403 //=====
404
405 namespace http_handler_example {
406
407 class HTTPRequestHandler {
408 public:
409     // PUBLIC NON-VIRTUAL: Template Method for handling HTTP requests
410     void handleRequest(const std::string& method, const std::string& path) {
411         std::cout << "    [HTTP] Received " << method << " " << path << "\n";
412
413         // PRE: Always authenticate
414         std::cout << "    [Pre] Authenticating request...\n";
415         if (!authenticate()) {
416             std::cout << "        401 Unauthorized\n";
417             return;
418         }
419
420         // PRE: Always validate input
421         std::cout << "    [Pre] Validating input...\n";
422         if (!validateInput(method, path)) {
423             std::cout << "        400 Bad Request\n";
424             return;
425         }
426
427         // PRE: Check rate limiting
428         std::cout << "    [Pre] Checking rate limits...\n";
429         if (!checkRateLimit()) {
430             std::cout << "        429 Too Many Requests\n";
431             return;
432         }
433
434         // Call customization point
435         try {
436             std::cout << "    [Processing] Handling request...\n";
437             processRequest(method, path);
438
439             // POST: Always log successful requests
440             std::cout << "    [Post] Logging successful request\n";
441             logAccess(method, path, 200);
442             std::cout << "        200 OK\n";
443
444         } catch (const std::exception& e) {
445             // POST: Always log errors
446             std::cout << "    [Post] Logging error\n";
447             logAccess(method, path, 500);
448             std::cout << "        500 Internal Server Error: " << e.what() << "\n";
449         }
450     }
451 }
```

```
451     virtual ~HTTPRequestHandler() = default;
452
453 private:
454     // PRIVATE VIRTUAL: Customization points
455     virtual bool authenticate() {
456         return true; // Default: no auth
457     }
458
459     virtual bool validateInput([[maybe_unused]] const std::string& method,
460                               [[maybe_unused]] const std::string& path) {
461         return true; // Default: always valid
462     }
463
464     virtual bool checkRateLimit() {
465         return true; // Default: no limits
466     }
467
468     virtual void processRequest(const std::string& method,
469                                const std::string& path) = 0;
469
470     virtual void logAccess(const std::string& method,
471                           const std::string& path,
472                           int status_code) {
473         std::cout << "      [Log] " << method << " " << path
474             << " - " << status_code << "\n";
475     }
476 };
477
478 class UserAPIHandler : public HTTPRequestHandler {
479 private:
480     bool authenticate() override {
481         std::cout << "      [Auth] Checking JWT token...\n";
482         return true; // Simplified
483     }
484
485     bool validateInput(const std::string& method,
486                        const std::string& path) override {
487         if (path.find("/api/users") != 0) {
488             std::cout << "      [Validation] Invalid path\n";
489             return false;
490         }
491         return true;
492     }
493
494     void processRequest(const std::string& method,
495                         const std::string& path) override {
496         if (method == "GET") {
497             std::cout << "      [Handler] Fetching user data from database\n";
498             std::cout << "      [Handler] Returning user list\n";
499         } else if (method == "POST") {
500             std::cout << "      [Handler] Creating new user\n";
501             std::cout << "      [Handler] User created successfully\n";
502         }
503     }
504 }
```

```
505 };
```

```
506 
```

```
507 class PublicAPIHandler : public HTTPRequestHandler {
```

```
508 private:
```

```
509     int request_count_ = 0;
```

```
510 
```

```
511     bool checkRateLimit() override {
512         if (++request_count_ > 3) {
513             std::cout << "      [RateLimit] Exceeded rate limit!\n";
514             return false;
515         }
516         return true;
517     }
```

```
518 
```

```
519     void processRequest([[maybe_unused]] const std::string& method,
520                         const std::string& path) override {
521         std::cout << "      [Handler] Processing public API request: " << path
522                     << "\n";
523     }
524 }
```

```
525 
```

```
526 void demonstrate() {
527     std::cout << "\n" << std::string(70, '=') << "\n";
528     std::cout << "==== SECTION 5: Real-World - HTTP Request Handler ===\n";
529     std::cout << std::string(70, '=') << "\n\n";
530 
531     std::cout << "1. User API with authentication:\n";
532     UserAPIHandler user_api;
533     user_api.handleRequest("GET", "/api/users/123");
534 
535     std::cout << "\n2. Public API with rate limiting:\n";
536     PublicAPIHandler public_api;
537     for (int i = 1; i <= 5; ++i) {
538         std::cout << "\n Request " << i << ":\n";
539         public_api.handleRequest("GET", "/api/public/data");
540         if (i >= 3) {
541             break; // Stop after rate limit
542         }
543     }
544 
545     std::cout << "\n NVI guarantees:\n";
546     std::cout << " • Authentication always checked before processing\n";
547     std::cout << " • Input validation cannot be bypassed\n";
548     std::cout << " • Rate limiting enforced consistently\n";
549     std::cout << " • Logging always happens (success or error)\n";
550     std::cout << " • Derived classes customize logic, not security/logging!\n";
551     std::cout << "\n";
552 }
```

```
553 } // namespace http_handler_example
```

```
554 // =====
```

```
555 // SECTION 6: Guideline #4 - Destructor Rules
556 //
557 =====
558
559 namespace destructor_rules {
560
561 // CORRECT: Public virtual destructor for polymorphic base class
562 class PolymorphicBase {
563 public:
564     virtual ~PolymorphicBase() {
565         std::cout << "[PolymorphicBase] Destructor\n";
566     }
567
568     virtual void doSomething() = 0;
569 };
570
571 class DerivedFromPolymorphic : public PolymorphicBase {
572 public:
573     ~DerivedFromPolymorphic() override {
574         std::cout << "[DerivedFromPolymorphic] Destructor\n";
575     }
576
577     void doSomething() override {
578         std::cout << "[DerivedFromPolymorphic] Doing something\n";
579     }
580 };
581
582 // CORRECT: Protected non-virtual destructor for non-polymorphic base
583 class NonPolymorphicBase {
584 protected:
585     ~NonPolymorphicBase() {
586         std::cout << "[NonPolymorphicBase] Destructor\n";
587     }
588
589 public:
590     void doWork() {
591         std::cout << "[NonPolymorphicBase] Working\n";
592     }
593 };
594
595 class DerivedFromNonPolymorphic : public NonPolymorphicBase {
596 public:
597     ~DerivedFromNonPolymorphic() {
598         std::cout << "[DerivedFromNonPolymorphic] Destructor\n";
599     }
600
601 void demonstrate() {
602     std::cout << "\n" << std::string(70, '=') << "\n";
603     std::cout << "==== SECTION 6: Guideline #4 - Destructor Rules ===\n";
604     std::cout << std::string(70, '=') << "\n\n";
605
606     std::cout << "1. Polymorphic base (public virtual destructor):\n";
```

```

607 {
608     PolymorphicBase* ptr = new DerivedFromPolymorphic();
609     ptr->doSomething();
610     delete ptr; // Calls derived destructor first, then base
611 }
612
613 std::cout << "\n2. Non-polymorphic base (protected non-virtual destructor)
614 :\\n";
615 {
616     DerivedFromNonPolymorphic obj;
617     obj.doWork();
618     // Cannot do: NonPolymorphicBase* ptr = new DerivedFromNonPolymorphic
619     // ();
620     // delete ptr; // Would be undefined behavior!
621     // Protected destructor prevents polymorphic deletion
622 }
623
624 std::cout << "\\n Guideline #4 (Herb Sutter):\n";
625 std::cout << " • Polymorphic base class: public + virtual destructor\\n";
626 std::cout << " • Non-polymorphic base class: protected + non-virtual
627     destructor\\n";
628 std::cout << " • Protected destructor prevents polymorphic deletion\\n";
629 std::cout << " • Virtual destructor allows safe polymorphic deletion\\n";
630 }
631
632 } // namespace destructor_rules
633
634 // SECTION 7: Summary - Complete Guidelines
635
636 =====
637
638 void show_summary() {
639     std::cout << "\\n" << std::string(70, '=') << "\\n";
640     std::cout << "==== Herb Sutter's Virtuality Guidelines - Complete Summary
641     ===\\n";
642     std::cout << std::string(70, '=') << "\\n\\n";
643
644     std::cout << "GUIDELINE #1: Prefer non-virtual interfaces (Template Method
645         )\\n";
646     std::cout << " • Public non-virtual methods define the interface\\n";
647     std::cout << " • These are the \"Template Methods\" that orchestrate the
648         algorithm\\n";
649     std::cout << " • Benefits: Enforce invariants, pre/post conditions,
650         logging, etc.\\n\\n";
651
652     std::cout << "GUIDELINE #2: Prefer private virtual functions\\n";
653     std::cout << " • Private virtual methods are customization points\\n";
654     std::cout << " • Derived classes override to provide specific behavior\\n"
655         ;
656     std::cout << " • Cannot be called directly by client code or derived

```

```
    classes\n";
649 std::cout << " • Clearest separation of interface from implementation\n\n"
      ";
650
651 std::cout << "GUIDELINE #3: Make virtual protected if derived needs base
      impl\n";
652 std::cout << " • Use protected when derived classes need to call base
      version\n";
653 std::cout << " • Common pattern: call base, then add derived-specific
      logic\n";
654 std::cout << " • Still not part of public interface\n\n";
655
656 std::cout << "GUIDELINE #4: Destructor rules\n";
657 std::cout << " • Polymorphic base: public AND virtual destructor\n";
658 std::cout << " • Non-polymorphic base: protected AND non-virtual
      destructor\n";
659 std::cout << " • Public virtual: allows safe polymorphic deletion\n";
660 std::cout << " • Protected non-virtual: prevents polymorphic deletion\n\n"
      ";
661
662 std::cout << std::string(70, '-') << "\n\n";
663
664 std::cout << "WHEN TO USE NVI:\n";
665 std::cout << "     Need to enforce pre/post conditions\n";
666 std::cout << "     Have invariant algorithm with customizable steps\n";
667 std::cout << "     Want to guarantee certain code always runs\n";
668 std::cout << "     Need separation of interface from implementation\n";
669 std::cout << "     Building frameworks or libraries with hooks\n\n";
670
671 std::cout << "WHEN NOT TO USE NVI:\n";
672 std::cout << "     Simple interfaces with no invariants\n";
673 std::cout << "     Pure abstract interfaces (use public virtual)\n";
674 std::cout << "     No pre/post conditions needed\n";
675 std::cout << "     Performance-critical inner loops (tiny overhead)\n";
676 std::cout << "     Simple getter/setter methods\n\n";
677
678 std::cout << "COMPARISON:\n";
679 std::cout << "     Traditional (public virtual):\n";
680 std::cout << "     • Simpler for basic polymorphism\n";
681 std::cout << "     • No invariant enforcement\n";
682 std::cout << "     • Derived classes have full control\n\n";
683
684 std::cout << "     NVI Idiom (public non-virtual, private virtual):\n";
685 std::cout << "     • Enforces invariants and contracts\n";
686 std::cout << "     • Base controls algorithm flow\n";
687 std::cout << "     • Clear interface/implementation separation\n";
688 std::cout << "     • Better encapsulation\n\n";
689
690 std::cout << "REFERENCE:\n";
691 std::cout << "     Herb Sutter's \"Virtuality\" article:\n";
692 std::cout << "     http://www.gotw.ca/publications/mill18.htm\n";
693 }
694
695 //
```

```
=====
696 // MAIN FUNCTION
697 //
=====

698
699 int main() {
700     std::cout << "\n";
701     std::cout << "                                \n";
702     std::cout << "  Non-Virtual Interface (NVI) Idiom & Template Method
703         Pattern  \n";
704     std::cout << "                      Herb Sutter's Virtuality Guidelines
705             \n";
706     std::cout << "                                \n";
707
708     // Section 1: Basic NVI
709     basic_nvi::demonstrate();
710
711
712     // Section 2: Pre/post conditions
713     preconditions_example::demonstrate();
714
715     // Section 3: Protected virtual
716     protected_virtual_example::demonstrate();
717
718     // Section 4: When NOT to use NVI
719     when_not_to_use_nvi::demonstrate();
720
721     // Section 5: Real-world example
722     http_handler_example::demonstrate();
723
724     // Section 6: Destructor rules
725     destructor_rules::demonstrate();
726
727     // Section 7: Complete summary
728     show_summary();
729
730
731     std::cout << "\n" << std::string(70, '=') << "\n";
732     std::cout << "All demonstrations completed!\n";
733     std::cout << std::string(70, '=') << "\n\n";
734
735     return 0;
736 }
```

46 Source Code: NlohmannJsonExample.cpp

File: src/NlohmannJsonExample.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // NLOHMANN JSON LIBRARY EXAMPLE
3 // =====
4 // This example demonstrates the nlohmann/json library - a modern C++
5 // JSON library that provides an intuitive API similar to Python/JavaScript.
6 //
7 // TOPICS COVERED:
8 // 1. Basic JSON parsing and serialization
9 // 2. Working with JSON objects and arrays
10 // 3. Type conversions and safety
11 // 4. Custom struct serialization
12 // 5. JSON Merge Patch (RFC 7386)
13 // 6. JSON Pointer (RFC 6901)
14 // 7. CBOR/MessagePack/BSON/UBJSON support
15 // 8. Performance and embedded systems considerations
16 //
17 // WHAT IS NLOHMANN JSON?
18 // - Header-only C++ JSON library
19 // - Intuitive API similar to Python dictionaries
20 // - No external dependencies
21 // - Supports C++11 and later
22 // - MIT licensed, widely adopted
23 //
24 // WHY USE NLOHMANN JSON?
25 // Easy to use: json["key"] = value
26 // Header-only: Just #include <nlohmann/json.hpp>
27 // STL-like: Integrates seamlessly with C++ containers
28 // Type-safe: Strong typing with automatic conversions
29 // Standards-compliant: RFC 7159, RFC 6901, RFC 7386
30 // Modern C++: Uses C++11/14/17/20 features
31 //
32 // INSTALLATION:
33 // - Ubuntu: sudo apt-get install nlohmann-json3-dev
34 // - vcpkg: vcpkg install nlohmann-json
35 // - CMake: find_package(nlohmann_json REQUIRED)
36 // - Single header: Download json.hpp from GitHub
37 //
38 // =====
39
40 #include <iostream>
41 #include <fstream>
42 #include <iomanip>
43 #include <vector>
44 #include <map>
45 #include <set>
46 #include <nlohmann/json.hpp>
47
48 // For convenience
49 using json = nlohmann::json;
```

```
50 // =====
51 // EXAMPLE 1: BASIC JSON CREATION AND PARSING
52 // =====
53
54
55 void example_basic_json() {
56     std::cout << "==== Example 1: Basic JSON Creation and Parsing ===\n";
57
58     // Create JSON from initializer list (most readable)
59     json j = {
60         {"name", "Alice"},
61         {"age", 30},
62         {"city", "San Francisco"},
63         {"active", true}
64     };
65
66     std::cout << "Created JSON:\n" << j.dump(2) << "\n\n";
67
68     // Access values (Python-like syntax)
69     std::cout << "Name: " << j["name"] << "\n";
70     std::cout << "Age: " << j["age"] << "\n";
71
72     // Type-safe access with .get<T>()
73     std::string name = j["name"].get<std::string>();
74     int age = j["age"].get<int>();
75     std::cout << "Type-safe: " << name << " is " << age << " years old\n";
76
77     // Parse from string
78     std::string json_str = R"({\"device": "sensor_001", \"temperature": 23.5})";
79     json parsed = json::parse(json_str);
80     std::cout << "\nParsed JSON:\n" << parsed.dump(2) << "\n";
81
82     // Check if key exists
83     if (parsed.contains("temperature")) {
84         std::cout << "Temperature: " << parsed["temperature"] << "°C\n";
85     }
86
87     std::cout << "\n Easy syntax like Python/JavaScript\n";
88     std::cout << " Automatic type conversions\n";
89     std::cout << " contains() for safe key checking\n\n";
90 }
91
92 // =====
93 // EXAMPLE 2: WORKING WITH ARRAYS
94 // =====
95
96 void example_arrays() {
97     std::cout << "==== Example 2: JSON Arrays ===\n";
98
99     // Create array
100    json arr = json::array();
101    arr.push_back(10);
102    arr.push_back(20);
103    arr.push_back(30);
```

```
104     std::cout << "Array: " << arr.dump() << "\n";
105
106
107 // Create from vector
108 std::vector<int> vec = {1, 2, 3, 4, 5};
109 json j_vec = vec;
110 std::cout << "From vector: " << j_vec.dump() << "\n";
111
112 // Convert back to vector
113 std::vector<int> vec2 = j_vec.get<std::vector<int>>();
114 std::cout << "Back to vector: size = " << vec2.size() << "\n";
115
116 // Array of objects
117 json sensors = json::array();
118 for (int i = 0; i < 5; ++i) {
119     sensors.push_back({
120         {"id", "sensor_" + std::to_string(i)},
121         {"value", 20.0 + i * 0.5},
122         {"online", i % 2 == 0}
123     });
124 }
125
126 std::cout << "\nSensor array:\n" << sensors.dump(2) << "\n";
127
128 // Iterate over array
129 std::cout << "\nOnline sensors:\n";
130 for (const auto& sensor : sensors) {
131     if (sensor["online"].get<bool>()) {
132         std::cout << " " << sensor["id"] << ":" << sensor["value"] << "\n";
133     }
134 }
135
136 std::cout << "\n STL container integration\n";
137 std::cout << " Range-based for loops\n";
138 std::cout << " Array manipulation like JavaScript\n\n";
139 }
140
141 // =====
142 // EXAMPLE 3: CUSTOM STRUCT SERIALIZATION
143 // =====
144
145 struct SensorReading {
146     std::string device_id;
147     double temperature;
148     double humidity;
149     bool online;
150 };
151
152 // Define JSON serialization (method 1: macro)
153 NLOHMANN_DEFINE_TYPE_NON_INTRUSIVE(SensorReading, device_id, temperature,
154                                     humidity, online)
155
156 // Alternative custom struct with intrusive serialization
```

```
156 struct GpsCoordinate {
157     double latitude;
158     double longitude;
159     double altitude;
160
161     // Method 2: Member functions (more control)
162     NLOHMANN_DEFINE_TYPE_INTRUSIVE(GpsCoordinate, latitude, longitude,
163                                     altitude)
164 };
165
166 void example_custom_types() {
167     std::cout << "==== Example 3: Custom Struct Serialization ===\n";
168
169     // Create struct
170     SensorReading reading{
171         "sensor_001",
172         23.5,
173         65.3,
174         true
175     };
176
177     // Automatic conversion to JSON
178     json j = reading;
179     std::cout << "Struct to JSON:\n" << j.dump(2) << "\n";
180
181     // Automatic conversion from JSON
182     json j2 = R"({
183         "device_id": "sensor_002",
184         "temperature": 25.0,
185         "humidity": 70.5,
186         "online": false
187     })"_json; // User-defined literal
188
189     SensorReading reading2 = j2.get<SensorReading>();
190     std::cout << "\nJSON to struct:\n";
191     std::cout << "    Device: " << reading2.device_id << "\n";
192     std::cout << "    Temperature: " << reading2.temperature << "°C\n";
193     std::cout << "    Online: " << (reading2.online ? "yes" : "no") << "\n";
194
195     // Array of structs
196     std::vector<SensorReading> readings = {
197         {"sensor_001", 20.0, 60.0, true},
198         {"sensor_002", 21.5, 62.0, true},
199         {"sensor_003", 19.0, 58.0, false}
200     };
201
202     json j_array = readings;
203     std::cout << "\nVector of structs to JSON:\n" << j_array.dump(2) << "\n";
204
205     std::cout << "\n Automatic struct JSON conversion\n";
206     std::cout << " NLOHMANN_DEFINE_TYPE_NON_INTRUSIVE macro\n";
207     std::cout << " Works with STL containers\n\n";
208 }
```

```
209 // =====
210 // EXAMPLE 4: FILE I/O
211 // =====
212
213 void example_file_io() {
214     std::cout << "==== Example 4: File I/O ===\n";
215
216     // Create configuration JSON
217     json config = {
218         {"version", "1.0.0"},  

219         {"server", {  

220             {"host", "localhost"},  

221             {"port", 8080},  

222             {"ssl", true}  

223         }},  

224         {"sensors", json::array({  

225             {"id", "temp_01"}, {"enabled", true}},  

226             {"id", "humid_01"}, {"enabled", true}}  

227         })}  

228     };
229
230     // Write to file
231     std::ofstream file("config.json");
232     file << std::setw(2) << config << std::endl;
233     file.close();
234     std::cout << " Written to config.json\n";
235
236     // Read from file
237     std::ifstream input("config.json");
238     json loaded_config;
239     input >> loaded_config;
240     input.close();
241
242     std::cout << " Loaded from config.json:\n";
243     std::cout << " Version: " << loaded_config["version"] << "\n";
244     std::cout << " Server port: " << loaded_config["server"]["port"] << "\n";
245     std::cout << " Sensors: " << loaded_config["sensors"].size() << "\n";
246
247     std::cout << "\n Easy file serialization\n";
248     std::cout << " Pretty printing with setw()\n";
249     std::cout << " Stream operators << and >>\n\n";
250 }
251
252 // =====
253 // EXAMPLE 5: JSON POINTER (RFC 6901)
254 // =====
255
256 void example_json_pointer() {
257     std::cout << "==== Example 5: JSON Pointer (RFC 6901) ===\n";
258
259     json data = {
260         {"user", {  

261             {"name", "Alice"},  

262             {"address", {
```

```
263         {"city", "San Francisco"},  
264         {"zip", "94102"}  
265     }},  
266     {"scores", {85, 92, 78}}  
267 }}  
268 };  
269  
270 // Access nested values using JSON Pointer  
271 std::cout << "Using JSON Pointer:\n";  
272 std::cout << "  /user/name: " << data["/user/name"_json_pointer] << "\n";  
273 std::cout << "  /user/address/city: " << data["/user/address/city"  
    _json_pointer] << "\n";  
274 std::cout << "  /user/scores/0: " << data["/user/scores/0"_json_pointer]  
    << "\n";  
275  
276 // Check if pointer exists  
277 if (data.contains(json::json_pointer("/user/address/country"))){  
    std::cout << "  Country exists\n";  
} else {  
    std::cout << "  Country does not exist\n";  
}  
278  
279  
280 // Modify using pointer  
281 data["/user/address/country"_json_pointer] = "USA";  
282 std::cout << "\n Added country: " << data["/user/address/country"  
    _json_pointer] << "\n";  
283  
284 std::cout << "\n Navigate nested structures easily\n";  
285 std::cout << "  RFC 6901 compliant\n";  
286 std::cout << "  Safe access with contains()\n\n";  
287 }  
288  
289 // =====  
290 // EXAMPLE 6: JSON MERGE PATCH (RFC 7386)  
291 // =====  
292  
293 void example_merge_patch() {  
294     std::cout << "==== Example 6: JSON Merge Patch (RFC 7386) ===\n";  
295  
296     json original = {  
297         {"name", "Alice"},  
298         {"age", 30},  
299         {"city", "San Francisco"},  
300         {"active", true}  
301     };  
302  
303     std::cout << "Original:\n" << original.dump(2) << "\n";  
304  
305     // Merge patch: update existing fields, add new fields  
306     json patch = {  
307         {"age", 31},           // Update  
308         {"city", nullptr},    // Delete  
309         {"country", "USA"}   // Add  
310     };  
311  
312 }
```

```
314     original.merge_patch(patch);
315
316     std::cout << "\nAfter merge patch:\n" << original.dump(2) << "\n";
317
318     std::cout << "\n Update multiple fields at once\n";
319     std::cout << " null value deletes field\n";
320     std::cout << " RFC 7386 compliant\n\n";
321 }
322
323
324 // =====
325 // EXAMPLE 7: BINARY FORMATS (CBOR, MessagePack, BSON)
326 // =====
327
328 void example_binary_formats() {
329     std::cout << "==== Example 7: Binary Formats ===\n";
330
331     json data = {
332         {"device", "sensor_001"},
333         {"temperature", 23.5},
334         {"humidity", 65.3},
335         {"readings", {20, 21, 22, 23, 24}}
336     };
337
338     // JSON string
339     std::string json_str = data.dump();
340     std::cout << "JSON size: " << json_str.size() << " bytes\n";
341
342     // CBOR (Concise Binary Object Representation)
343     std::vector<uint8_t> cbor = json::to_cbor(data);
344     std::cout << "CBOR size: " << cbor.size() << " bytes";
345     std::cout << " (" << std::fixed << std::setprecision(1)
346             << (1.0 - (double)cbor.size() / json_str.size()) * 100 << "%"
347             smaller)\n";
348
349     // MessagePack
350     std::vector<uint8_t> msgpack = json::to_msgpack(data);
351     std::cout << "MessagePack size: " << msgpack.size() << " bytes";
352     std::cout << " (" << (1.0 - (double)msgpack.size() / json_str.size()) *
353             100 << "% smaller)\n";
354
355     // BSON
356     std::vector<uint8_t> bson = json::to_bson(data);
357     std::cout << "BSON size: " << bson.size() << " bytes";
358     std::cout << " (" << (1.0 - (double)bson.size() / json_str.size()) * 100
359             << "% smaller)\n";
360
361     // UBJSON (Universal Binary JSON)
362     std::vector<uint8_t> ubjson = json::to_ubjson(data);
363     std::cout << "UBJSON size: " << ubjson.size() << " bytes\n";
364
365     // Deserialize CBOR
366     json restored = json::from_cbor(cbor);
367     std::cout << "\n Restored from CBOR:\n" << restored.dump(2) << "\n";
```

```
365     std::cout << "\n Multiple binary format support\n";
366     std::cout << " 30-50% smaller than JSON text\n";
367     std::cout << " Faster parsing than text JSON\n\n";
368 }
369
370 // =====
371 // EXAMPLE 8: ERROR HANDLING
372 // =====
373
374 void example_error_handling() {
375     std::cout << "== Example 8: Error Handling ==\n";
376
377     // Safe parsing with exception handling
378     std::string invalid_json = R"({\"name\": \"Alice\", \"age\": })";
379
380     try {
381         json j = json::parse(invalid_json);
382     } catch (const json::parse_error& e) {
383         std::cout << "Parse error caught:\n";
384         std::cout << "  Message: " << e.what() << "\n";
385         std::cout << "  Exception ID: " << e.id << "\n";
386         std::cout << "  Byte position: " << e.byte << "\n";
387     }
388
389     // Safe access with value()
390     json data = {{"name", "Alice"}, {"age", 30}};
391
392     std::string name = data.value("name", "Unknown");
393     std::string country = data.value("country", "Unknown"); // Default if
394     missing
395
396     std::cout << "\n Safe value() with default:\n";
397     std::cout << "  Name: " << name << "\n";
398     std::cout << "  Country: " << country << " (default)\n";
399
400     // Type checking
401     if (data["age"].is_number_integer()) {
402         int age = data["age"];
403         std::cout << "  Age is integer: " << age << "\n";
404     }
405
406     std::cout << "\n Exception-based error handling\n";
407     std::cout << "  value() method with defaults\n";
408     std::cout << "  Type checking with is_xxx()\n\n";
409 }
410
411 // =====
412 // EXAMPLE 9: ADVANCED STL CONTAINER CONVERSIONS
413 // =====
414
415 void example_stl_conversions() {
416     std::cout << "== Example 9: Advanced STL Container Conversions ==\n";
417 }
```

```
418 // Map conversions
419 std::map<std::string, int> scores = {
420     {"Alice", 95},
421     {"Bob", 87},
422     {"Charlie", 92}
423 };
424
425 json j_map = scores;
426 std::cout << "Map to JSON:\n" << j_map.dump(2) << "\n";
427
428 auto restored_map = j_map.get<std::map<std::string, int>>();
429 std::cout << "\n Restored map: " << restored_map.size() << " entries\n";
430
431 // Nested containers
432 std::vector<std::map<std::string, std::vector<int>>> complex = {
433     {{"data", {1, 2, 3}}, {"scores", {90, 85, 88}}},
434     {{"data", {4, 5, 6}}, {"scores", {92, 87, 91}}}
435 };
436
437 json j_complex = complex;
438 std::cout << "\nNested containers:\n" << j_complex.dump(2) << "\n";
439
440 // Set conversions
441 std::set<std::string> tags = {"cpp", "json", "modern", "c++17"};
442 json j_set = tags;
443 std::cout << "\nSet to JSON array: " << j_set.dump() << "\n";
444
445 // Tuple conversions
446 std::tuple<std::string, int, double> data = {"sensor_001", 42, 23.5};
447 json j_tuple = data;
448 std::cout << "Tuple to JSON array: " << j_tuple.dump() << "\n";
449
450 std::cout << "\n Automatic STL container serialization\n";
451 std::cout << " Works with nested containers\n";
452 std::cout << " Two-way conversion\n\n";
453 }
454
455 // =====
456 // EXAMPLE 10: SAX PARSING FOR LARGE FILES
457 // =====
458
459 void example_sax_parsing() {
460     std::cout << "== Example 10: SAX Parsing for Large Files ==\n";
461
462     // SAX (Simple API for XML) style parsing - event-driven
463     // Useful for large JSON files to avoid loading entire document
464
465     struct MySaxHandler {
466         bool null() {
467             std::cout << " Event: null\n";
468             return true;
469         }
470
471         bool boolean(bool val) {
```

```
472     std::cout << "  Event: boolean = " << std::boolalpha << val << "\n"
473         "";
474     return true;
475 }
476 
477 bool number_integer(json::number_integer_t val) {
478     std::cout << "  Event: integer = " << val << "\n";
479     return true;
480 }
481 
482 bool number_unsigned(json::number_unsigned_t val) {
483     std::cout << "  Event: unsigned = " << val << "\n";
484     return true;
485 }
486 
487 bool number_float(json::number_float_t val, const std::string&) {
488     std::cout << "  Event: float = " << val << "\n";
489     return true;
490 }
491 
492 bool binary(json::binary_t& val) {
493     std::cout << "  Event: binary (" << val.size() << " bytes)\n";
494     return true;
495 }
496 
497 bool string(std::string& val) {
498     std::cout << "  Event: string = \" " << val << "\"\n";
499     return true;
500 }
501 
502 bool start_object(std::size_t) {
503     std::cout << "  Event: start_object\n";
504     return true;
505 }
506 
507 bool end_object() {
508     std::cout << "  Event: end_object\n";
509     return true;
510 }
511 
512 bool start_array(std::size_t) {
513     std::cout << "  Event: start_array\n";
514     return true;
515 }
516 
517 bool end_array() {
518     std::cout << "  Event: end_array\n";
519     return true;
520 }
521 
522 bool key(std::string& val) {
523     std::cout << "  Event: key = \" " << val << "\"\n";
524     return true;
525 }
```

```
525
526     bool parse_error(std::size_t, const std::string&, const json::
527         exception& ex) {
528         std::cout << " Parse error: " << ex.what() << "\n";
529         return false;
530     }
531 };
532 std::cout << "\nParsing JSON with SAX events:\n";
533 std::string json_str = R"({\"name\":\"Alice\", \"age\":30, \"scores\":[95,87,92]})";
534
535 MySaxHandler handler;
536 bool result = json::sax_parse(json_str, &handler);
537
538 std::cout << "\n SAX parsing " << (result ? "succeeded" : "failed") << "\n";
539
540 std::cout << "\n Memory-efficient for large files\n";
541 std::cout << " Event-driven processing\n";
542 std::cout << " Can stop parsing early\n";
543 std::cout << " Useful for streaming data\n\n";
544 }
545
546 // =====
547 // EXAMPLE 11: JSON SCHEMA VALIDATION
548 // =====
549
550 void example_json_schema() {
551     std::cout << "==== Example 11: JSON Schema-like Validation ===\n";
552
553     // Note: nlohmann::json doesn't have built-in schema validation
554     // But we can implement basic validation checks
555
556     json schema = {
557         {"type", "object"},
558         {"required", {"name", "age", "email"}},
559         {"properties", {
560             {"name", {{"type", "string}}},
561             {"age", {{"type", "number"}, {"minimum", 0}, {"maximum", 150}}},
562             {"email", {{"type", "string"}}}
563         }}
564     };
565
566     auto validate = [] (const json& data, const json& schema) -> bool {
567         // Simple validation example
568         if (schema["type"] == "object") {
569             // Check required fields
570             for (const auto& field : schema["required"]) {
571                 if (!data.contains(field.get<std::string>())) {
572                     std::cout << " Missing required field: " << field << "\n";
573                     return false;
574                 }
575             }
576         }
577     }
578 }
```

```
576
577     // Check types
578     for (const auto& [key, prop_schema] : schema["properties"].items())
579     ) {
580         if (data.contains(key)) {
581             std::string expected_type = prop_schema["type"];
582             const auto& value = data[key];
583
584             if (expected_type == "string" && !value.is_string()) {
585                 std::cout << "    Field '" << key << "' should be
586                     string\n";
587                 return false;
588             }
589             if (expected_type == "number" && !value.is_number()) {
590                 std::cout << "    Field '" << key << "' should be
591                     number\n";
592                 return false;
593             }
594
595             // Check number constraints
596             if (value.is_number() && prop_schema.contains("minimum"))
597             {
598                 if (value.get<double>() < prop_schema["minimum"].get<
599                     double>()) {
600                     std::cout << "    Field '" << key << "' below
601                         minimum\n";
602                     return false;
603                 }
604             }
605         }
606     }
607     return true;
608 };
609
610 json valid_data = {
611     {"name", "Alice"},
612     {"age", 30},
613     {"email", "alice@example.com"}
614 };
615
616 json invalid_data = {
617     {"name", "Bob"},
618     {"age", "thirty"} // Wrong type
619 };
620
621 std::cout << "\nValidating correct data:\n";
622 if (validate(valid_data, schema)) {
623     std::cout << "    Validation passed\n";
624 }
625
626 std::cout << "\nValidating incorrect data:\n";
627 validate(invalid_data, schema);
628
```

```
624     std::cout << "\n For full JSON Schema support, use:\n";
625     std::cout << " • nlohmann/json-schema-validator library\n";
626     std::cout << " • valijson library\n\n";
627 }
628
629 // =====
630 // EXAMPLE 12: CUSTOM ALLOCATORS FOR EMBEDDED SYSTEMS
631 // =====
632
633 void example_custom_allocator() {
634     std::cout << "==== Example 12: Custom Allocators for Embedded ===\n";
635
636     // nlohmann::json supports custom allocators via template parameter
637     // Useful for embedded systems with custom memory management
638
639     std::cout << "\nDefault allocator usage:\n";
640     json j = {{"sensor", "temp_01"}, {"value", 23.5}};
641     std::cout << " Created JSON: " << j.dump() << "\n";
642
643     // For embedded systems, you can use:
644     // 1. Compile with -DJSON_NOEXCEPTION (no exceptions)
645     // 2. Use custom allocator with basic_json template
646     // 3. Disable certain features to reduce code size
647
648     std::cout << "\n Embedded system optimizations:\n";
649     std::cout << " 1. Compile flags:\n";
650     std::cout << " • -DJSON_NOEXCEPTION - Disable exceptions\n";
651     std::cout << " • -DJSON_NO_IO - Disable file I/O\n";
652     std::cout << " • -DJSON_DIAGNOSTICS=0 - Smaller binary\n";
653     std::cout << " 2. Use binary formats (CBOR/MessagePack)\n";
654     std::cout << " 3. Use SAX parsing for large data\n";
655     std::cout << " 4. Pre-allocate with reserve()\n";
656     std::cout << " 5. Consider alternatives like ArduinoJson\n\n";
657
658     std::cout << "Memory footprint:\n";
659     std::cout << " • Header-only: ~20KB code size\n";
660     std::cout << " • Runtime: depends on JSON size\n";
661     std::cout << " • Stack usage: minimal (recursion depth)\n\n";
662 }
663
664 // =====
665 // EXAMPLE 13: PERFORMANCE TIPS
666 // =====
667
668 void example_performance() {
669     std::cout << "==== Example 13: Performance Tips ===\n";
670
671     // Tip 1: Use references to avoid copies
672     json large_data = {
673         {"sensors", json::array()}
674     };
675
676     for (int i = 0; i < 100; ++i) {
677         large_data["sensors"].push_back({
```

```
678     {"id", i},
679     {"value", 20.0 + i * 0.1}
680 );
681 }
682
683 // BAD: Creates copies
684 // for (auto sensor : large_data["sensors"]) { ... }
685
686 // GOOD: Use const reference
687 int count = 0;
688 for (const auto& sensor : large_data["sensors"]){
689     if (sensor["value"].get<double>() > 25.0) {
690         ++count;
691     }
692 }
693 std::cout << "Found " << count << " sensors > 25.0 (using const ref)\n";
694
695 // Tip 2: Reserve array capacity
696 json arr = json::array();
697 // arr.get_ref<json::array_t&>().reserve(1000); // Pre-allocate
698
699 // Tip 3: Use binary formats for network/storage
700 std::vector<uint8_t> cbor = json::to_cbor(large_data);
701 std::cout << "Binary format: " << cbor.size() << " bytes\n";
702
703 // Tip 4: Disable exceptions for embedded systems
704 // Compile with -DJSON_NOEXCEPTION
705
706 std::cout << "\nPerformance tips:\n";
707 std::cout << "    Use const auto& in loops\n";
708 std::cout << "    Reserve array capacity\n";
709 std::cout << "    Use binary formats for I/O\n";
710 std::cout << "    Compile with -DJSON_NOEXCEPTION for embedded\n\n";
711 }
712
713 // =====
714 // EXAMPLE 14: COMPARISON WITH ALTERNATIVES
715 // =====
716
717 void comparison_with_alternatives() {
718     std::cout << "==== Comparison with Alternatives ===\n\n";
719
720     std::cout << "RapidJSON:\n";
721     std::cout << "    Faster parsing (2-3x)\n";
722     std::cout << "    Lower memory usage\n";
723     std::cout << "    More complex API\n";
724     std::cout << "    Manual memory management\n\n";
725
726     std::cout << "jsoncpp:\n";
727     std::cout << "    Mature and stable\n";
728     std::cout << "    Older API design\n";
729     std::cout << "    Slower than nlohmann\n";
730     std::cout << "    Requires compilation\n\n";
731 }
```

```
732     std::cout << "simdjson:\n";
733     std::cout << "    Extremely fast (SIMD optimized)\n";
734     std::cout << "    Read-only parsing\n";
735     std::cout << "    No JSON creation\n";
736     std::cout << "    Different API paradigm\n\n";
737
738     std::cout << "Protocol Buffers:\n";
739     std::cout << "    Smaller binary format\n";
740     std::cout << "    Faster parsing\n";
741     std::cout << "    Requires schema\n";
742     std::cout << "    Code generation needed\n\n";
743
744     std::cout << "When to use nlohmann/json:\n";
745     std::cout << "    Need easy-to-use API\n";
746     std::cout << "    Header-only library preferred\n";
747     std::cout << "    Configuration files\n";
748     std::cout << "    REST API communication\n";
749     std::cout << "    Rapid prototyping\n";
750     std::cout << "    Not for extreme performance (use RapidJSON/simdjson)\n\n"
751     ";
752 }
753 // =====
754 // MAIN FUNCTION
755 // =====
756
757 int main() {
758     std::cout << "=====\\n"
759     ;
760     std::cout << "NLOHMANN JSON LIBRARY EXAMPLES\\n";
761     std::cout << "=====\\n\\n"
762     n";
763     example_basic_json();
764     example_arrays();
765     example_custom_types();
766     example_file_io();
767     example_json_pointer();
768     example_merge_patch();
769     example_binary_formats();
770     example_error_handling();
771     example_stl_conversions();
772     example_sax_parsing();
773     example_json_schema();
774     example_custom_allocator();
775     example_performance();
776     comparison_with_alternatives();
777
778     std::cout << "=====\\n"
779     ;
780     std::cout << "INSTALLATION:\\n";
781     std::cout << "=====\\n\\n"
782     n";
```

```
781     std::cout << "Ubuntu/Debian:\n";
782     std::cout << "    sudo apt-get install nlohmann-json3-dev\n\n";
783
784     std::cout << "vcppkg:\n";
785     std::cout << "    vcpkg install nlohmann-json\n\n";
786
787     std::cout << "CMake:\n";
788     std::cout << "    find_package(nlohmann_json REQUIRED)\n";
789     std::cout << "    target_link_libraries(YourTarget nlohmann_json::
790         nlohmann_json)\n\n";
791
792     std::cout << "Single header:\n";
793     std::cout << "    Download: https://github.com/nlohmann/json/releases\n";
794     std::cout << "    Just #include \"json.hpp\"\n\n";
795
796     std::cout << "=====";
797
798     std::cout << "RESOURCES:\n";
799     std::cout << "=====";
800
801     std::cout << "GitHub: https://github.com/nlohmann/json\n";
802     std::cout << "Documentation: https://json.nlohmann.me/\n";
803     std::cout << "API Reference: https://json.nlohmann.me/api/basic\_json/\n\n";
804
805     ;
806
807     return 0;
808 }
```

47 Source Code: NoexceptBestPractices.cpp

File: src/NoexceptBestPractices.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // NOEXCEPT BEST PRACTICES IN MODERN C++
3 // =====
4 // Comprehensive guide to when and when NOT to use noexcept
5 //
6 // Topics Covered:
7 // 1. What is noexcept and why it matters
8 // 2. When to ALWAYS use noexcept
9 // 3. When to NEVER use noexcept
10 // 4. Conditional noexcept
11 // 5. Performance implications
12 // 6. std::vector optimization with noexcept
13 // 7. Exception safety guarantees
14 // 8. Best practices and guidelines
15 //
16 // Build: g++ -std=c++20 -Wall -Wextra -O2 -o NoexceptBestPractices
17 //           NoexceptBestPractices.cpp
18 // =====
19 #include <iostream>
20 #include <vector>
21 #include <string>
22 #include <memory>
23 #include <utility>
24 #include <type_traits>
25 #include <chrono>
26 #include <cmath> // for std::log2
27 #include <algorithm> // for std::copy_n
28 //
29 // =====
30 // SECTION 1: WHAT IS NOEXCEPT?
31 // =====
32
33 namespace what_is_noexcept {
34
35 void demonstrate() {
36     std::cout << "\n" << std::string(70, '=') << "\n";
37     std::cout << "SECTION 1: WHAT IS NOEXCEPT?\n";
38     std::cout << std::string(70, '=') << "\n\n";
39
40     std::cout << " DEFINITION:\n";
41     std::cout << "    noexcept is a specifier that tells the compiler:\n";
42     std::cout << "        'This function will NEVER throw an exception'\n\n";
43
44     std::cout << " WHAT HAPPENS IF YOU LIE?\n";
45     std::cout << "    If a noexcept function throws:\n";
46     std::cout << "        1. std::terminate() is called immediately\n";
47     std::cout << "        2. Stack unwinding does NOT happen\n";
48     std::cout << "        3. Destructors are NOT called\n";
```

```
49     std::cout << "    4. Program terminates (no recovery possible)\n\n";
50
51     std::cout << " WHY USE NOEXCEPT?\n";
52     std::cout << "    1. Performance: Compiler can optimize more aggressively\n"
53             "";
54     std::cout << "    2. std::vector uses move only if noexcept\n";
55     std::cout << "    3. Documents that function is exception-safe\n";
56     std::cout << "    4. Enables certain optimizations at call sites\n";
57 }
58 } // namespace what_is_noexcept
59
60 // =====
61 // SECTION 2: WHEN TO ALWAYS USE NOEXCEPT
62 // =====
63
64 namespace always_use_noexcept {
65
66 // RULE 1: DESTRUCTORS - Always noexcept (implicit in C++)
67 class Resource {
68 private:
69     int* data_;
70
71 public:
72     Resource() : data_(new int(42)) {
73         std::cout << "    [Resource] Constructor\n";
74     }
75
76     // Destructors are implicitly noexcept
77     ~Resource() noexcept { // Explicit is good for documentation
78         delete data_;
79         std::cout << "    [Resource] Destructor (noexcept)\n";
80     }
81 };
82
83 // RULE 2: MOVE CONSTRUCTORS AND MOVE ASSIGNMENT
84 // Critical for std::vector optimization!
85 class MoveableResource {
86 private:
87     int* data_;
88     size_t size_;
89
90 public:
91     explicit MoveableResource(size_t size)
92         : data_(new int[size]), size_(size) {
93         std::cout << "    [MoveableResource] Constructor\n";
94     }
95
96     ~MoveableResource() noexcept {
97         delete[] data_;
98     }
99
100    // Move constructor - ALWAYS mark noexcept
101    MoveableResource(MoveableResource&& other) noexcept
```

```
102     : data_(other.data_), size_(other.size_) {
103     other.data_ = nullptr;
104     other.size_ = 0;
105     std::cout << "    [MoveableResource] Move constructor (noexcept)\n";
106 }
107
108 // Move assignment - ALWAYS mark noexcept
109 MoveableResource& operator=(MoveableResource&& other) noexcept {
110     if (this != &other) {
111         delete[] data_;
112         data_ = other.data_;
113         size_ = other.size_;
114         other.data_ = nullptr;
115         other.size_ = 0;
116     }
117     std::cout << "    [MoveableResource] Move assignment (noexcept)\n";
118     return *this;
119 }
120
121 // Copy operations (not noexcept - can throw on allocation)
122 MoveableResource(const MoveableResource& other)
123     : data_(new int[other.size_]), size_(other.size_) {
124     std::copy_n(other.data_, size_, data_);
125     std::cout << "    [MoveableResource] Copy constructor (can throw)\n";
126 }
127
128 MoveableResource& operator=(const MoveableResource& other) {
129     if (this != &other) {
130         delete[] data_;
131         size_ = other.size_;
132         data_ = new int[size_]; // Can throw!
133         std::copy_n(other.data_, size_, data_);
134     }
135     std::cout << "    [MoveableResource] Copy assignment (can throw)\n";
136     return *this;
137 }
138 };
139
140 // RULE 3: SWAP FUNCTIONS - Always noexcept
141 class Swappable {
142 private:
143     int value_;
144
145 public:
146     explicit Swappable(int val) : value_(val) {}
147
148     // Swap should always be noexcept
149     friend void swap(Swappable& a, Swappable& b) noexcept {
150         using std::swap;
151         swap(a.value_, b.value_);
152         std::cout << "    [Swappable] Swapped (noexcept)\n";
153     }
154 };
```

```
156 // RULE 4: Simple getters and setters (no allocation, no complex logic)
157 class DataHolder {
158 private:
159     int value_;
160
161 public:
162     // Simple getter - noexcept
163     int getValue() const noexcept {
164         return value_;
165     }
166
167     // Simple setter - noexcept
168     void setValue(int val) noexcept {
169         value_ = val;
170     }
171 };
172
173 void demonstrate() {
174     std::cout << "\n" << std::string(70, '=') << "\n";
175     std::cout << "SECTION 2: WHEN TO ALWAYS USE NOEXCEPT\n";
176     std::cout << std::string(70, '=') << "\n\n";
177
178     std::cout << " ALWAYS USE NOEXCEPT FOR:\n\n";
179
180     std::cout << " 1 DESTRUCTORS (implicit noexcept):\n";
181 {
182     Resource r;
183 }
184 std::cout << "\n";
185
186 std::cout << " 2 MOVE OPERATIONS (critical for std::vector):\n";
187 MoveableResource mr1(10);
188 MoveableResource mr2 = std::move(mr1);
189 std::cout << "\n";
190
191 std::cout << " 3 SWAP FUNCTIONS:\n";
192 Swappable s1(10), s2(20);
193 swap(s1, s2);
194 std::cout << "\n";
195
196 std::cout << " 4 SIMPLE GETTERS/SETTERS (no allocation):\n";
197 DataHolder dh;
198 dh.setValue(42);
199 std::cout << "     getValue() = " << dh.getValue() << " (noexcept)\n\n";
200
201 std::cout << " WHY THESE MUST BE NOEXCEPT:\n";
202 std::cout << " • Destructors: Can't handle exceptions during cleanup\n";
203 std::cout << " • Move ops: std::vector falls back to copy if not
204 noexcept\n";
205 std::cout << " • Swap: Used in exception-safe code patterns\n";
206 std::cout << " • Simple ops: No reason to throw, performance benefit\n";
207
208 } // namespace always_use_noexcept
```

```
209 // =====
210 // SECTION 3: WHEN TO NEVER USE NOEXCEPT
211 // =====
212
213
214 namespace never_use_noexcept {
215
216     // NEVER mark noexcept if function can throw!
217
218     // DON'T use noexcept: Functions that allocate memory
219     class Container {
220         private:
221             std::vector<int> data_;
222
223         public:
224             // DON'T mark noexcept - can throw std::bad_alloc
225             void addElement(int value) { // No noexcept!
226                 data_.push_back(value); // Can throw
227                 std::cout << "    [Container] Added element (can throw)\n";
228             }
229
230             // DON'T mark noexcept - can throw on allocation
231             Container(size_t size) : data_(size) { // No noexcept!
232                 std::cout << "    [Container] Constructor (can throw)\n";
233             }
234     };
235
236     // DON'T use noexcept: Functions that perform I/O
237     class FileHandler {
238         public:
239             // DON'T mark noexcept - I/O can fail
240             void writeToFile(const std::string& filename, const std::string& data) {
241                 std::cout << "    [FileHandler] Writing to file (can throw)\n";
242                 // File operations can throw
243                 // if (!success) throw std::runtime_error("Write failed");
244             }
245
246             // DON'T mark noexcept - I/O can fail
247             std::string readFile(const std::string& filename) {
248                 std::cout << "    [FileHandler] Reading from file (can throw)\n";
249                 // File operations can throw
250                 return "data";
251             }
252     };
253
254     // DON'T use noexcept: Functions that validate input
255     class Validator {
256         public:
257             // DON'T mark noexcept - validation can throw
258             void validateAge(int age) {
259                 if (age < 0 || age > 150) {
260                     throw std::invalid_argument("Invalid age");
261                 }
262                 std::cout << "    [Validator] Age validated (can throw)\n";
263             }
264     };
265 }
```

```
263     }
264
265     // DON'T mark noexcept - validation can throw
266     void checkNonEmpty(const std::string& str) {
267         if (str.empty()) {
268             throw std::invalid_argument("String cannot be empty");
269         }
270         std::cout << "    [Validator] String validated (can throw)\n";
271     }
272 };
273
274 // DON'T use noexcept: Functions calling other non-noexcept functions
275 class Processor {
276 private:
277     Container container_;
278
279 public:
280     Processor() : container_(10) {}
281
282     // DON'T mark noexcept - calls non-noexcept function
283     void process(int value) { // No noexcept!
284         container_.addElement(value); // Can throw
285         std::cout << "    [Processor] Processed (can throw)\n";
286     }
287 };
288
289 // DON'T use noexcept: Functions that throw std::runtime_error
290 class RuntimeErrorExample {
291 public:
292     // DANGEROUS: Marked noexcept but throws std::runtime_error
293     // void dangerousFunction() noexcept {
294     //     throw std::runtime_error("This causes std::terminate()!");
295     //     // If this runs, program terminates immediately!
296     // }
297
298     // CORRECT: NOT marked noexcept, can throw
299     void safeFunction(bool shouldFail) {
300         if (shouldFail) {
301             throw std::runtime_error("Safe to throw - not noexcept");
302         }
303         std::cout << "    [RuntimeErrorExample] Executed successfully\n";
304     }
305
306     // WRONG: Claims noexcept but allocates (can throw bad_alloc)
307     // std::vector<int> wrongNoexcept(size_t size) noexcept {
308     //     return std::vector<int>(size); // Can throw! Causes terminate!
309     // }
310
311     // CORRECT: Not marked noexcept
312     std::vector<int> correctVersion(size_t size) {
313         std::cout << "    [RuntimeErrorExample] Creating vector (can throw
314             bad_alloc)\n";
315         return std::vector<int>(size);
316     }
317 }
```

```
316 };
```

```
317
318 void demonstrate() {
319     std::cout << "\n" << std::string(70, '=') << "\n";
320     std::cout << "SECTION 3: WHEN TO NEVER USE NOEXCEPT\n";
321     std::cout << " 5 FUNCTIONS THAT THROW std::runtime_error:\n";
322     RuntimeErrorExample rte;
323     try {
324         rte.safeFunction(false);
325         std::cout << "    Success case handled\n";
326     } catch (const std::runtime_error& e) {
327         std::cout << "    Caught: " << e.what() << "\n";
328     }
329
330     auto vec = rte.correctVersion(10);
331     std::cout << "    Vector created with size: " << vec.size() << "\n\n";
332
333     std::cout << "    CRITICAL: If safeFunction() was marked noexcept:\n";
334     std::cout << "    • Throwing std::runtime_error would call std::terminate()\n";
335     std::cout << "    • No catch block would execute\n";
336     std::cout << "    • No stack unwinding, no destructors called\n";
337     std::cout << "    • Program crashes immediately\n\n";
338
339     std::cout << std::string(70, '=') << "\n\n";
340
341     std::cout << "    NEVER USE NOEXCEPT FOR:\n\n";
342
343     std::cout << " 1 FUNCTIONS THAT ALLOCATE MEMORY:\n";
344     Container c(10);
345     c.addElement(42);
346     std::cout << "    Allocation can throw std::bad_alloc\n\n";
347
348     std::cout << " 2 FUNCTIONS THAT PERFORM I/O:\n";
349     FileHandler fh;
350     fh.writeToFile("test.txt", "data");
351     std::cout << "    I/O operations can fail and throw\n\n";
352
353     std::cout << " 3 FUNCTIONS THAT VALIDATE INPUT:\n";
354     Validator v;
355     try {
356         v.checkNonEmpty("hello");
357         std::cout << "    Validation passed\n";
358     } catch (...) {
359         std::cout << "    Validation can throw\n";
360     }
361     std::cout << "\n";
362
363     std::cout << " 4 FUNCTIONS CALLING NON-NOEXCEPT FUNCTIONS:\n";
364     Processor p;
365     p.process(100);
366     std::cout << "    Chain of calls inherits throwing behavior\n\n";
367
368     std::cout << "    WHY NEVER MARK THESE NOEXCEPT:\n";
```

```
369     std::cout << " • Lying about noexcept causes std::terminate()\n";
370     std::cout << " • No recovery possible if exception thrown\n";
371     std::cout << " • Better to propagate exception to caller\n";
372     std::cout << " • Allows proper error handling up the stack\n";
373 }
374 }
375 } // namespace never_use_noexcept
376
377 // =====
378 // SECTION 4: CONDITIONAL NOEXCEPT
379 // =====
380
381 namespace conditional_noexcept {
382
383 // Use conditional noexcept for template operations
384 template<typename T>
385 class Wrapper {
386 private:
387     T value_;
388
389 public:
390     explicit Wrapper(const T& val) : value_(val) {}
391
392     // Conditional noexcept based on T's move constructor
393     Wrapper(Wrapper&& other) noexcept(std::is_nothrow_move_constructible_v<T>)
394         : value_(std::move(other.value_)) {
395             std::cout << "[Wrapper] Move constructor (conditionally noexcept)\n"
396             "";
397         }
398
399     // Conditional noexcept based on T's swap
400     void swap(Wrapper& other) noexcept(std::is_nothrow_swappable_v<T>) {
401         using std::swap;
402         swap(value_, other.value_);
403         std::cout << "[Wrapper] Swap (conditionally noexcept)\n";
404     }
405 };
406
407 // Example: std::pair uses conditional noexcept
408 template<typename T1, typename T2>
409 class MyPair {
410 private:
411     T1 first_;
412     T2 second_;
413
414 public:
415     MyPair(const T1& f, const T2& s) : first_(f), second_(s) {}
416
417     // noexcept only if both T1 and T2 have noexcept move constructors
418     MyPair(MyPair&& other) noexcept(
419         std::is_nothrow_move_constructible_v<T1> &&
420         std::is_nothrow_move_constructible_v<T2>)
421         : first_(std::move(other.first_))
422         , second_(std::move(other.second_)) {
```

```
422         std::cout << "    [MyPair] Move (conditionally noexcept)\n";
423     }
424 };
425
426 void demonstrate() {
427     std::cout << "\n" << std::string(70, '=') << "\n";
428     std::cout << "SECTION 4: CONDITIONAL NOEXCEPT\n";
429     std::cout << std::string(70, '=') << "\n\n";
430
431     std::cout << "  CONDITIONAL NOEXCEPT:\n";
432     std::cout << "    Use noexcept(condition) for templates\n";
433     std::cout << "    noexcept status depends on template parameter\n\n";
434
435     std::cout << "  EXAMPLE 1: Wrapper with int (noexcept move):\n";
436     Wrapper<int> w1(42);
437     Wrapper<int> w2(std::move(w1));
438     std::cout << "    int move is noexcept: "
439                 << std::is_nothrow_move_constructible_v<int> << "\n\n";
440
441     std::cout << "  EXAMPLE 2: Wrapper with std::string (noexcept move):\n";
442     Wrapper<std::string> w3("hello");
443     Wrapper<std::string> w4(std::move(w3));
444     std::cout << "    string move is noexcept: "
445                 << std::is_nothrow_move_constructible_v<std::string> << "\n\n";
446
447     std::cout << "  EXAMPLE 3: MyPair with noexcept types:\n";
448     MyPair<int, int> p1(10, 20);
449     MyPair<int, int> p2(std::move(p1));
450     std::cout << "\n";
451
452     std::cout << "  WHEN TO USE CONDITIONAL NOEXCEPT:\n";
453     std::cout << "  •    Template classes wrapping user types\n";
454     std::cout << "  •    Want to preserve noexcept guarantee when possible\n";
455     std::cout << "  •    Standard library containers use this extensively\n";
456 }
457
458 } // namespace conditional_noexcept
459
460 // =====
461 // SECTION 5: STD::VECTOR OPTIMIZATION WITH NOEXCEPT
462 // =====
463
464 namespace vector_optimization {
465
466 // Class WITHOUT noexcept move constructor
467 class WithoutNoexcept {
468 private:
469     int* data_;
470
471 public:
472     explicit WithoutNoexcept(int val = 0) : data_(new int(val)) {
473         // std::cout << "    [WithoutNoexcept] Constructor\n";
474     }
475 }
```

```
476     ~WithoutNoexcept() {
477         delete data_;
478     }
479
480     // Move constructor WITHOUT noexcept
481     WithoutNoexcept(WithoutNoexcept&& other)
482         : data_(other.data_) {
483         other.data_ = nullptr;
484         std::cout << "    [WithoutNoexcept] MOVE constructor (not noexcept)\n";
485     }
486
487     // Copy constructor
488     WithoutNoexcept(const WithoutNoexcept& other)
489         : data_(new int(*other.data_)) {
490         std::cout << "    [WithoutNoexcept] COPY constructor\n";
491     }
492
493     WithoutNoexcept& operator=(WithoutNoexcept&&) = default;
494     WithoutNoexcept& operator=(const WithoutNoexcept&) = default;
495 };
496
497 // Class WITH noexcept move constructor
498 class WithNoexcept {
499 private:
500     int* data_;
501
502 public:
503     explicit WithNoexcept(int val = 0) : data_(new int(val)) {
504         // std::cout << "    [WithNoexcept] Constructor\n";
505     }
506
507     ~WithNoexcept() {
508         delete data_;
509     }
510
511     // Move constructor WITH noexcept
512     WithNoexcept(WithNoexcept&& other) noexcept
513         : data_(other.data_) {
514         other.data_ = nullptr;
515         std::cout << "    [WithNoexcept] MOVE constructor (noexcept)\n";
516     }
517
518     // Copy constructor
519     WithNoexcept(const WithNoexcept& other)
520         : data_(new int(*other.data_)) {
521         std::cout << "    [WithNoexcept] COPY constructor\n";
522     }
523
524     WithNoexcept& operator=(WithNoexcept&&) noexcept = default;
525     WithNoexcept& operator=(const WithNoexcept&) = default;
526 };
527
528 void demonstrate() {
529     std::cout << "\n" << std::string(70, '=') << "\n";
```

```
530     std::cout << "SECTION 5: STD::VECTOR OPTIMIZATION WITH NOEXCEPT\n";
531     std::cout << std::string(70, '=') << "\n\n";
532
533     std::cout << " THE CRITICAL DIFFERENCE:\n";
534     std::cout << " std::vector uses MOVE only if noexcept\n";
535     std::cout << " Otherwise, it uses COPY for exception safety\n\n";
536
537     std::cout << " WITHOUT noexcept move (vector uses COPY on resize):\n";
538 {
539     std::vector<WithoutNoexcept> vec;
540     vec.reserve(2);
541     vec.emplace_back(1);
542     vec.emplace_back(2);
543
544     std::cout << " Resizing vector (triggers reallocation):\n";
545     vec.emplace_back(3); // Triggers resize - uses COPY!
546 }
547 std::cout << "\n";
548
549     std::cout << " WITH noexcept move (vector uses MOVE on resize):\n";
550 {
551     std::vector<WithNoexcept> vec;
552     vec.reserve(2);
553     vec.emplace_back(1);
554     vec.emplace_back(2);
555
556     std::cout << " Resizing vector (triggers reallocation):\n";
557     vec.emplace_back(3); // Triggers resize - uses MOVE!
558 }
559 std::cout << "\n";
560
561     std::cout << " PERFORMANCE IMPACT:\n";
562     std::cout << " Without noexcept: O(n) COPY during resize\n";
563     std::cout << " With noexcept:    O(n) MOVE during resize (much faster!)\n";
564     std::cout << " For 1000 objects: 1000x COPY vs 1000x MOVE\n";
565     std::cout << " Speedup can be 10x-100x+ depending on object size!\n";
566 }
567
568 } // namespace vector_optimization
569
570 // =====
571 // SECTION 6: PERFORMANCE COMPARISON
572 // =====
573
574 namespace performance_comparison {
575
576 class HeavyObject {
577 private:
578     std::vector<int> data_;
579
580 public:
581     explicit HeavyObject(size_t size = 1000) : data_(size, 42) {}
582 }
```

```
583 // Copy constructor (expensive)
584 HeavyObject(const HeavyObject& other) : data_(other.data_) {}
585
586 // Move constructor (cheap) - WITH noexcept
587 HeavyObject(HeavyObject&& other) noexcept : data_(std::move(other.data_))
588     {}
589
590 HeavyObject& operator=(const HeavyObject&) = default;
591 HeavyObject& operator=(HeavyObject&&) noexcept = default;
592 };
593
594 void benchmark() {
595     const size_t num_objects = 10000;
596
597     auto start = std::chrono::high_resolution_clock::now();
598
599     std::vector<HeavyObject> vec;
600     for (size_t i = 0; i < num_objects; ++i) {
601         vec.emplace_back(1000);
602     }
603
604     auto end = std::chrono::high_resolution_clock::now();
605     auto duration = std::chrono::duration_cast<std::chrono::milliseconds>(end
606         - start);
607
608     std::cout << "    Created " << num_objects << " objects\n";
609     std::cout << "    Total resizes performed: ~"
610             << static_cast<int>(std::log2(num_objects)) << "\n";
611     std::cout << "    Time: " << duration.count() << " ms\n";
612     std::cout << "    Because move is noexcept, vector uses MOVE on resize\n";
613 }
614
615 void demonstrate() {
616     std::cout << "\n" << std::string(70, '=') << "\n";
617     std::cout << "SECTION 6: PERFORMANCE COMPARISON\n";
618     std::cout << std::string(70, '=') << "\n\n";
619
620     std::cout << "  BENCHMARK: Vector growth with noexcept move\n";
621     benchmark();
622     std::cout << "\n";
623
624     std::cout << "  WITHOUT NOEXCEPT:\n";
625     std::cout << "    Same test would use COPY instead of MOVE\n";
626     std::cout << "    Could be 10x-100x slower!\n";
627 }
628
629 } // namespace performance_comparison
630
631 // =====
632 // SECTION 7: BEST PRACTICES SUMMARY
633 // =====
634
635 namespace best_practices {
```

```

635 void demonstrate() {
636     std::cout << "\n" << std::string(70, '=') << "\n";
637     std::cout << "SECTION 7: BEST PRACTICES SUMMARY\n";
638     std::cout << std::string(70, '=') << "\n\n";
639
640     std::cout << "    ALWAYS MARK NOEXCEPT:\n";
641     std::cout << "        1. Destructors (implicit, but explicit is clearer)\n";
642     std::cout << "        2. Move constructors\n";
643     std::cout << "        3. Move assignment operators\n";
644     std::cout << "        4. Swap functions\n";
645     std::cout << "        5. Simple getters/setters (no allocation)\n";
646     std::cout << "        6. Default constructors (if they don't allocate)\n\n";
647
648     std::cout << "    NEVER MARK NOEXCEPT:\n";
649     std::cout << "        1. Functions that allocate memory\n";
650     std::cout << "        2. Functions that perform I/O\n";
651     std::cout << "        3. Functions that validate/throw on bad input\n";
652     std::cout << "        4. Copy constructors/assignment (allocation can fail)\n";
653     std::cout << "        5. Functions calling non-noexcept functions\n\n";
654
655     std::cout << "    USE CONDITIONAL NOEXCEPT:\n";
656     std::cout << "        1. Template functions wrapping user types\n";
657     std::cout << "        2. Operations depending on template parameter traits\n";
658     std::cout << "        3. When you want to preserve noexcept when possible\n\n";
659
660     std::cout << "    CRITICAL WARNINGS:\n";
661     std::cout << "    • Lying about noexcept = std::terminate() (instant crash)
662         \n";
662     std::cout << "    • No recovery possible, no stack unwinding\n";
663     std::cout << "    • When in doubt, DON'T use noexcept\n";
664     std::cout << "    • Better to allow exception than cause termination\n\n";
665
666     std::cout << "    THE GOLDEN RULE:\n";
667     std::cout << "        'Use noexcept ONLY when you're 100% certain\n";
668     std::cout << "        the function will NEVER throw under ANY circumstances'\n
669         \n";
670
670     std::cout << "    PERFORMANCE BENEFITS:\n";
671     std::cout << "    • std::vector uses move instead of copy (10x-100x faster)
672         \n";
672     std::cout << "    • Compiler can optimize more aggressively\n";
673     std::cout << "    • No exception handling overhead\n";
674     std::cout << "    • Better code generation at call sites\n";
675 }
676
677 } // namespace best_practices
678
679 // =====
680 // MAIN - Demonstrate All Sections
681 // =====
682
683 int main() {
684     std::cout << "\n";
685     std::cout << "
686         \n";

```

```
686     std::cout << "          NOEXCEPT BEST PRACTICES IN MODERN C++  
687     std::cout << "          \n";  
688     std::cout << "          When to Use and When NOT to Use noexcept  
689     std::cout << "          \n";  
690     std::cout << "          \n";  
691     try {  
692         what_is_noexcept::demonstrate();  
693         always_use_noexcept::demonstrate();  
694         never_use_noexcept::demonstrate();  
695         conditional_noexcept::demonstrate();  
696         vector_optimization::demonstrate();  
697         performance_comparison::demonstrate();  
698         best_practices::demonstrate();  
699         std::cout << "\n          \n";  
700         std::cout << "          ALL NOEXCEPT CONCEPTS DEMONSTRATED!  
701         std::cout << "          \n";  
702         std::cout << "          \n\n";  
703     } catch (const std::exception& e) {  
704         std::cerr << " Error: " << e.what() << "\n";  
705         return 1;  
706     }  
707  
708     return 0;  
709 }
```

48 Source Code: ObjectSlicingCpp20.cpp

File: src/ObjectSlicingCpp20.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <memory>
3 #include <vector>
4 #include <string>
5 #include <span>
6 #include <ranges>
7 #include <concepts>
8
9 // =====
10 // PREVENTING OBJECT SLICING WITH C++20 FEATURES
11 // =====
12
13 // Base class
14 class Shape {
15 protected:
16     std::string name;
17
18 public:
19     Shape(const std::string& n) : name(n) {}
20     virtual ~Shape() = default;
21
22     virtual void draw() const {
23         std::cout << "Drawing Shape: " << name << std::endl;
24     }
25
26     virtual double area() const { return 0.0; }
27
28     virtual std::string type() const { return "Shape"; }
29 };
30
31 class Circle : public Shape {
32 private:
33     double radius;
34
35 public:
36     Circle(const std::string& n, double r) : Shape(n), radius(r) {}
37
38     void draw() const override {
39         std::cout << "Drawing Circle: " << name << " (radius=" << radius << ")"
40             << std::endl;
41     }
42
43     double area() const override {
44         return 3.14159 * radius * radius;
45     }
46
47     std::string type() const override { return "Circle"; }
48 };
```

```
49 class Rectangle : public Shape {
50 private:
51     double width, height;
52
53 public:
54     Rectangle(const std::string& n, double w, double h)
55         : Shape(n), width(w), height(h) {}
56
57     void draw() const override {
58         std::cout << "Drawing Rectangle: " << name << " (" << width << "x" <<
59             height << ")" << std::endl;
60     }
61
62     double area() const override {
63         return width * height;
64     }
65
66     std::string type() const override { return "Rectangle"; }
67 };
68 // =====
69 // 1. C++20 CONCEPTS - ENFORCE POINTER TYPES AT COMPILE TIME
70 // =====
71
72 // Concept: Must be a pointer or smart pointer to a type derived from Shape
73 template<typename T>
74 concept ShapePointer = requires(T t) {
75     { *t }; // Must be dereferenceable
76     requires std::derived_from<std::remove_reference_t<decltype(*t)>, Shape>;
77 };
78
79 // Concept: Must be a smart pointer
80 template<typename T>
81 concept SmartPointer = requires(T t) {
82     typename T::element_type; // Must have element_type (shared_ptr/
83     unique_ptr trait)
84     { t.get() } -> std::same_as<typename T::element_type*>;
85     { *t } -> std::same_as<typename T::element_type&>;
86 };
87
88 // Function that ONLY accepts pointers/smart pointers - prevents slicing at
89 // compile time
90 template<ShapePointer T>
91 void draw_shape(const T& shape_ptr) {
92     shape_ptr->draw();
93 }
94
95 // Function that ONLY accepts smart pointers specifically
96 template<SmartPointer T>
97     requires std::derived_from<typename T::element_type, Shape>
98 void process_shape(const T& shape_ptr) {
99     std::cout << "Type: " << shape_ptr->type() << ", Area: " << shape_ptr->
100        area() << std::endl;
101 }
```

```

99
100 void example_concepts_prevent_slicing() {
101     std::cout << "\n==== 1. C++20 CONCEPTS - COMPILE-TIME PREVENTION ===" <<
102         std::endl;
103     std::cout << "Solution: Use concepts to enforce pointer usage at compile
104         time\n" << std::endl;
105
106     auto circle = std::make_shared<Circle>("ConceptCircle", 5.0);
107     auto rect = std::make_unique<Rectangle>("ConceptRect", 4.0, 6.0);
108
109     std::cout << " These calls compile (using pointers):" << std::endl;
110     draw_shape(circle);           // Works with shared_ptr
111     draw_shape(rect);           // Works with unique_ptr
112
113     Circle* raw_circle = circle.get();
114     draw_shape(raw_circle);      // Works with raw pointer
115
116     process_shape(circle);      // Works with smart pointers
117     process_shape(rect);        // Works with smart pointers
118
119     std::cout << "\n Concepts prevent slicing at compile time!" << std::endl;
120     std::cout << " (Uncommenting the line below would cause a compile error)
121         " << std::endl;
122 }
123
124 // =====
125 // 2. C++20 RANGES - WORK WITH REFERENCES, NOT COPIES
126 // =====
127
128 void example_ranges_prevent_slicing() {
129     std::cout << "\n==== 2. C++20 RANGES - REFERENCE-BASED OPERATIONS ===" <<
130         std::endl;
131     std::cout << "Solution: Ranges work with references, preventing copies\n"
132         << std::endl;
133
134     std::vector<std::shared_ptr<Shape>> shapes;
135     shapes.push_back(std::make_shared<Circle>("RangeCircle1", 3.0));
136     shapes.push_back(std::make_shared<Rectangle>("RangeRect1", 5.0, 4.0));
137     shapes.push_back(std::make_shared<Circle>("RangeCircle2", 2.5));
138
139     std::cout << "Using ranges to filter and transform (no slicing):" << std::endl;
140
141     // Filter shapes with area > 20 and draw them
142     auto large_shapes = shapes
143         | std::views::filter([](const auto& s) { return s->area() > 20.0; })
144         | std::views::transform([](const auto& s) { return s.get(); });
145
146     for (const auto* shape : large_shapes) {
147         shape->draw();
148         std::cout << " Area: " << shape->area() << std::endl;

```

```
147     }
148
149     std::cout << "\n Ranges operate on references - no slicing occurs!" <<
150         std::endl;
151 }
152 // =====
153 // 3. C++20 SPAN - NON-OWNING VIEWS WITHOUT SLICING
154 // =====
155
156 // Function taking span of Shape pointers
157 void draw_all_shapes(std::span<const std::shared_ptr<Shape>> shapes) {
158     std::cout << "Drawing " << shapes.size() << " shapes:" << std::endl;
159     for (const auto& shape : shapes) {
160         shape->draw();
161     }
162 }
163
164 // Function taking span of raw pointers
165 void process_shapes(std::span<const Shape*> const shapes) {
166     double total_area = 0.0;
167     for (const auto* shape : shapes) {
168         total_area += shape->area();
169     }
170     std::cout << "Total area: " << total_area << std::endl;
171 }
172
173 void example_span_prevent_slicing() {
174     std::cout << "\n== 3. C++20 SPAN - NON-OWNING VIEWS ==" << std::endl;
175     std::cout << "Solution: std::span provides views without copying\n" << std
176         ::endl;
177
178     std::vector<std::shared_ptr<Shape>> shapes;
179     shapes.push_back(std::make_shared<Circle>("SpanCircle", 4.0));
180     shapes.push_back(std::make_shared<Rectangle>("SpanRect", 3.0, 5.0));
181
182     std::cout << "Passing span of smart pointers:" << std::endl;
183     draw_all_shapes(shapes); // No slicing - span of pointers
184
185     std::cout << "\nPassing span of raw pointers:" << std::endl;
186     std::vector<const Shape*> raw_ptrs;
187     for (const auto& s : shapes) {
188         raw_ptrs.push_back(s.get());
189     }
190     process_shapes(raw_ptrs); // No slicing - span of raw pointers
191
192     std::cout << "\n std::span is non-owning - operates on existing pointers!
193         " << std::endl;
194 }
195 // =====
196 // 4. C++20 CONSTRAINTS - DELETE SLICING-PRONE FUNCTIONS
197 // =====
```

```
198 template<typename T>
199     requires std::derived_from<T, Shape>
200 class ShapeContainer {
201 private:
202     std::vector<std::unique_ptr<T>> items;
203
204 public:
205     // CORRECT: Add by pointer (transfers ownership)
206     void add(std::unique_ptr<T> shape) {
207         items.push_back(std::move(shape));
208     }
209
210     // DELETED: Prevent adding by value (would cause slicing)
211     void add(const T& shape) = delete;
212     void add(T&& shape) = delete;
213
214     // CORRECT: Access via reference
215     const T& get(size_t index) const {
216         return *items[index];
217     }
218
219     void draw_all() const {
220         for (const auto& item : items) {
221             item->draw();
222         }
223     }
224
225     size_t size() const { return items.size(); }
226 };
227
228 void example_delete_slicing_functions() {
229     std::cout << "\n==== 4. DELETE SLICING-PRONE FUNCTIONS ===" << std::endl;
230     std::cout << "Solution: Use = delete to prevent value-based operations\n"
231             << std::endl;
232
233     ShapeContainer<Shape> container;
234
235     std::cout << " These operations work (using pointers):" << std::endl;
236     container.add(std::make_unique<Circle>("DeleteCircle", 5.0));
237     container.add(std::make_unique<Rectangle>("DeleteRect", 4.0, 3.0));
238
239     container.draw_all();
240
241     std::cout << "\n Deleted functions prevent slicing at compile time!" <<
242             std::endl;
243     std::cout << " (Uncommenting the lines below would cause compile errors)"
244             << std::endl;
245
246     // Circle circle("ByValueCircle", 3.0);
247     // container.add(circle);           // Compile error! Function deleted
248     // container.add(std::move(circle)); // Compile error! Function deleted
249 }
250
251 // =====
```

```
249 // 5. C++20 DESIGNATED INITIALIZERS WITH SMART POINTERS
250 // =====
251
252 struct ShapeConfig {
253     std::shared_ptr<Shape> primary;
254     std::shared_ptr<Shape> secondary;
255     std::string label;
256 };
257
258 void example_designated_initializers() {
259     std::cout << "\n==== 5. DESIGNATED INITIALIZERS - SAFE INITIALIZATION ==="
260         << std::endl;
261     std::cout << "Solution: Initialize with pointers using designated
262         initializers\n" << std::endl;
263
264     // CORRECT: Designated initializers with smart pointers
265     ShapeConfig config {
266         .primary = std::make_shared<Circle>("Primary", 6.0),
267         .secondary = std::make_shared<Rectangle>("Secondary", 5.0, 4.0),
268         .label = "MyShapes"
269     };
270
271     std::cout << "Configuration: " << config.label << std::endl;
272     config.primary->draw();
273     config.secondary->draw();
274
275     std::cout << "\n Designated initializers ensure proper pointer
276         initialization!" << std::endl;
277 }
278
279 // =====
280 // 6. C++20 REQUIRES CLAUSE - POLYMORPHIC CONTAINERS ONLY
281 // =====
282
283 template<typename Container>
284     requires requires(Container c) {
285         // Require that container holds pointers to Shape-derived types
286         { *c.begin() } -> std::convertible_to<std::shared_ptr<Shape>>;
287     }
288 void draw_container(const Container& shapes) {
289     std::cout << "Drawing " << shapes.size() << " shapes from container:" <<
290         std::endl;
291     for (const auto& shape : shapes) {
292         shape->draw();
293     }
294 }
295
296 void example_requires_clause() {
297     std::cout << "\n==== 6. REQUIRES CLAUSE - CONSTRAIN CONTAINER TYPES ===" <<
298         std::endl;
299     std::cout << "Solution: Require containers to hold pointers only\n" << std
300         ::endl;
301
302     std::vector<std::shared_ptr<Shape>> shapes;
```

```
297     shapes.push_back(std::make_shared<Circle>("RequiresCircle", 4.5));
298     shapes.push_back(std::make_shared<Rectangle>("RequiresRect", 6.0, 2.0));
299
300     std::cout << " This works (container of shared_ptr):" << std::endl;
301     draw_container(shapes);
302
303     std::cout << "\n Requires clause ensures polymorphic container usage!" <<
304             std::endl;
305     std::cout << " (Uncommenting the lines below would cause a compile error
306             )" << std::endl;
307
308 //   std::vector<Circle> value_circles;
309 //   value_circles.push_back(Circle("ValueCircle", 3.0));
310 //   draw_container(value_circles); // Compile error! Container holds
311 //   values, not pointers
312 }
313
314 // =====
315 // 7. COMPARISON: C++11/14 VS C++20 PREVENTION
316 // =====
317
318 void example_comparison() {
319     std::cout << "\n==== 7. C++11/14 VS C++20 PREVENTION COMPARISON ===" << std
320             ::endl;
321
322     std::cout << "\n C++11/14 APPROACH (Runtime/Developer Discipline):" <<
323             std::endl;
324     std::cout << " • Manually use smart pointers everywhere" << std::endl;
325     std::cout << " • Remember to not pass by value" << std::endl;
326     std::cout << " • Runtime errors if you forget" << std::endl;
327     std::cout << " • Code reviews needed to catch mistakes" << std::endl;
328
329     std::cout << "\n C++20 APPROACH (Compile-Time Enforcement):" << std::endl
330             ;
331     std::cout << " • Concepts enforce pointer usage at compile time" << std
332             ::endl;
333     std::cout << " • = delete prevents slicing-prone operations" << std::
334             endl;
335     std::cout << " • Requires clauses constrain templates" << std::endl;
336     std::cout << " • Compiler catches mistakes before runtime!" << std::endl
337             ;
338     std::cout << " • std::span provides safe non-owning views" << std::endl;
339     std::cout << " • Ranges work with references by default" << std::endl;
340 }
341
342 // =====
343 // MAIN FUNCTION
344 // =====
345
346 int main() {
347     std::cout << "\n
348             =====" <<
349             std::endl;
350     std::cout << " PREVENTING OBJECT SLICING WITH C++20 FEATURES" << std::
```

```
            endl;
340     std::cout << "
341             ====="
342     std::endl;
343
344     example_concepts_prevent_slicing();
345     example_ranges_prevent_slicing();
346     example_span_prevent_slicing();
347     example_delete_slicing_functions();
348     example_designated_initializers();
349     example_requires_clause();
350     example_comparison();
351
352     std::cout << "\n"
353             ====="
354     std::endl;
355     std::cout << "  C++20 SLICING PREVENTION SUMMARY" << std::endl;
356     std::cout << "
357             ====="
358     std::endl;
359     std::cout << "\n1.  CONCEPTS:" << std::endl;
360     std::cout << "  • Define ShapePointer concept to enforce pointer types"
361             << std::endl;
362     std::cout << "  • Compile-time error if trying to pass by value" << std::endl;
363     std::cout << "  • Example: template<ShapePointer T> void draw(const T&
364         ptr)" << std::endl;
365
366     std::cout << "\n2.  RANGES:" << std::endl;
367     std::cout << "  • Operate on references, not copies" << std::endl;
368     std::cout << "  • views::filter and views::transform preserve types" <<
369             std::endl;
370     std::cout << "  • No accidental slicing during transformations" << std::endl;
371
372     std::cout << "\n3.  STD::SPAN:" << std::endl;
373     std::cout << "  • Non-owning view of container" << std::endl;
374     std::cout << "  • std::span<shared_ptr<Shape>> - no copies" << std::endl;
375     std::cout << "  • Safe passing of pointer collections" << std::endl;
376
377     std::cout << "\n4.  = DELETE:" << std::endl;
378     std::cout << "  • Explicitly delete value-based operations" << std::endl;
379     std::cout << "  • void add(const T& shape) = delete" << std::endl;
380     std::cout << "  • Compiler prevents slicing attempts" << std::endl;
381
382     std::cout << "\n5.  REQUIRES CLAUSES:" << std::endl;
383     std::cout << "  • Constrain templates to pointer-holding containers" <<
384             std::endl;
385     std::cout << "  • requires { *c.begin() } -> convertible_to<shared_ptr<
386         Shape>>" << std::endl;
387     std::cout << "  • Type-safe generic programming" << std::endl;
388
389     std::cout << "\n6.  DESIGNATED INITIALIZERS:" << std::endl;
```

```
380     std::cout << " • Clear initialization syntax" << std::endl;
381     std::cout << " • Config { .shape = make_shared<Circle>(...)}" << std::
382         endl;
383     std::cout << " • Prevents accidental by-value initialization" << std::
384         endl;
385
386     std::cout << "\n KEY ADVANTAGE OF C++20:" << std::endl;
387     std::cout << " • C++11/14: Prevent slicing through discipline (runtime
388         errors)" << std::endl;
389     std::cout << " • C++20: Prevent slicing through type system (compile-
390         time errors)" << std::endl;
391     std::cout << " • Shift from \"remember not to\" → \"impossible to\"" <<
392         std::endl;
393
394     std::cout << "\n BEST PRACTICE (C++20):" << std::endl;
395     std::cout << "     Use concepts to enforce pointer parameters" << std::
396         endl;
397     std::cout << "     Use requires clauses for container constraints" << std
398         ::endl;
399     std::cout << "     Use = delete for slicing-prone operations" << std::endl
400         ;
401     std::cout << "     Use std::span for non-owning views" << std::endl;
402     std::cout << "     Use ranges for safe transformations" << std::endl;
403     std::cout << "     Let the compiler catch slicing at compile time!" << std
404         ::endl;
405
406     std::cout << "\n
407     ======\n" << std::endl;
408
409     return 0;
410 }
```

49 Source Code: ObjectSlicingSmartPtr.cpp

File: src/ObjectSlicingSmartPtr.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <memory>
3 #include <vector>
4 #include <string>
5
6 // =====
7 // OBJECT SLICING AND SMART POINTERS (C++11/14)
8 // =====
9
10 // Base class
11 class Shape {
12 protected:
13     std::string name;
14
15 public:
16     Shape(const std::string& n) : name(n) {
17         std::cout << "Shape constructor: " << name << std::endl;
18     }
19
20     virtual ~Shape() {
21         std::cout << "Shape destructor: " << name << std::endl;
22     }
23
24     virtual void draw() const {
25         std::cout << "Drawing Shape: " << name << std::endl;
26     }
27
28     virtual double area() const {
29         return 0.0;
30     }
31
32     virtual void info() const {
33         std::cout << "Shape: " << name << std::endl;
34     }
35 };
36
37 // Derived class: Circle
38 class Circle : public Shape {
39 private:
40     double radius;
41
42 public:
43     Circle(const std::string& n, double r) : Shape(n), radius(r) {
44         std::cout << "Circle constructor: " << name << " (radius=" << radius
45             << ")" << std::endl;
46     }
47
48     ~Circle() override {
49         std::cout << "Circle destructor: " << name << std::endl;
```

```
49     }
50
51     void draw() const override {
52         std::cout << "Drawing Circle: " << name << " with radius " << radius
53         << std::endl;
54     }
55
56     double area() const override {
57         return 3.14159 * radius * radius;
58     }
59
60     void info() const override {
61         std::cout << "Circle: " << name << ", radius=" << radius << ", area="
62         << area() << std::endl;
63     }
64 };
65
66 // Derived class: Rectangle
67 class Rectangle : public Shape {
68 private:
69     double width;
70     double height;
71
72 public:
73     Rectangle(const std::string& n, double w, double h)
74         : Shape(n), width(w), height(h) {
75         std::cout << "Rectangle constructor: " << name
76         << " (width=" << width << ", height=" << height << ")" <<
77         std::endl;
78     }
79
80     ~Rectangle() override {
81         std::cout << "Rectangle destructor: " << name << std::endl;
82     }
83
84     void draw() const override {
85         std::cout << "Drawing Rectangle: " << name
86         << " (" << width << "x" << height << ")" << std::endl;
87     }
88
89     double area() const override {
90         return width * height;
91     }
92
93     void info() const override {
94         std::cout << "Rectangle: " << name << ", " << width << "x" << height
95         << ", area=" << area() << std::endl;
96     }
97
98 // =====
99 // 1. CLASSIC OBJECT SLICING (WITHOUT SMART POINTERS)
100 // =====
```

```
100 void example_classic_slicing() {
101     std::cout << "\n==== 1. CLASSIC OBJECT SLICING ===" << std::endl;
102     std::cout << "Problem: Assigning derived object to base object by value\n"
103             << std::endl;
104
105     Circle circle("MyCircle", 5.0);
106     Shape shape = circle; // SLICING! Circle parts are lost
107
108     std::cout << "\nCalling draw() on sliced object:" << std::endl;
109     shape.draw(); // Calls Shape::draw(), not Circle::draw()!
110
111     std::cout << "\nArea of sliced object: " << shape.area() << std::endl; // Returns 0.0, not circle area!
112
113 }
114
115 // =====
116 // 2. OBJECT SLICING WITH SHARED_PTR - WRONG WAY
117 // =====
118
119 void example_shared_ptr_slicing_wrong() {
120     std::cout << "\n==== 2. OBJECT SLICING WITH SHARED_PTR (WRONG) ===" << std::endl;
121     std::cout << "Problem: Creating shared_ptr to base from derived object by value\n" << std::endl;
122
123     Circle circle("SlicedCircle", 7.0);
124
125     // WRONG: This creates a shared_ptr<Shape> pointing to a SLICED copy
126     std::shared_ptr<Shape> shape_ptr = std::make_shared<Shape>(circle);
127
128     std::cout << "\nCalling draw() through shared_ptr:" << std::endl;
129     shape_ptr->draw(); // Calls Shape::draw(), not Circle::draw()!
130
131     std::cout << "\nArea: " << shape_ptr->area() << std::endl; // Returns 0.0!
132
133     std::cout << "\nObject was sliced when passed by value to make_shared<Shape>!" << std::endl;
134 }
135
136 // =====
137 // 3. CONTAINER OF SHARED_PTR - WRONG WAY (SLICING)
138 // =====
139
140 void example_container_slicing_wrong() {
141     std::cout << "\n==== 3. CONTAINER WITH SLICING (WRONG) ===" << std::endl;
142     std::cout << "Problem: Storing objects by value in container\n" << std::endl;
143
144     std::vector<Shape> shapes; // WRONG: Stores Shape objects by value
145 }
```

```
146     shapes.push_back(Circle("Circle1", 3.0));           // Sliced!
147     shapes.push_back(Rectangle("Rect1", 4.0, 5.0)); // Sliced!
148
149     std::cout << "\nDrawing shapes from container:" << std::endl;
150     for (const auto& shape : shapes) {
151         shape.draw(); // Always calls Shape::draw()!
152         std::cout << " Area: " << shape.area() << std::endl; // Always
153         returns 0.0!
154     }
155
156     std::cout << "\n All derived class data was sliced off!" << std::endl;
157 }
158 // =====
159 // 4. COPYING SMART POINTERS - POTENTIAL SLICING
160 // =====
161
162 void process_shape_wrong(std::shared_ptr<Shape> shape) {
163     // If we copy the object instead of using the pointer
164     Shape copy = *shape; // SLICING!
165     copy.draw(); // Calls Shape::draw(), not the derived version
166 }
167
168 void example_copying_smart_ptr_wrong() {
169     std::cout << "\n== 4. COPYING OBJECT FROM SMART_PTR (WRONG) ==" << std::endl;
170     std::cout << "Problem: Dereferencing smart_ptr and copying by value\n" <<
171         std::endl;
172
173     auto circle = std::make_shared<Circle>("PointerCircle", 6.0);
174
175     std::cout << "\nOriginal (via pointer):" << std::endl;
176     circle->draw();
177
178     std::cout << "\nCopied value from pointer:" << std::endl;
179     process_shape_wrong(circle); // Slicing happens inside function
180
181     std::cout << "\n Dereferencing and copying caused slicing!" << std::endl;
182 }
183 // =====
184 // 5. CORRECT WAY: SHARED_PTR TO DERIVED CLASS
185 // =====
186
187 void example_shared_ptr_correct() {
188     std::cout << "\n== 5. CORRECT: SHARED_PTR TO DERIVED CLASS ==" << std::endl;
189     std::cout << "Solution: Create shared_ptr directly to derived class\n" <<
190         std::endl;
191
192     // CORRECT: Create shared_ptr<Circle> directly
193     std::shared_ptr<Circle> circle = std::make_shared<Circle>("CorrectCircle",
194         8.0);
195 }
```

```
194 // Upcast to base class pointer (no slicing!)
195 std::shared_ptr<Shape> shape_ptr = circle;
196
197 std::cout << "\nCalling draw() through base pointer:" << std::endl;
198 shape_ptr->draw(); // Calls Circle::draw() via polymorphism
199
200 std::cout << "\nArea: " << shape_ptr->area() << std::endl; // Returns
201 actual circle area
202
203 std::cout << "\n Polymorphism works correctly - no slicing!" << std::endl
204 ;
205
206 // =====
207 // 6. CORRECT WAY: CONTAINER OF SMART POINTERS
208 // =====
209
210 void example_container_correct() {
211     std::cout << "\n== 6. CORRECT: CONTAINER OF SMART_PTR ==" << std::endl;
212     std::cout << "Solution: Store pointers to base class, not objects\n" <<
213         std::endl;
214
215     // CORRECT: Vector of pointers to Shape
216     std::vector<std::shared_ptr<Shape>> shapes;
217
218     shapes.push_back(std::make_shared<Circle>("Circle2", 4.0));
219     shapes.push_back(std::make_shared<Rectangle>("Rect2", 6.0, 3.0));
220     shapes.push_back(std::make_shared<Circle>("Circle3", 2.5));
221
222     std::cout << "\nDrawing shapes from container:" << std::endl;
223     for (const auto& shape : shapes) {
224         shape->draw(); // Calls correct derived class method
225         std::cout << " Area: " << shape->area() << std::endl; // Returns
226             actual area
227     }
228
229     std::cout << "\n Polymorphism works - each object retains its type!" <<
230         std::endl;
231 }
232
233 // =====
234 // 7. CORRECT WAY: UNIQUE_PTR (C++11/14)
235 // =====
236
237 void example_unique_ptr_correct() {
238     std::cout << "\n== 7. CORRECT: UNIQUE_PTR FOR OWNERSHIP ==" << std::endl
239         ;
240     std::cout << "Solution: Use unique_ptr for exclusive ownership\n" << std::endl;
241
242     // CORRECT: unique_ptr to derived class
243     std::unique_ptr<Circle> circle = std::make_unique<Circle>("UniqueCircle",
244         5.5);
245 }
```

```
240 // Move to base class pointer (transfer ownership)
241 std::unique_ptr<Shape> shape_ptr = std::move(circle);
242
243 std::cout << "\nCalling methods through unique_ptr:" << std::endl;
244 shape_ptr->draw(); // Calls Circle::draw()
245 shape_ptr->info(); // Calls Circle::info()
246
247 std::cout << "\n unique_ptr maintains polymorphism without slicing!" <<
248     std::endl;
249 }
250
251 // =====
252 // 8. FACTORY PATTERN WITH SMART POINTERS (CORRECT)
253 // =====
254
255 std::unique_ptr<Shape> createShape(const std::string& type, const std::string&
256 name) {
257     if (type == "circle") {
258         return std::make_unique<Circle>(name, 10.0);
259     } else if (type == "rectangle") {
260         return std::make_unique<Rectangle>(name, 8.0, 6.0);
261     }
262     return std::make_unique<Shape>(name);
263 }
264
265 void example_factory_pattern() {
266     std::cout << "\n== 8. FACTORY PATTERN (CORRECT) ==" << std::endl;
267     std::cout << "Solution: Return base class pointer to derived objects\n" <<
268         std::endl;
269
270     auto shape1 = createShape("circle", "FactoryCircle");
271     auto shape2 = createShape("rectangle", "FactoryRect");
272
273     std::cout << "\nUsing factory-created objects:" << std::endl;
274     shape1->draw();
275     shape2->draw();
276
277     std::cout << "\n Factory pattern prevents slicing by returning pointers!" <<
278         std::endl;
279 }
280
281 // =====
282 // 9. COMPARISON: WRONG VS RIGHT
283 // =====
284
285 void example_side_by_side_comparison() {
286     std::cout << "\n== 9. SIDE-BY-SIDE COMPARISON ==" << std::endl;
287
288     std::cout << "\n WRONG - Object Slicing:" << std::endl;
289     Circle c1("WrongCircle", 5.0);
290     Shape s1 = c1; // Slicing!
291     s1.draw(); // Calls Shape::draw()
292     std::cout << " Area: " << s1.area() << " (lost circle data!)" << std::
293         endl;
```

```
289     std::cout << "\n CORRECT - Pointer (no slicing):" << std::endl;
290     auto c2 = std::make_shared<Circle>("RightCircle", 5.0);
291     std::shared_ptr<Shape> s2 = c2; // No slicing!
292     s2->draw(); // Calls Circle::draw()
293     std::cout << "    Area: " << s2->area() << " (preserves circle data!)" <<
294             std::endl;
295 }
296
297 // =====
298 // MAIN FUNCTION
299 // =====
300
301 int main() {
302     std::cout << "\n
303         =====" <<
304         std::endl;
305     std::cout << "    OBJECT SLICING AND SMART POINTERS (C++11/14)" << std::endl
306         ;
307     std::cout << "
308         =====" <<
309         std::endl;
310
311     // Wrong ways (demonstrating slicing)
312     example_classic_slicing();
313     example_shared_ptr_slicing_wrong();
314     example_container_slicing_wrong();
315     example_copying_smart_ptr_wrong();
316
317     // Correct ways (avoiding slicing)
318     example_shared_ptr_correct();
319     example_container_correct();
320     example_unique_ptr_correct();
321     example_factory_pattern();
322
323     // Comparison
324     example_side_by_side_comparison();
325
326     std::cout << "\n
327         =====" <<
328         std::endl;
329     std::cout << "    KEY TAKEAWAYS" << std::endl;
330     std::cout << "
331         =====" <<
332         std::endl;
333     std::cout << "\n    CAUSES OF OBJECT SLICING:" << std::endl;
334     std::cout << "        1. Assigning derived object to base object by value" <<
335             std::endl;
336     std::cout << "        2. Passing derived object by value to function expecting
337             base" << std::endl;
338     std::cout << "        3. Storing objects by value in containers of base type"
339             << std::endl;
340     std::cout << "        4. Creating smart_ptr<Base>(derived_object) - copies by
341             value" << std::endl;
```

```
329     std::cout << "    5. Dereferencing smart pointer and copying: Base copy = *  
330         ptr" << std::endl;  
331  
331     std::cout << "\n HOW TO AVOID SLICING WITH SMART POINTERS:" << std::endl;  
332     std::cout << "    1. Always create smart_ptr to the actual derived type" <<  
333         std::endl;  
333     std::cout << "    2. Use make_shared<DerivedType>() or make_unique<  
334         DerivedType>()" << std::endl;  
334     std::cout << "    3. Store smart_ptr<Base> in containers, not objects" <<  
335         std::endl;  
335     std::cout << "    4. Pass smart pointers by reference or const reference"  
336         << std::endl;  
336     std::cout << "    5. Never dereference and copy: always use pointer access  
337         (->)" << std::endl;  
337  
338     std::cout << "\n C++11/14 BEST PRACTICES:" << std::endl;  
339     std::cout << " • Use std::unique_ptr for exclusive ownership" << std:::  
340         endl;  
340     std::cout << " • Use std::shared_ptr for shared ownership" << std::endl;  
341     std::cout << " • Always use make_shared/make_unique (C++14)" << std:::  
341         endl;  
342     std::cout << " • Prefer polymorphism via pointers, not by value" << std  
342         ::endl;  
343     std::cout << " • Virtual destructors are essential for polymorphic  
343         classes" << std::endl;  
344  
345     std::cout << "\n  
345         ======\n" <<  
345         std::endl;  
346  
347     return 0;  
348 }
```

50 Source Code: OptionalExamples.cpp

File: src/OptionalExamples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <optional>
4 #include <vector>
5 #include <map>
6 #include <algorithm>
7 #include <cmath>
8
9 // =====
10 // 1. BASIC OPTIONAL USAGE
11 // =====
12 void example_basic_optional() {
13     std::cout << "\n== 1. BASIC OPTIONAL USAGE ==" << std::endl;
14
15     std::optional<int> maybe_value; // Empty optional
16
17     std::cout << "Has value: " << (maybe_value.has_value() ? "Yes" : "No") <<
18         std::endl;
19
20     maybe_value = 42; // Assign value
21     std::cout << "Has value: " << (maybe_value.has_value() ? "Yes" : "No") <<
22         std::endl;
23     std::cout << "Value: " << *maybe_value << std::endl;
24     std::cout << "Value (using .value()): " << maybe_value.value() << std::
25         endl;
26 }
27
28 // =====
29 // 2. OPTIONAL WITH VALUE_OR
30 // =====
31 void example_value_or() {
32     std::cout << "\n== 2. OPTIONAL WITH VALUE_OR ==" << std::endl;
33
34     std::optional<int> empty_opt;
35     std::optional<int> filled_opt = 100;
36
37     std::cout << "Empty optional value_or(0): " << empty_opt.value_or(0) <<
38         std::endl;
39     std::cout << "Filled optional value_or(0): " << filled_opt.value_or(0) <<
40         std::endl;
41
42     std::optional<std::string> empty_str;
43     std::cout << "Empty string value_or: " << empty_str.value_or("default") <<
44         std::endl;
45 }
46
47 // =====
48 // 3. OPTIONAL AS FUNCTION RETURN TYPE
49 // =====
```

```
44 std::optional<int> find_value(const std::vector<int>& vec, int target) {
45     auto it = std::find(vec.begin(), vec.end(), target);
46     if (it != vec.end()) {
47         return *it;
48     }
49     return std::nullopt; // Return empty optional
50 }
51
52 std::optional<std::string> get_name_by_id(int id) {
53     std::map<int, std::string> database = {
54         {1, "Alice"}, 
55         {2, "Bob"}, 
56         {3, "Charlie"}
57     };
58
59     auto it = database.find(id);
60     if (it != database.end()) {
61         return it->second;
62     }
63     return std::nullopt;
64 }
65
66 void example_optional_return() {
67     std::cout << "\n== 3. OPTIONAL AS FUNCTION RETURN TYPE ==" << std::endl;
68
69     std::vector<int> numbers = {10, 20, 30, 40, 50};
70
71     auto result1 = find_value(numbers, 30);
72     if (result1) {
73         std::cout << "Found: " << *result1 << std::endl;
74     } else {
75         std::cout << "Not found" << std::endl;
76     }
77
78     auto result2 = find_value(numbers, 99);
79     if (result2) {
80         std::cout << "Found: " << *result2 << std::endl;
81     } else {
82         std::cout << "Not found" << std::endl;
83     }
84
85     auto name1 = get_name_by_id(2);
86     std::cout << "ID 2: " << name1.value_or("Unknown") << std::endl;
87
88     auto name2 = get_name_by_id(99);
89     std::cout << "ID 99: " << name2.value_or("Unknown") << std::endl;
90 }
91
92 // =====
93 // 4. OPTIONAL WITH IF STATEMENT
94 // =====
95 void example_optional_if() {
96     std::cout << "\n== 4. OPTIONAL WITH IF STATEMENT ==" << std::endl;
```

```
98     auto maybe_name = get_name_by_id(1);
99
100    // C++17 if with initializer
101    if (auto name = get_name_by_id(1); name.has_value()) {
102        std::cout << "Found name: " << *name << std::endl;
103    } else {
104        std::cout << "Name not found" << std::endl;
105    }
106
107    if (auto name = get_name_by_id(999); name) {
108        std::cout << "Found name: " << *name << std::endl;
109    } else {
110        std::cout << "Name not found" << std::endl;
111    }
112}
113
114// =====
115// 5. OPTIONAL WITH EXCEPTIONS
116// =====
117void example_optional_exceptions() {
118    std::cout << "\n== 5. OPTIONAL WITH EXCEPTIONS ==" << std::endl;
119
120    std::optional<int> empty_opt;
121    std::optional<int> filled_opt = 42;
122
123    try {
124        std::cout << "Filled optional value: " << filled_opt.value() << std::endl;
125        std::cout << "Empty optional value: " << empty_opt.value() << std::endl; // Throws!
126    } catch (const std::bad_optional_access& e) {
127        std::cout << "Exception caught: " << e.what() << std::endl;
128    }
129}
130
131// =====
132// 6. OPTIONAL WITH CUSTOM TYPES
133// =====
134struct Person {
135    std::string name;
136    int age;
137
138    Person(const std::string& n, int a) : name(n), age(a) {}
139
140    friend std::ostream& operator<<(std::ostream& os, const Person& p) {
141        os << p.name << " (age " << p.age << ")";
142        return os;
143    }
144};
145
146std::optional<Person> find_person(const std::string& name) {
147    std::vector<Person> people = {
148        {"Alice", 30},
149        {"Bob", 25},
```

```
150     {"Charlie", 35}  
151 };  
152  
153 auto it = std::find_if(people.begin(), people.end(),  
154 [&name](const Person& p) { return p.name == name; });  
155  
156 if (it != people.end()) {  
157     return *it;  
158 }  
159 return std::nullopt;  
160 }  
161  
162 void example_optional_custom_type() {  
163     std::cout << "\n== 6. OPTIONAL WITH CUSTOM TYPES ==" << std::endl;  
164  
165     auto person1 = find_person("Alice");  
166     if (person1) {  
167         std::cout << "Found: " << *person1 << std::endl;  
168     }  
169  
170     auto person2 = find_person("David");  
171     if (person2) {  
172         std::cout << "Found: " << *person2 << std::endl;  
173     } else {  
174         std::cout << "Person not found" << std::endl;  
175     }  
176 }  
177  
178 // =====  
179 // 7. OPTIONAL WITH EMPLACE  
180 // =====  
181 void example_optional_emplace() {  
182     std::cout << "\n== 7. OPTIONAL WITH EMPLACE ==" << std::endl;  
183  
184     std::optional<Person> opt_person;  
185  
186     std::cout << "Before emplace: " << (opt_person.has_value() ? "Has value" :  
187         "Empty") << std::endl;  
188  
189     opt_person.emplace("John", 28); // Construct in-place  
190  
191     std::cout << "After emplace: " << *opt_person << std::endl;  
192  
193     opt_person.emplace("Jane", 32); // Replace existing value  
194     std::cout << "After second emplace: " << *opt_person << std::endl;  
195 }  
196  
197 // =====  
198 // 8. OPTIONAL WITH RESET  
199 // =====  
200 void example_optional_reset() {  
201     std::cout << "\n== 8. OPTIONAL WITH RESET ==" << std::endl;  
202  
203     std::optional<int> value = 100;
```

```
203     std::cout << "Initial value: " << *value << std::endl;
204
205     value.reset(); // Clear the optional
206     std::cout << "After reset: " << (value.has_value() ? "Has value" : "Empty"
207         ) << std::endl;
208
209     value = 200;
210     std::cout << "After reassignment: " << *value << std::endl;
211
212     value = std::nullopt; // Another way to clear
213     std::cout << "After nullopt: " << (value.has_value() ? "Has value" : "
214         Empty) << std::endl;
215 }
216
217 // =====
218 // 9. OPTIONAL CHAINING WITH TRANSFORM (C++23-style)
219 // =====
220 std::optional<double> safe_sqrt(double value) {
221     if (value >= 0.0) {
222         return std::sqrt(value);
223     }
224     return std::nullopt;
225 }
226
227 std::optional<double> safe_divide(double numerator, double denominator) {
228     if (denominator != 0.0) {
229         return numerator / denominator;
230     }
231     return std::nullopt;
232 }
233
234 void example_optional_chaining() {
235     std::cout << "\n== 9. OPTIONAL CHAINING ==" << std::endl;
236
237     auto result1 = safe_divide(100, 4);
238     if (result1) {
239         auto sqrt_result = safe_sqrt(*result1);
240         if (sqrt_result) {
241             std::cout << "sqrt(100/4) = " << *sqrt_result << std::endl;
242         }
243     }
244
245     auto result2 = safe_divide(100, 0);
246     std::cout << "Division by zero result: "
247         << (result2.has_value() ? "Has value" : "Empty") << std::endl;
248 }
249
250 // =====
251 // 10. OPTIONAL WITH COMPARISON
252 // =====
253 void example_optional_comparison() {
254     std::cout << "\n== 10. OPTIONAL WITH COMPARISON ==" << std::endl;
255
256     std::optional<int> opt1 = 10;
```

```
255     std::optional<int> opt2 = 20;
256     std::optional<int> opt3 = 10;
257     std::optional<int> empty;
258
259     std::cout << "opt1 == opt3: " << (opt1 == opt3 ? "true" : "false") << std::
260         ::endl;
261     std::cout << "opt1 < opt2: " << (opt1 < opt2 ? "true" : "false") << std::
262         ::endl;
263     std::cout << "opt1 == 10: " << (opt1 == 10 ? "true" : "false") << std::
264         ::endl;
265     std::cout << "empty == nullopt: " << (empty == std::nullopt ? "true" : "
266         false") << std::endl;
267 }
268
269 // =====
270 // 11. OPTIONAL IN CONTAINERS
271 // =====
272 void example_optional_in_containers() {
273     std::cout << "\n== 11. OPTIONAL IN CONTAINERS ==" << std::endl;
274
275     std::vector<std::optional<int>> values = {
276         10,
277         std::nullopt,
278         20,
279         std::nullopt,
280         30
281     };
282
283     std::cout << "Processing optional values:" << std::endl;
284     for (size_t i = 0; i < values.size(); ++i) {
285         if (values[i]) {
286             std::cout << "    Index " << i << ": " << *values[i] << std::endl;
287         } else {
288             std::cout << "    Index " << i << ": empty" << std::endl;
289         }
290     }
291
292     // Count non-empty values
293     int count = 0;
294     for (const auto& opt : values) {
295         if (opt) ++count;
296     }
297     std::cout << "Non-empty values: " << count << std::endl;
298 }
299
300 // =====
301 // 12. OPTIONAL WITH MAKE_OPTIONAL
302 // =====
303 std::optional<Person> create_person_if_valid(const std::string& name, int age)
304 {
305     if (!name.empty() && age > 0 && age < 150) {
306         return Person(name, age);
307     }
308     return std::nullopt;
```

```
304 }
305
306 void example_make_optional() {
307     std::cout << "\n==== 12. OPTIONAL WITH MAKE_OPTIONAL ===" << std::endl;
308
309     auto person1 = create_person_if_valid("Alice", 30);
310     if (person1) {
311         std::cout << "Valid person: " << *person1 << std::endl;
312     }
313
314     auto person2 = create_person_if_valid("", 25);
315     if (person2) {
316         std::cout << "Valid person: " << *person2 << std::endl;
317     } else {
318         std::cout << "Invalid person (empty name)" << std::endl;
319     }
320
321     auto person3 = create_person_if_valid("Bob", -5);
322     if (person3) {
323         std::cout << "Valid person: " << *person3 << std::endl;
324     } else {
325         std::cout << "Invalid person (negative age)" << std::endl;
326     }
327 }
328
329 // =====
330 // MAIN FUNCTION
331 // =====
332 int main() {
333     std::cout << "\n====="
334         endl;
335     std::cout << "      C++17 STD::OPTIONAL EXAMPLES" << std::endl;
336     std::cout << "====="
337         endl;
338
339     example_basic_optional();
340     example_value_or();
341     example_optional_return();
342     example_optional_if();
343     example_optional_exceptions();
344     example_optional_custom_type();
345     example_optional_emplace();
346     example_optional_reset();
347     example_optional_chaining();
348     example_optional_comparison();
349     example_optional_in_containers();
350     example_make_optional();
351
352     std::cout << "\n====="
353         endl;
354     std::cout << "      ALL EXAMPLES COMPLETED" << std::endl;
355     std::cout << "=====\\n"
356         endl;
```

354 **return** 0;
355 }

51 Source Code: PerfectForwardingAndRequires.cpp

File: src/PerfectForwardingAndRequires.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // ADVANCED PERFECT FORWARDING, CONCEPTS, AND REQUIRES-EXPRESSIONS
3 // =====
4 // This example covers:
5 // 1. std::forward and perfect forwarding with concepts
6 // 2. "requires requires" - nested requires explained
7 // 3. Requirement clauses vs requirement expressions
8 // 4. When to use and when to avoid "requires requires"
9 // 5. Embedded systems considerations
10 //
11 // TOPICS:
12 // - Perfect forwarding with universal references
13 // - Concepts constraining forwarding functions
14 // - requires clause (starts constraint)
15 // - requires expression (tests validity)
16 // - SFINAE vs Concepts comparison
17 // - Zero-cost abstractions for embedded systems
18 // =====
19
20 #include <iostream>
21 #include <string>
22 #include <vector>
23 #include <memory>
24 #include <type_traits>
25 #include <concepts>
26 #include <utility>
27
28 // =====
29 // SECTION 1: PERFECT FORWARDING BASICS WITH std::forward
30 // =====
31
32 // Without perfect forwarding - INEFFICIENT
33 template<typename T>
34 void call_by_value(T arg) {
35     std::cout << " Value parameter (copy made)" << std::endl;
36 }
37
38 // With perfect forwarding - EFFICIENT
39 template<typename T>
40 void call_with_forward(T&& arg) {
41     std::cout << " Universal reference with forward" << std::endl;
42     // std::forward<T>(arg) preserves value category:
43     // - lvalue stays lvalue (no move)
44     // - rvalue stays rvalue (enables move)
45 }
46
47 void demonstrate_perfect_forwarding() {
48     std::cout << "\n== 1. PERFECT FORWARDING BASICS ==" << std::endl;
49 }
```

```
50     std::string lvalue = "Hello";
51
52     std::cout << "\nCalling by value:" << std::endl;
53     call_by_value(lvalue); // Copy
54     call_by_value(std::string("World")); // Copy + move
55
56     std::cout << "\nCalling with forward:" << std::endl;
57     call_with_forward(lvalue); // No copy
58     call_with_forward(std::string("World")); // No copy
59
60     std::cout << "\n KEY POINT:" << std::endl;
61     std::cout << "    T&& in template = universal reference" << std::endl;
62     std::cout << "    std::forward<T> preserves value category" << std::endl;
63 }
64
65 // =====
66 // SECTION 2: REQUIRES CLAUSE VS REQUIRES EXPRESSION
67 // =====
68
69 // TERMINOLOGY:
70 // - requires clause: Introduces a constraint (keyword 'requires')
71 // - requires expression: Tests if expressions are valid
72
73 // Example 1: requires clause WITHOUT requires expression
74 template<typename T>
75 requires std::integral<T> // <- This is a requires CLAUSE
76 T square(T x) {
77     return x * x;
78 }
79
80 // Example 2: requires clause WITH requires expression
81 template<typename T>
82 requires requires(T x) { // <- First 'requires' = clause, second =
83     x + x; // Check if x can be added
84     x * x; // Check if x can be multiplied
85 }
86 T compute(T x) {
87     return x * x + x;
88 }
89
90 void demonstrate_requires_syntax() {
91     std::cout << "\n== 2. REQUIRES CLAUSE VS REQUIRES EXPRESSION ==" << std
92         ::endl;
93
94     std::cout << "\n TERMINOLOGY:" << std::endl;
95     std::cout << "    requires clause:      'requires <constraint>'" << std::
96         endl;
97     std::cout << "    requires expression: 'requires(params) { tests; }'" <<
98         std::endl;
99
100    std::cout << "\n square(5) = " << square(5) << std::endl;
101    std::cout << "    compute(5) = " << compute(5) << std::endl;
```

```
100     // square(3.14);    // ERROR: not integral
101     // compute("hi");   // ERROR: can't add/multiply strings
102 }
103
104 // =====
105 // SECTION 3: THE "REQUIRES REQUIRES" PATTERN
106 // =====
107
108 // WHAT IS "requires requires"?
109 //
110 // Template<typename T>
111 // requires requires(T t) { ... }
112 //           ^          ^
113 //           |          |
114 //           |          +- requires EXPRESSION (tests code validity)
115 //           +----- requires CLAUSE (introduces constraint)
116 //
117 // WHEN TO USE:
118 // - You need to test if specific operations are valid
119 // - Standard concepts don't cover your needs
120 // - You're checking syntax, not just type properties
121
122 // Example: Check if type has specific member function
123 template<typename T>
124 requires requires(T obj) {           // "requires requires"
125     { obj.serialize() } -> std::same_as<std::string>;
126 }
127 void save(const T& obj) {
128     std::string data = obj.serialize();
129     std::cout << "    Saved: " << data << std::endl;
130 }
131
132 // Example: Check if type supports arithmetic and comparison
133 template<typename T>
134 requires requires(T a, T b) {           // "requires requires"
135     { a + b } -> std::convertible_to<T>;
136     { a - b } -> std::convertible_to<T>;
137     { a < b } -> std::convertible_to<bool>;
138     { a > b } -> std::convertible_to<bool>;
139 }
140 T clamp(T value, T min, T max) {
141     if (value < min) return min;
142     if (value > max) return max;
143     return value;
144 }
145
146 // Test classes
147 class Serializable {
148 public:
149     std::string serialize() const { return "Serializable{data}"; }
150 };
151
152 void demonstrate_requires_requires() {
153     std::cout << "\n==== 3. THE 'REQUIRES REQUIRES' PATTERN ===" << std::endl;
```

```
154     std::cout << "\n EXPLANATION:" << std::endl;
155     std::cout << "    First 'requires': Starts the constraint clause" << std::
156         endl;
157     std::cout << "    Second 'requires': Begins the expression testing code" <<
158         std::endl;
159     std::cout << "    Inside { ... }: Operations that must be valid" << std::
160         endl;
161
162     std::cout << "\n Using save() with Serializable:" << std::endl;
163     Serializable obj;
164     save(obj);
165
166     std::cout << "\n Using clamp() with int:" << std::endl;
167     std::cout << "    clamp(150, 0, 100) = " << clamp(150, 0, 100) << std::endl
168         ;
169     std::cout << "    clamp(-10, 0, 100) = " << clamp(-10, 0, 100) << std::endl
170         ;
171     std::cout << "    clamp(50, 0, 100) = " << clamp(50, 0, 100) << std::endl;
172 }
173
174 // =====
175 // SECTION 4: PERFECT FORWARDING WITH CONCEPTS
176 // =====
177
178 // Constrain what types can be forwarded
179 template<typename T>
180 concept Movable = std::is_move_constructible_v<T>;
181
182 template<typename T>
183 concept Copyable = std::is_copy_constructible_v<T>;
184
185 // Factory function with perfect forwarding and concepts
186 template<typename T, typename... Args>
187 requires std::constructible_from<T, Args...> // Concept constrains
188     construction
189 std::unique_ptr<T> make_unique_constrained(Args&&... args) {
190     return std::make_unique<T>(std::forward<Args>(args)...);
191 }
192
193 // Forwarding wrapper with requires requires
194 template<typename Func, typename... Args>
195 requires requires(Func f, Args... args) { // Check if callable
196     f(std::forward<Args>(args)...);
197 }
198 auto forward_call(Func&& func, Args&&... args) {
199     std::cout << "    Forwarding call..." << std::endl;
200     return func(std::forward<Args>(args)...);
201 }
202
203 void demonstrate_forwarding_with_concepts() {
204     std::cout << "\n==== 4. PERFECT FORWARDING WITH CONCEPTS ===" << std::endl;
205
206     std::cout << "\n make_unique_constrained:" << std::endl;
```

```
202 auto ptr1 = make_unique_constrained<std::string>("Hello", 5, 'X');
203 std::cout << "    Created: " << *ptr1 << std::endl;
204
205 auto ptr2 = make_unique_constrained<std::vector<int>>(10, 42);
206 std::cout << "    Created vector of size: " << ptr2->size() << std::endl;
207
208 std::cout << "\n forward_call with lambda:" << std::endl;
209 auto lambda = [](int x, int y) {
210     return x + y;
211 };
212 int result = forward_call(lambda, 10, 20);
213 std::cout << "    Result: " << result << std::endl;
214 }
215
216 // =====
217 // SECTION 5: WHEN TO USE "REQUIRES REQUIRES"
218 // =====
219
220 void explain_when_to_use_requires_requires() {
221     std::cout << "\n== 5. WHEN TO USE 'REQUIRES REQUIRES' ==" << std::endl;
222
223     std::cout << "\n USE 'requires requires' WHEN:" << std::endl;
224     std::cout << "    1. Testing specific syntax/operations:" << std::endl;
225     std::cout << "        requires requires(T t) { t.foo(); t.bar(); }" << std::endl;
226     std::cout << "\n    2. No standard concept exists:" << std::endl;
227     std::cout << "        requires requires(T t) { t.serialize(); }" << std::endl;
228     std::cout << "\n    3. Complex compound expressions:" << std::endl;
229     std::cout << "        requires requires(T a, T b) { a + b * 2; }" << std::endl;
230     std::cout << "\n    4. Return type checking:" << std::endl;
231     std::cout << "        requires requires(T t) { { t.size() } -> std::same_as<
232         size_t>; }" << std::endl;
233
234     std::cout << "\n AVOID 'requires requires' WHEN:" << std::endl;
235     std::cout << "    1. Standard concept exists:" << std::endl;
236     std::cout << "        requires requires(T t) { t == t; }" << std::endl;
237     std::cout << "        requires std::equality_comparable<T>" << std::endl;
238     std::cout << "\n    2. Simple type trait works:" << std::endl;
239     std::cout << "        requires requires { typename T::value_type; }" <<
240         std::endl;
241     std::cout << "        requires requires { typename T::value_type; } # OK
242         if needed" << std::endl;
243     std::cout << "\n    3. Makes code harder to read:" << std::endl;
244     std::cout << "        Define a named concept instead!" << std::endl;
245
246     std::cout << "\n BEST PRACTICE:" << std::endl;
247     std::cout << "    Wrap 'requires requires' in a named concept:" << std::endl;
248     std::cout << "        template<typename T>" << std::endl;
249     std::cout << "        concept MyConstraint = requires(T t) { /* tests */ };" <<
250         std::endl;
251 }
```

```

248
249 // =====
250 // SECTION 6: READABILITY - NAMED CONCEPTS VS INLINE REQUIRES
251 // =====
252
253 // BAD: Inline requires requires - hard to read and reuse
254 template<typename T>
255 requires requires(T container) {
256     { container.begin() } -> std::input_or_output_iterator;
257     { container.end() } -> std::input_or_output_iterator;
258     { container.size() } -> std::convertible_to<std::size_t>;
259     requires std::is_same_v<typename T::value_type, int>;
260 }
261 void process_bad(const T& container) {
262     std::cout << "Size: " << container.size() << std::endl;
263 }
264
265 // GOOD: Named concept - readable and reusable
266 template<typename T>
267 concept IntContainer = requires(T container) {
268     { container.begin() } -> std::input_or_output_iterator;
269     { container.end() } -> std::input_or_output_iterator;
270     { container.size() } -> std::convertible_to<std::size_t>;
271     requires std::is_same_v<typename T::value_type, int>;
272 };
273
274 template<IntContainer T>
275 void process_good(const T& container) {
276     std::cout << "Size: " << container.size() << std::endl;
277 }
278
279 void demonstrate_readability() {
280     std::cout << "\n==== 6. READABILITY: NAMED CONCEPTS VS INLINE ===" << std::endl;
281
282     std::cout << "\n BAD - Inline 'requires requires':"
283     std::cout << " template<typename T>" << std::endl;
284     std::cout << "     requires requires(T t) { /* 10 lines */ }"
285     std::cout << "     void func(T x) { ... }"
286     std::cout << "     Problems: Hard to read, can't reuse, error messages
287     unclear" << std::endl;
288
289     std::cout << "\n GOOD - Named concept:"
290     std::cout << " template<typename T>" << std::endl;
291     std::cout << "     concept MyConstraint = requires(T t) { /* tests */ };" <<
292         std::endl;
293     std::cout << "\n     template<MyConstraint T>" << std::endl;
294     std::cout << "     void func(T x) { ... }"
295     std::cout << "     Benefits: Readable, reusable, clear error messages" <<
296         std::endl;
297
298     std::vector<int> vec = {1, 2, 3, 4, 5};
299     process_good(vec);
300 }
```

```
298 // =====
299 // SECTION 7: EMBEDDED SYSTEMS CONSIDERATIONS
300 // =====
301
302 void explain_embedded_systems() {
303     std::cout << "\n==== 7. EMBEDDED SYSTEMS CONSIDERATIONS ===" << std::endl;
304
305     std::cout << "\n ARE CONCEPTS USEFUL FOR EMBEDDED SYSTEMS?" << std::endl;
306     std::cout << "    YES! Here's why:" << std::endl;
307
308     std::cout << "\n1. ZERO RUNTIME COST:" << std::endl;
309     std::cout << " • Concepts are compile-time only" << std::endl;
310     std::cout << " • No runtime overhead vs unconstrained templates" << std
311         ::endl;
312     std::cout << " • Generated code is identical" << std::endl;
313     std::cout << " • Same as SFINAE but cleaner" << std::endl;
314
315     std::cout << "\n2. REDUCE CODE SIZE:" << std::endl;
316     std::cout << " • Catch errors early = fewer template instantiations" <<
317         std::endl;
318     std::cout << " • Better error messages = less debugging code" << std::
319         endl;
320     std::cout << " • Explicit constraints prevent accidental instantiations"
321         << std::endl;
322
323     std::cout << "\n3. TYPE SAFETY:" << std::endl;
324     std::cout << " • Catch type errors at compile time" << std::endl;
325     std::cout << " • No runtime checks needed" << std::endl;
326     std::cout << " • Perfect for safety-critical systems" << std::endl;
327
328     std::cout << "\n4. SELF-DOCUMENTING:" << std::endl;
329     std::cout << " • Requirements are explicit in code" << std::endl;
330     std::cout << " • No need for extensive comments" << std::endl;
331     std::cout << " • Easier code review and maintenance" << std::endl;
332
333     std::cout << "\n WHEN TO BE CAUTIOUS:" << std::endl;
334     std::cout << " 1. Compiler support: Need C++20" << std::endl;
335     std::cout << " 2. Compilation time: Complex concepts slow builds" << std
336         ::endl;
337     std::cout << " 3. Code size: Templates can increase binary size" << std
338         ::endl;
339     std::cout << " 4. Debugging: Template errors can be complex" << std::
340         endl;
341
342     std::cout << "\n EMBEDDED BEST PRACTICES:" << std::endl;
343     std::cout << "    Use concepts for HAL (Hardware Abstraction Layer)" <<
344         std::endl;
345     std::cout << "    Constrain register access templates" << std::endl;
346     std::cout << "    Type-safe peripheral interfaces" << std::endl;
347     std::cout << "    Compile-time buffer size checking" << std::endl;
348     std::cout << "    Avoid deep template nesting" << std::endl;
349     std::cout << "    Measure binary size impact" << std::endl;
350 }
```

```
344 // =====
345 // SECTION 8: EMBEDDED EXAMPLE - REGISTER ACCESS
346 // =====
347
348 // Embedded systems often need type-safe register access
349 template<typename T>
350 concept RegisterType = requires {
351     requires std::is_integral_v<T>;
352     requires sizeof(T) <= 4; // 32-bit or smaller
353     requires std::is_trivially_copyable_v<T>;
354 };
355
356
357 template<RegisterType T>
358 class Register {
359     private:
360         volatile T* address_;
361
362     public:
363         explicit Register(uintptr_t addr) : address_(reinterpret_cast<volatile T
364             *>(addr)) {}
365
366         void write(T value) const {
367             *address_ = value;
368         }
369
370         T read() const {
371             return *address_;
372         }
373
374         void set_bit(unsigned bit) requires std::unsigned_integral<T> {
375             *address_ |= (T{1} << bit);
376         }
377
378         void clear_bit(unsigned bit) requires std::unsigned_integral<T> {
379             *address_ &= ~(T{1} << bit);
380         }
381
382     void demonstrate_embedded_concepts() {
383         std::cout << "\n==== 8. EMBEDDED EXAMPLE - REGISTER ACCESS ===" << std::
384             endl;
385
386         std::cout << "\n Type-safe register access with concepts:" << std::endl;
387
388         // Simulate hardware registers
389         uint32_t mock_register = 0x00000000;
390         Register<uint32_t> gpio_control(reinterpret_cast<uintptr_t>(&mock_register
391             ));
392
393         std::cout << "    Initial value: 0x" << std::hex << mock_register << std::
394             dec << std::endl;
395
396         gpio_control.write(0xAABBCCDD);
```

```
394     std::cout << "    After write:  0x" << std::hex << mock_register << std::::dec << std::endl;
395
396     gpio_control.set_bit(4);
397     std::cout << "    After set_bit(4): 0x" << std::hex << mock_register << std::::dec << std::endl;
398
399     std::cout << "\n Benefits:" << std::endl;
400     std::cout << " •  Compile-time type checking" << std::endl;
401     std::cout << " •  No runtime overhead" << std::endl;
402     std::cout << " •  Can't use wrong size types" << std::endl;
403     std::cout << " •  set_bit/clear_bit only for unsigned types" << std::endl;
404     ;
405 }
406
407 // =====
408 // SECTION 9: COMPARISON - SFINAE VS CONCEPTS
409 // =====
410
411 // Old way: SFINAE (Substitution Failure Is Not An Error)
412 template<typename T, typename = std::enable_if_t<std::is_integral_v<T>>>
413 T old_square(T x) {
414     return x * x;
415 }
416
417 // New way: Concepts
418 template<std::integral T>
419 T new_square(T x) {
420     return x * x;
421 }
422
423 void compare_sfinae_vs_concepts() {
424     std::cout << "\n== 9. COMPARISON: SFINAЕ VS CONCEPTS ==" << std::endl;
425
426     std::cout << "\n OLD WAY (SFINAE):" << std::endl;
427     std::cout << "    template<typename T, typename = std::enable_if_t<...>>" << std::endl;
428     std::cout << "        T func(T x) { ... }" << std::endl;
429     std::cout << "\n    Problems:" << std::endl;
430     std::cout << " •  Hard to read and write" << std::endl;
431     std::cout << " •  Terrible error messages" << std::endl;
432     std::cout << " •  Verbose and error-prone" << std::endl;
433
434     std::cout << "\n NEW WAY (CONCEPTS):" << std::endl;
435     std::cout << "    template<std::integral T>" << std::endl;
436     std::cout << "        T func(T x) { ... }" << std::endl;
437     std::cout << "\n    Benefits:" << std::endl;
438     std::cout << " •  Clean and readable" << std::endl;
439     std::cout << " •  Clear error messages" << std::endl;
440     std::cout << " •  Intent is obvious" << std::endl;
441     std::cout << " •  Easier to maintain" << std::endl;
442
443     std::cout << "\n Both work the same:" << std::endl;
444     std::cout << "    old_square(5) = " << old_square(5) << std::endl;
```

```
444     std::cout << "    new_square(5) = " << new_square(5) << std::endl;
445     std::cout << "\n Same runtime cost: ZERO" << std::endl;
446 }
447
448 // =====
449 // SECTION 10: COMPLETE EXAMPLE - THREAD-SAFE QUEUE
450 // =====
451
452 #include <mutex>
453 #include <queue>
454 #include <optional>
455
456 template<typename T>
457 concept ThreadSafeElement = requires {
458     requires std::is_move_constructible_v<T> || std::is_copy_constructible_v<T
459         >;
460     requires std::is_destructible_v<T>;
461 };
462
463 template<ThreadSafeElement T>
464 class ThreadSafeQueue {
465 private:
466     mutable std::mutex mutex_;
467     std::queue<T> queue_;
468
469 public:
470     // Perfect forwarding with concepts
471     template<typename U>
472     requires std::constructible_from<T, U>
473     void push(U&& item) {
474         std::lock_guard<std::mutex> lock(mutex_);
475         queue_.push(std::forward<U>(item));
476     }
477
478     std::optional<T> try_pop() {
479         std::lock_guard<std::mutex> lock(mutex_);
480         if (queue_.empty()) {
481             return std::nullopt;
482         }
483         T item = std::move(queue_.front());
484         queue_.pop();
485         return item;
486     }
487
488     bool empty() const {
489         std::lock_guard<std::mutex> lock(mutex_);
490         return queue_.empty();
491     }
492
493 void demonstrate_complete_example() {
494     std::cout << "\n==== 10. COMPLETE EXAMPLE - THREAD-SAFE QUEUE ===" << std::
495         endl;
```

```
496 ThreadSafeQueue<std::string> queue;
497
498 std::cout << "\n Pushing items with perfect forwarding:" << std::endl;
499
500 std::string lval = "lvalue string";
501 queue.push(lval); // Copy (lvalue)
502 std::cout << " Pushed lvalue (copied)" << std::endl;
503
504 queue.push(std::string("rvalue")); // Move (rvalue)
505 std::cout << " Pushed rvalue (moved)" << std::endl;
506
507 queue.push("literal"); // Construct in place
508 std::cout << " Pushed literal (constructed)" << std::endl;
509
510 std::cout << "\n Popping items:" << std::endl;
511 while (auto item = queue.try_pop()) {
512     std::cout << " Popped: " << *item << std::endl;
513 }
514
515 std::cout << "\n Combines:" << std::endl;
516 std::cout << " • Concepts (ThreadSafeElement)" << std::endl;
517 std::cout << " • Perfect forwarding (std::forward)" << std::endl;
518 std::cout << " • requires clause (std::constructible_from)" << std::endl;
519 std::cout << " • Modern C++ (std::optional, std::mutex)" << std::endl;
520 }
521
522 // =====
523 // MAIN FUNCTION
524 // =====
525
526 int main() {
527     std::cout << "\n";
528     std::cout << " \n";
529     std::cout << " ADVANCED PERFECT FORWARDING & CONCEPTS
530             \n";
531     std::cout << " \n";
532     std::cout << " \n";
533
534     demonstrate_perfect_forwarding();
535     demonstrate_requires_syntax();
536     demonstrate_requires_requires();
537     demonstrate_forwarding_with_concepts();
538     explain_when_to_use_requires_requires();
539     demonstrate_readability();
540     explain_embedded_systems();
541     demonstrate_embedded_concepts();
542     compare_sfinae_vs_concepts();
543     demonstrate_complete_example();
544
545     std::cout << "\n" << std::string(70, '=') << std::endl;
```

```
546     std::cout << "SUMMARY:\n";
547     std::cout << std::string(70, '=') << std::endl;
548
549     std::cout << "\n KEY TAKEAWAYS:" << std::endl;
550     std::cout << "\n1. PERFECT FORWARDING:" << std::endl;
551     std::cout << " • Use T&& (universal reference) in templates" << std::endl;
552     std::cout << " • Always use std::forward<T> when forwarding" << std::endl;
553     std::cout << " • Preserves lvalue/rvalue value category" << std::endl;
554
555     std::cout << "\n2. 'REQUIRES REQUIRES':"
556     std::cout << " • First: starts constraint clause" << std::endl;
557     std::cout << " • Second: begins expression testing" << std::endl;
558     std::cout << " • Use for testing specific operations" << std::endl;
559     std::cout << " • Prefer named concepts for readability" << std::endl;
560
561     std::cout << "\n3. EMBEDDED SYSTEMS:"
562     std::cout << " • Zero runtime cost (compile-time only)" << std::endl;
563     std::cout << " • Perfect for safety-critical code" << std::endl;
564     std::cout << " • Use for register access, HAL, type safety" << std::endl;
565     std::cout << " • Watch compilation time and binary size" << std::endl;
566
567     std::cout << "\n4. BEST PRACTICES:"
568     std::cout << " • Use standard concepts when available" << std::endl;
569     std::cout << " • Name complex constraints as concepts" << std::endl;
570     std::cout << " • Prefer concepts over SFINAE" << std::endl;
571     std::cout << " • Document requirements clearly" << std::endl;
572
573     std::cout << "\n Modern C++ = Type Safety + Zero Cost\n" << std::endl;
574
575     return 0;
576 }
```

52 Source Code: PimplIdiom.cpp

File: [src/PimplIdiom.cpp](#)

Repository: [View on GitHub](#)

```
1 // =====
2 // PIMPL IDIOM IN MODERN C++ - STILL RELEVANT?
3 // =====
4 // Comprehensive guide covering:
5 // 1. What is Pimpl (Pointer to Implementation)?
6 // 2. Traditional benefits and use cases
7 // 3. Is it still relevant in Modern C++ (C++11/14/17/20/23)?
8 // 4. Performance implications (especially for real-time systems)
9 // 5. Cache locality and memory indirection problems
10 // 6. Alternatives and mitigations
11 // 7. When to use and when to avoid Pimpl
12 //
13 // KEY QUESTION: Why Pimpl may be BAD for real-time systems?
14 // ANSWER: Pointer indirection breaks cache locality, causes memory jumps,
15 //         unpredictable latency, and extra heap allocation overhead
16 //
17 // Build: g++ -std=c++20 -Wall -Wextra -O2 -o PimplIdiom PimplIdiom.cpp
18 // =====
19
20 #include <iostream>
21 #include <memory>
22 #include <string>
23 #include <vector>
24 #include <chrono>
25 #include <iomanip>
26
27 // =====
28 // SECTION 1: WHAT IS THE PIMPL IDIOM?
29 // =====
30
31 namespace what_is_pimpl {
32
33 // =====
34 // WITHOUT PIMPL - Traditional approach
35 // =====
36
37 // Widget.h (header file)
38 class WidgetNoPimpl {
39 private:
40     // ALL implementation details exposed in header
41     std::string name_;
42     int id_;
43     std::vector<double> data_;
44
45     // Private helper functions also exposed
46     void validateData();
47     void processInternal();
48
49 public:
```

```
50     WidgetNoPimpl(const std::string& name, int id);
51     ~WidgetNoPimpl();
52
53     void doSomething();
54     void process();
55 };
56
57 // PROBLEMS WITHOUT PIMPL:
58 // 1. All private members visible in header (no encapsulation)
59 // 2. Changing private members requires recompiling ALL clients
60 // 3. Implementation details leak to users
61 // 4. Longer compile times (includes propagate)
62 // 5. Binary compatibility issues (ABI breaks easily)
63
64 // =====
65 // WITH PIMPL - Pointer to Implementation
66 // =====
67
68 // Widget.h (header file)
69 class WidgetWithPimpl {
70 private:
71     // ONLY pointer to implementation - opaque pointer
72     struct Impl; // Forward declaration
73     std::unique_ptr<Impl> pImpl_;
74
75 public:
76     WidgetWithPimpl(const std::string& name, int id);
77     ~WidgetWithPimpl(); // Must be in .cpp (where Impl is complete)
78
79     // Move operations (copy disabled by default with unique_ptr)
80     WidgetWithPimpl(WidgetWithPimpl&&) noexcept;
81     WidgetWithPimpl& operator=(WidgetWithPimpl&&) noexcept;
82
83     void doSomething();
84     void process();
85 };
86
87 // Widget.cpp (implementation file)
88 struct WidgetWithPimpl::Impl {
89     // ALL implementation details hidden here
90     std::string name;
91     int id;
92     std::vector<double> data;
93
94     Impl(const std::string& n, int i) : name(n), id(i) {}
95
96     void validateData() {
97         std::cout << "      Validating data for " << name << "\n";
98     }
99
100    void processInternal() {
101        std::cout << "      Processing " << data.size() << " elements\n";
102    }
103};
```

```
104 // Implementation
105 WidgetWithPimpl::WidgetWithPimpl(const std::string& name, int id)
106     : pImpl_(std::make_unique<Impl>(name, id)) {
107     std::cout << "    WidgetWithPimpl constructed: " << name << "\n";
108 }
109
110 // Destructor must be in .cpp where Impl is complete type
111 WidgetWithPimpl::~WidgetWithPimpl() = default;
112
113 // Move operations
114 WidgetWithPimpl::WidgetWithPimpl(WidgetWithPimpl&&) noexcept = default;
115 WidgetWithPimpl& WidgetWithPimpl::operator=(WidgetWithPimpl&&) noexcept =
116     default;
117
118 void WidgetWithPimpl::doSomething() {
119     pImpl_->validateData();
120     std::cout << "    Doing something with " << pImpl_->name << "\n";
121 }
122
123 void WidgetWithPimpl::process() {
124     pImpl_->data.push_back(1.0);
125     pImpl_->data.push_back(2.0);
126     pImpl_->processInternal();
127 }
128
129 void demonstrate() {
130     std::cout << "\n" << std::string(80, '=') << "\n";
131     std::cout << "SECTION 1: WHAT IS THE PIMPL IDIOM?\n";
132     std::cout << std::string(80, '=') << "\n\n";
133
134     std::cout << "PIMPL = Pointer to IMPLementation (also called Opaque
135         Pointer)\n\n";
136
137     std::cout << "CONCEPT:\n";
138     std::cout << " • Public class holds ONLY a pointer to implementation\n";
139     std::cout << " • Implementation struct defined in .cpp file\n";
140     std::cout << " • All data members and private functions hidden in Impl\n"
141         ;
142     std::cout << " • Forwards all operations to pImpl pointer\n\n";
143
144     std::cout << "EXAMPLE:\n";
145     WidgetWithPimpl widget("Sensor", 42);
146     widget.doSomething();
147     widget.process();
148
149     std::cout << "\n TRADITIONAL BENEFITS:\n";
150     std::cout << "    1. COMPILETIME FIREWALL\n";
151     std::cout << " • Change private members without recompiling clients\n"
152         ;
153     std::cout << " • Faster incremental builds\n";
154     std::cout << " • Reduces header dependencies\n\n";
155
156     std::cout << "    2. BINARY COMPATIBILITY (ABI STABILITY)\n";
```

```
154     std::cout << " •      Can modify Impl without breaking ABI\n";
155     std::cout << " •      Important for shared libraries\n";
156     std::cout << " •      No need to relink client code\n\n";
157
158     std::cout << "   3. INFORMATION HIDING\n";
159     std::cout << " •      Private members truly hidden\n";
160     std::cout << " •      Can use incomplete types in Impl\n";
161     std::cout << " •      Better encapsulation\n\n";
162
163     std::cout << "   4. HEADER FILE SIMPLICITY\n";
164     std::cout << " •      Minimal includes in header\n";
165     std::cout << " •      Cleaner public interface\n";
166     std::cout << " •      Easier to read and maintain\n";
167 }
168
169 } // namespace what_is_pimpl
170
171 // =====
172 // SECTION 2: MODERN C++ IMPROVEMENTS - STILL RELEVANT?
173 // =====
174
175 namespace modern_cpp_pimpl {
176
177 // C++98: Raw pointer (manual memory management)
178 class WidgetCpp98 {
179 private:
180     struct Impl;
181     Impl* pImpl_; // Raw pointer
182
183 public:
184     WidgetCpp98();
185     ~WidgetCpp98();
186
187     // Rule of Three needed
188     WidgetCpp98(const WidgetCpp98&);
189     WidgetCpp98& operator=(const WidgetCpp98&);
190 };
191
192 // C++11: unique_ptr (automatic memory management)
193 class WidgetCpp11 {
194 private:
195     struct Impl;
196     std::unique_ptr<Impl> pImpl_; // Smart pointer
197
198 public:
199     WidgetCpp11();
200     ~WidgetCpp11(); // Still needed for incomplete type
201
202     // Rule of Five: Move-only by default (unique_ptr)
203     WidgetCpp11(WidgetCpp11&&) noexcept;
204     WidgetCpp11& operator=(WidgetCpp11&&) noexcept;
205
206     // Copy operations require custom implementation if needed
207     WidgetCpp11(const WidgetCpp11&) = delete;
```

```
208     WidgetCpp11& operator=(const WidgetCpp11&) = delete;
209 };
210
211 // C++11: shared_ptr (for copyable Pimpl)
212 class WidgetCpp11Shared {
213 private:
214     struct Impl;
215     std::shared_ptr<Impl> pImpl_; // Shared ownership
216
217 public:
218     WidgetCpp11Shared();
219     ~WidgetCpp11Shared() = default; // No explicit destructor needed!
220
221     // Copyable and movable by default
222     WidgetCpp11Shared(const WidgetCpp11Shared&) = default;
223     WidgetCpp11Shared& operator=(const WidgetCpp11Shared&) = default;
224     WidgetCpp11Shared(WidgetCpp11Shared&&) noexcept = default;
225     WidgetCpp11Shared& operator=(WidgetCpp11Shared&&) noexcept = default;
226 };
227
228 void demonstrate() {
229     std::cout << "\n" << std::string(80, '=') << "\n";
230     std::cout << "SECTION 2: MODERN C++ IMPROVEMENTS - STILL RELEVANT?\n";
231     std::cout << std::string(80, '=') << "\n\n";
232
233     std::cout << "EVOLUTION OF PIMPL:\n\n";
234
235     std::cout << "C++98: Raw pointer (manual memory management)\n";
236     std::cout << "    Manual new/delete\n";
237     std::cout << "    Must implement Rule of Three\n";
238     std::cout << "    Risk of memory leaks\n";
239     std::cout << "    Exception safety issues\n\n";
240
241     std::cout << "C++11: std::unique_ptr\n";
242     std::cout << "    Automatic memory management\n";
243     std::cout << "    Move-only by default\n";
244     std::cout << "    Exception safe\n";
245     std::cout << "    Still need destructor in .cpp (incomplete type)\n\n";
246
247     std::cout << "C++11: std::shared_ptr\n";
248     std::cout << "    Automatic memory management\n";
249     std::cout << "    Copyable by default\n";
250     std::cout << "    No destructor needed in .cpp!\n";
251     std::cout << "    Reference counting overhead\n";
252     std::cout << "    Two heap allocations (control block + Impl)\n\n";
253
254     std::cout << "IS PIMPL STILL RELEVANT IN MODERN C++?\n\n";
255
256     std::cout << "    YES, when you need:\n";
257     std::cout << "        1. BINARY STABILITY (shared libraries, plugins)\n";
258     std::cout << "            • Qt framework uses Pimpl extensively\n";
259     std::cout << "            • Windows API uses opaque handles (HWND, HANDLE)\n";
260     std::cout << "            • Linux kernel uses opaque pointers\n\n";
```

```
262     std::cout << "    2. COMPILATION FIREWALL (large projects)\n";
263     std::cout << " •      Reduce compilation dependencies\n";
264     std::cout << " •      Faster incremental builds\n";
265     std::cout << " •      Important for multi-million line codebases\n\n";
266
267     std::cout << "    3. INTERFACE STABILITY (APIs)\n";
268     std::cout << " •      Public interface never changes\n";
269     std::cout << " •      Implementation can evolve freely\n";
270     std::cout << " •      Versioning becomes easier\n\n";
271
272     std::cout << " LESS RELEVANT when:\n";
273     std::cout << " 1. Using header-only libraries (templates)\n";
274     std::cout << " 2. Internal classes (not exposed in API)\n";
275     std::cout << " 3. Performance-critical code (real-time systems)\n";
276     std::cout << " 4. Small classes with simple members\n";
277     std::cout << " 5. Using modules (C++20) - reduces header dependencies\n"
278     ;
279 }
280 } // namespace modern_cpp_pimpl
281
282 // =====
283 // SECTION 3: PERFORMANCE PROBLEMS - THE REAL-TIME KILLER
284 // =====
285
286 namespace performance_problems {
287
288 // Simple data structure for testing
289 struct SensorData {
290     int id;
291     double value;
292     int64_t timestamp;
293
294     SensorData(int i = 0, double v = 0.0)
295         : id(i), value(v), timestamp(0) {}
296 };
297
298 // =====
299 // VERSION 1: NO PIMPL - Direct data access
300 // =====
301
302 class SensorNoPimpl {
303 private:
304     int id_;
305     double value_;
306     int64_t timestamp_;
307
308 public:
309     SensorNoPimpl(int id, double value)
310         : id_(id), value_(value), timestamp_(0) {}
311
312     void update(double new_value) {
313         value_ = new_value;
314         timestamp_++;
315     }
316 }
```

```
315     }
316
317     double getValue() const { return value_; }
318     int getId() const { return id_; }
319 };
320
321 // =====
322 // VERSION 2: WITH PIMPL - Pointer indirection
323 // =====
324
325 class SensorWithPimpl {
326 private:
327     struct Impl {
328         int id;
329         double value;
330         int64_t timestamp;
331
332         Impl(int i, double v) : id(i), value(v), timestamp(0) {}
333     };
334
335     std::unique_ptr<Impl> pImpl_;
336
337 public:
338     SensorWithPimpl(int id, double value)
339         : pImpl_(std::make_unique<Impl>(id, value)) {}
340
341     ~SensorWithPimpl() = default;
342
343     void update(double new_value) {
344         pImpl_->value = new_value;
345         pImpl_->timestamp++;
346     }
347
348     double getValue() const { return pImpl_->value; }
349     int getId() const { return pImpl_->id; }
350 };
351
352 void demonstrate() {
353     std::cout << "\n" << std::string(80, '=') << "\n";
354     std::cout << "SECTION 3: PERFORMANCE PROBLEMS - THE REAL-TIME KILLER\n";
355     std::cout << std::string(80, '=') << "\n\n";
356
357     std::cout << "PROBLEM 1: POINTER INDIRECTION OVERHEAD\n\n";
358
359     std::cout << "Without Pimpl:\n";
360     std::cout << "    sensor.getValue() → Direct access: sensor.value_\n";
361     std::cout << "    • ONE memory access\n";
362     std::cout << "    • CPU loads value directly from sensor object\n";
363     std::cout << "    • Predictable: O(1) memory access\n\n";
364
365     std::cout << "With Pimpl:\n";
366     std::cout << "    sensor.getValue() → sensor.pImpl_->value\n";
367     std::cout << "    • TWO memory accesses:\n";
368     std::cout << "        1. Load pImpl_ pointer from sensor object\n";
```

```
369     std::cout << "      2. Follow pointer to load value from Impl\n";
370     std::cout << " •  Unpredictable: pointer could point anywhere in heap\n\n"
371         ;
372 
373     std::cout << "PROBLEM 2: CACHE LOCALITY DESTROYED\n\n";
374 
375     std::cout << "Without Pimpl (Array of sensors):\n";
376     std::cout << "    Memory layout: [Sensor1][Sensor2][Sensor3][Sensor4]\n";
377     std::cout << " •  Contiguous memory (cache-friendly)\n";
378     std::cout << " •  CPU prefetcher loads next sensors automatically\n";
379     std::cout << " •  All data in same cache line (64 bytes)\n\n";
380 
381     std::cout << "With Pimpl (Array of sensors):\n";
382     std::cout << "    Memory layout: [Sensor1->*]Impl1 [Sensor2->*]Impl2\n";
383     std::cout << "                      scattered           scattered\n";
384     std::cout << "                      in heap            in heap\n";
385     std::cout << " •  Impl objects scattered across heap (cache-hostile)\n";
386     std::cout << " •  Each access causes cache miss\n";
387     std::cout << " •  CPU prefetcher cannot predict pattern\n";
388     std::cout << " •  Every pointer dereference = potential cache miss\n\n";
389 
390     std::cout << "PROBLEM 3: HEAP ALLOCATION OVERHEAD\n\n";
391 
392     std::cout << "Without Pimpl:\n";
393     std::cout << "    SensorNoPimpl sensor(1, 3.14); // Stack allocation\n";
394     std::cout << " •  O(1) construction time\n";
395     std::cout << " •  No malloc/free overhead\n";
396     std::cout << " •  Deterministic\n\n";
397 
398     std::cout << "With Pimpl:\n";
399     std::cout << "    SensorWithPimpl sensor(1, 3.14); // Heap allocation!\n";
400     std::cout << " •  Calls malloc() for Impl\n";
401     std::cout << " •  O(?) allocation time (non-deterministic)\n";
402     std::cout << " •  Heap fragmentation over time\n";
403     std::cout << " •  Destructor calls free() (non-deterministic)\n\n";
404 
405     // Benchmark
406     constexpr int ITERATIONS = 1000000;
407 
408     std::cout << "BENCHMARK: " << ITERATIONS << " operations\n\n";
409 
410     // Test 1: No Pimpl
411     {
412         SensorNoPimpl sensor(1, 100.0);
413         auto start = std::chrono::high_resolution_clock::now();
414 
415         for (int i = 0; i < ITERATIONS; ++i) {
416             sensor.update(i * 0.1);
417             [[maybe_unused]] volatile double val = sensor.getValue();
418         }
419 
420         auto end = std::chrono::high_resolution_clock::now();
421         auto duration = std::chrono::duration_cast<std::chrono::microseconds>(
422             end - start);
```

```
421     std::cout << " WITHOUT Pimpl: " << std::setw(8) << duration.count()
422             << " s\n";
423 }
424
425 // Test 2: With Pimpl
426 {
427     SensorWithPimpl sensor(1, 100.0);
428     auto start = std::chrono::high_resolution_clock::now();
429
430     for (int i = 0; i < ITERATIONS; ++i) {
431         sensor.update(i * 0.1);
432         [[maybe_unused]] volatile double val = sensor.getValue();
433     }
434
435     auto end = std::chrono::high_resolution_clock::now();
436     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(
437                     end - start);
438
439     std::cout << " WITH Pimpl: " << std::setw(8) << duration.count()
440             << " s\n";
441 }
442
443 std::cout << "\n PIMPL OVERHEAD:\n";
444 std::cout << " • 50-200% slower (depends on cache behavior)\n";
445 std::cout << " • Non-deterministic timing variations\n";
446 std::cout << " • Extra heap allocation per object\n";
447 std::cout << " • Destroys cache locality\n";
448 }
449
450 // =====
451 // SECTION 4: WHY PIMPL IS BAD FOR REAL-TIME SYSTEMS
452 // =====
453
454 namespace realtime_problems {
455
456 void demonstrate() {
457     std::cout << "\n" << std::string(80, '=') << "\n";
458     std::cout << "SECTION 4: WHY PIMPL IS BAD FOR REAL-TIME SYSTEMS\n";
459     std::cout << std::string(80, '=') << "\n\n";
460
461     std::cout << "REAL-TIME SYSTEM REQUIREMENTS:\n";
462     std::cout << " 1. DETERMINISTIC TIMING - Predictable worst-case execution
463                 time (WCET)\n";
464     std::cout << " 2. BOUNDED LATENCY - Maximum response time guaranteed\n";
465     std::cout << " 3. NO HEAP ALLOCATION - At runtime (malloc/free non-
466                 deterministic)\n";
467     std::cout << " 4. CACHE PREDICTABILITY - Minimize cache misses\n";
468     std::cout << " 5. NO MEMORY JUMPS - Sequential memory access for
469                 prefetcher\n\n";
470
471     std::cout << "PIMPL VIOLATIONS:\n\n";
```

```

469
470     std::cout << "  VIOLATION 1: NON-DETERMINISTIC HEAP ALLOCATION\n";
471     std::cout << "    Problem:\n";
472     std::cout << "    •      Each Pimpl object requires malloc() for Impl\n";
473     std::cout << "    •      malloc() time depends on heap state (fragmentation)\n"
474     ";\n";
475     std::cout << "    •      WCET becomes unpredictable\n";
476     std::cout << "    Impact on Real-Time:\n";
477     std::cout << "    •      Cannot prove deadline guarantees\n";
478     std::cout << "    •      Violates MISRA C++ Rule 18-4-1 (no dynamic allocation\n"
479     ")\n";
480     std::cout << "    •      Violates ISO 26262 (automotive safety) guidelines\n";
481     std::cout << "    •      Unacceptable for hard real-time (ASIL-D)\n\n";
482
483     std::cout << "  VIOLATION 2: POINTER INDIRECTION = CACHE MISSES\n";
484     std::cout << "    Problem:\n";
485     std::cout << "    •      Every operation requires following pImpl_ pointer\n";
486     std::cout << "    •      Impl object allocated somewhere in heap\n";
487     std::cout << "    •      High probability of cache miss on every access\n";
488     std::cout << "    Impact on Real-Time:\n";
489     std::cout << "    •      Cache miss = 100+ cycles (vs 1 cycle for cache hit)\n"
490     ";\n";
491     std::cout << "    •      Unpredictable latency spikes\n";
492     std::cout << "    •      Worst-case timing analysis becomes pessimistic\n";
493     std::cout << "    •      May cause deadline misses in tight loops\n\n";
494
495     std::cout << "  VIOLATION 3: DESTROYED CACHE LOCALITY\n";
496     std::cout << "    Problem:\n";
497     std::cout << "    •      Array of Pimpl objects:\n";
498     std::cout << "    [Obj1 ptr] Impl1 (heap addr 0x1000)\n";
499     std::cout << "    [Obj2 ptr] Impl2 (heap addr 0x5000) ← 16KB away!\n";
500     std::cout << "    [Obj3 ptr] Impl3 (heap addr 0x2000)\n";
501     std::cout << "    •      Each Impl scattered randomly in heap\n";
502     std::cout << "    •      CPU prefetcher cannot help\n";
503     std::cout << "    Impact on Real-Time:\n";
504     std::cout << "    •      Sequential access becomes random access\n";
505     std::cout << "    •      10-100x slower than contiguous data\n";
506     std::cout << "    •      Unacceptable for sensor processing, control loops\n\n"
507     ";\n";
508
509     std::cout << "  VIOLATION 4: HEAP FRAGMENTATION OVER TIME\n";
510     std::cout << "    Problem:\n";
511     std::cout << "    •      Repeated allocation/deallocation of Impl objects\n";
512     std::cout << "    •      Heap becomes fragmented (Swiss cheese memory)\n";
513     std::cout << "    •      Allocation time increases over time\n";
514     std::cout << "    Impact on Real-Time:\n";
515     std::cout << "    •      System degrades over runtime\n";
516     std::cout << "    •      May fail after hours/days of operation\n";
517     std::cout << "    •      Cannot certify for long-running systems\n";
518     std::cout << "    •      Requires periodic restart (unacceptable)\n\n";
519
520     std::cout << "  VIOLATION 5: DOUBLE DEALLOCATION (shared_ptr Pimpl)\n";
521     std::cout << "    Problem:\n";
522     std::cout << "    •      shared_ptr has control block (heap allocation)\n";

```

```

519 std::cout << " • Plus Impl object (another heap allocation)\n";
520 std::cout << " • TWO heap operations per object\n";
521 std::cout << " • Reference counting overhead on every copy\n";
522 std::cout << " • Impact on Real-Time:\n";
523 std::cout << " • Doubles the allocation overhead\n";
524 std::cout << " • Atomic operations for ref counting (slow)\n";
525 std::cout << " • Even worse for real-time systems\n\n";
526
527 std::cout << "REAL-WORLD EXAMPLE:\n\n";
528 std::cout << "Scenario: Automotive ECU processing 100 sensor values at 1
      kHz\n\n";
529
530 std::cout << "WITHOUT Pimpl:\n";
531 std::cout << " • struct Sensor { int id; double value; };\n";
532 std::cout << " • std::array<Sensor, 100> sensors; // Contiguous, no heap
      \n";
533 std::cout << " • for (auto& s : sensors) process(s.value); // Cache-
      friendly\n";
534 std::cout << " • Total time: ~500 cycles (all in cache)\n";
535 std::cout << " • Deterministic: Always 500 ± 10 cycles\n";
536 std::cout << " • PASSES WCET analysis\n\n";
537
538 std::cout << "WITH Pimpl:\n";
539 std::cout << " • class Sensor { unique_ptr<Impl> pImpl_; };\n";
540 std::cout << " • std::array<Sensor, 100> sensors; // 100 heap
      allocations!\n";
541 std::cout << " • for (auto& s : sensors) process(s->value); // Cache
      misses\n";
542 std::cout << " • Total time: ~5000-50000 cycles (cache misses)\n";
543 std::cout << " • Non-deterministic: 5000-50000 cycles (10x variation!)\n"
      ;
544 std::cout << " • FAILS WCET analysis (unpredictable)\n\n";
545
546 std::cout << "STANDARDS VIOLATIONS:\n\n";
547 std::cout << " • MISRA C++ Rule 18-4-1: Dynamic heap allocation shall not
      be used\n";
548 std::cout << " • AUTOSAR A18-5-1: malloc/calloc/realloc/free shall not be
      used\n";
549 std::cout << " • ISO 26262 (ASIL-D): Static allocation required\n";
550 std::cout << " • DO-178C Level A: Dynamic allocation discouraged\n";
551 std::cout << " • JSF AV C++ Rule 207: new/delete not used after
      initialization\n\n";
552
553 std::cout << "VERDICT: PIMPL IS FORBIDDEN IN REAL-TIME SYSTEMS\n";
554 }
555
556 } // namespace realtime_problems
557
558 // =====
559 // SECTION 5: ALTERNATIVES AND MITIGATIONS
560 // =====
561
562 namespace alternatives {
563

```

```
564 // =====
565 // ALTERNATIVE 1: NO PIMPL - Expose implementation (if acceptable)
566 // =====
567
568 class DirectImplementation {
569 private:
570     int id_;
571     double value_;
572
573 public:
574     DirectImplementation(int id, double value) : id_(id), value_(value) {}
575
576     void process() { value_ *= 2.0; }
577     double getValue() const { return value_; }
578 };
579
580 // Pros: Fast, cache-friendly, deterministic
581 // Cons: Breaks ABI on changes, longer compile times
582
583 // =====
584 // ALTERNATIVE 2: FAST PIMPL - Pre-allocated storage
585 // =====
586
587 template<typename T, size_t Size, size_t Alignment = alignof(std::max_align_t)>
588 class FastPimpl {
589 private:
590     alignas(Alignment) std::byte storage_[Size];
591
592     T* ptr() { return reinterpret_cast<T*>(storage_); }
593     const T* ptr() const { return reinterpret_cast<const T*>(storage_); }
594
595 public:
596     template<typename... Args>
597     FastPimpl(Args&&... args) {
598         static_assert(sizeof(T) <= Size, "Storage too small");
599         static_assert(alignof(T) <= Alignment, "Alignment too small");
600         new (storage_) T(std::forward<Args>(args)...);
601     }
602
603     ~FastPimpl() { ptr()~T(); }
604
605     // Delete copy/move (or implement if needed)
606     FastPimpl(const FastPimpl&) = delete;
607     FastPimpl& operator=(const FastPimpl&) = delete;
608
609     T* operator->() { return ptr(); }
610     const T* operator->() const { return ptr(); }
611
612     T& operator*() { return *ptr(); }
613     const T& operator*() const { return *ptr(); }
614 };
615
616 class SensorFastPimpl {
```

```

617 private:
618     struct Impl {
619         int id;
620         double value;
621         Impl(int i, double v) : id(i), value(v) {}
622         void process() { value *= 2.0; }
623     };
624
625     FastPimpl<Impl, 32> pImpl_; // Storage in object itself!
626
627 public:
628     SensorFastPimpl(int id, double value) : pImpl_(id, value) {}
629
630     void process() { pImpl_->process(); }
631     double getValue() const { return pImpl_->value; }
632 };
633
634 // Pros: NO heap allocation, cache-friendly, ABI stable (if size doesn't
635 // change)
636 // Cons: Must know maximum Impl size at compile time
637 // =====
638 // ALTERNATIVE 3: Type Erasure (std::function style)
639 // =====
640
641 class TypeErasedSensor {
642 private:
643     struct ConceptBase {
644         virtual ~ConceptBase() = default;
645         virtual void process() = 0;
646         virtual double getValue() const = 0;
647         virtual std::unique_ptr<ConceptBase> clone() const = 0;
648     };
649
650     template<typename T>
651     struct ConceptModel : ConceptBase {
652         T data;
653
654         ConceptModel(T d) : data(std::move(d)) {}
655
656         void process() override { data.process(); }
657         double getValue() const override { return data.getValue(); }
658         std::unique_ptr<ConceptBase> clone() const override {
659             return std::make_unique<ConceptModel<T>>(data);
660         }
661     };
662
663     std::unique_ptr<ConceptBase> pImpl_;
664
665 public:
666     template<typename T>
667     TypeErasedSensor(T sensor)
668         : pImpl_(std::make_unique<ConceptModel<T>>(std::move(sensor))) {}
669

```

```
670     void process() { pImpl_->process(); }
671     double getValue() const { return pImpl_->getValue(); }
672 };
673
674 // Pros: Flexible, any type works, no template in interface
675 // Cons: Still uses heap, virtual function overhead
676
677 // =====
678 // ALTERNATIVE 4: SBO (Small Buffer Optimization) Pimpl
679 // =====
680
681 template<size_t BufferSize = 64>
682 class SBOPimpl {
683 private:
684     alignas(std::max_align_t) std::byte buffer_[BufferSize];
685     void* heap_ptr_ = nullptr;
686
687     void* storage() { return heap_ptr_ ? heap_ptr_ : buffer_; }
688     const void* storage() const { return heap_ptr_ ? heap_ptr_ : buffer_; }
689
690 public:
691     template<typename T, typename... Args>
692     void emplace(Args&&... args) {
693         if (sizeof(T) <= BufferSize && alignof(T) <= alignof(std::max_align_t))
694             {
695                 // Small: use buffer (no heap)
696                 new (buffer_) T(std::forward<Args>(args)...);
697                 heap_ptr_ = nullptr;
698             } else {
699                 // Large: use heap
700                 heap_ptr_ = new T(std::forward<Args>(args)...);
701             }
702     }
703
704     T* get() { return static_cast<T*>(storage()); }
705
706     template<typename T>
707     const T* get() const { return static_cast<const T*>(storage()); }
708
709     ~SBOPimpl() {
710         if (heap_ptr_) {
711             // Must know type to delete - requires type erasure
712         }
713     }
714 };
715
716 // Pros: Avoids heap for small objects
717 // Cons: Complex, requires type erasure for destruction
718
719 // =====
720 // ALTERNATIVE 5: Interface Segregation + Direct Storage
721 // =====
```

```

723 // Pure interface (header file)
724 class ISensor {
725 public:
726     virtual ~ISensor() = default;
727     virtual void process() = 0;
728     virtual double getValue() const = 0;
729 };
730
731 // Concrete implementation (cpp file)
732 class ConcreteSensor : public ISensor {
733 private:
734     int id_;
735     double value_;
736
737 public:
738     ConcreteSensor(int id, double value) : id_(id), value_(value) {}
739
740     void process() override { value_ *= 2.0; }
741     double getValue() const override { return value_; }
742 };
743
744 // Factory function (cpp file)
745 std::unique_ptr<ISensor> createSensor(int id, double value) {
746     return std::make_unique<ConcreteSensor>(id, value);
747 }
748
749 // Pros: Clean interface, implementation hidden
750 // Cons: Still uses heap, virtual function overhead
751
752 void demonstrate() {
753     std::cout << "\n" << std::string(80, '=') << "\n";
754     std::cout << "SECTION 5: ALTERNATIVES AND MITIGATIONS\n";
755     std::cout << std::string(80, '=') << "\n\n";
756
757     std::cout << "ALTERNATIVE 1: NO PIMPL (Direct Implementation)\n";
758     std::cout << "    BEST for performance and real-time systems\n";
759     std::cout << "    Zero overhead, cache-friendly\n";
760     std::cout << "    Breaks ABI on changes\n";
761     std::cout << "    Longer compile times\n";
762     std::cout << "    USE WHEN: Performance critical, internal classes\n\n";
763
764     DirectImplementation direct(1, 100.0);
765     direct.process();
766     std::cout << "    Example: Direct value = " << direct.getValue() << "\n\n";
767
768     std::cout << "ALTERNATIVE 2: FAST PIMPL (Pre-allocated storage)\n";
769     std::cout << "    NO heap allocation (storage in object)\n";
770     std::cout << "    Cache-friendly (contiguous memory)\n";
771     std::cout << "    ABI stable (if size doesn't change)\n";
772     std::cout << "    Must know maximum Impl size\n";
773     std::cout << "    USE WHEN: Need ABI stability + performance\n\n";
774
775     SensorFastPimpl fast(1, 100.0);
776     fast.process();

```

```

777 std::cout << " Example: FastPimpl value = " << fast.getValue() << "\n\n";
778
779 std::cout << " ALTERNATIVE 3: TYPE ERASURE\n";
780 std::cout << "     Flexible (any type works)\n";
781 std::cout << "     Clean generic interface\n";
782 std::cout << "     Still uses heap\n";
783 std::cout << "     Virtual function overhead\n";
784 std::cout << " USE WHEN: Need runtime polymorphism\n\n";
785
786 std::cout << " ALTERNATIVE 4: SBO (Small Buffer Optimization)\n";
787 std::cout << "     Avoids heap for small objects\n";
788 std::cout << "     Fallback to heap for large objects\n";
789 std::cout << "     Complex implementation\n";
790 std::cout << "     Similar to std::string SSO\n";
791 std::cout << " USE WHEN: Mix of small and large objects\n\n";
792
793 std::cout << " ALTERNATIVE 5: INTERFACE + FACTORY\n";
794 std::cout << "     Clean separation of interface/implementation\n";
795 std::cout << "     Implementation hidden in .cpp\n";
796 std::cout << "     Still uses heap\n";
797 std::cout << "     Virtual function overhead\n";
798 std::cout << " USE WHEN: Need polymorphism + information hiding\n\n";
799
800 std::cout << " MITIGATION STRATEGIES FOR REAL-TIME:\n\n";
801
802 std::cout << " 1. INITIALIZATION PHASE PATTERN\n";
803 std::cout << "   • Allocate ALL Pimpl objects during initialization\n";
804 std::cout << "   • Use object pools (pre-allocated)\n";
805 std::cout << "   • Never allocate/deallocate during runtime\n";
806 std::cout << "   • Acceptable: init phase not time-critical\n\n";
807
808 std::cout << " 2. CUSTOM POOL ALLOCATOR\n";
809 std::cout << "   • Pre-allocate pool of Impl objects\n";
810 std::cout << "   • Custom allocator for unique_ptr<Impl>\n";
811 std::cout << "   • Bounded, deterministic allocation\n";
812 std::cout << "   • Improves cache locality (pool in contiguous memory)\n\n";
813
814 std::cout << " 3. PLACEMENT NEW IN FIXED BUFFER\n";
815 std::cout << "   • Static buffer for all Impl objects\n";
816 std::cout << "   • Placement new to construct in buffer\n";
817 std::cout << "   • Zero heap allocation\n";
818 std::cout << "   • Requires careful lifetime management\n\n";
819
820 std::cout << " 4. C++20 MODULES\n";
821 std::cout << "   • Reduce need for Pimpl (compilation firewall)\n";
822 std::cout << "   • Faster builds without Pimpl overhead\n";
823 std::cout << "   • Still evolving, limited tooling support\n\n";
824
825 std::cout << " RECOMMENDATION FOR REAL-TIME SYSTEMS:\n\n";
826 std::cout << "   FIRST CHOICE: No Pimpl (Direct implementation)\n";
827 std::cout << "   • Best performance\n";
828 std::cout << "   • Deterministic\n";
829 std::cout << "   • Accept longer compile times as trade-off\n\n";

```

```

830
831     std::cout << "      SECOND CHOICE: FastPimpl (in-object storage)\n";
832     std::cout << " •      Good compromise\n";
833     std::cout << " •      No heap, ABI stable\n";
834     std::cout << " •      Requires careful sizing\n\n";
835
836     std::cout << "      THIRD CHOICE: Pimpl with pool allocator\n";
837     std::cout << " •      Acceptable with pre-allocation\n";
838     std::cout << " •      Only during initialization phase\n";
839     std::cout << " •      Requires justification for certification\n\n";
840
841     std::cout << "      NEVER: Traditional heap-based Pimpl at runtime\n";
842     std::cout << " •      Non-deterministic\n";
843     std::cout << " •      Violates real-time standards\n";
844     std::cout << " •      Unacceptable for safety-critical systems\n";
845 }
846
847 } // namespace alternatives
848
849 // =====
850 // SECTION 6: DECISION GUIDE
851 // =====
852
853 namespace decision_guide {
854
855 void demonstrate() {
856     std::cout << "\n" << std::string(80, '=') << "\n";
857     std::cout << "SECTION 6: WHEN TO USE PIMPL - DECISION GUIDE\n";
858     std::cout << std::string(80, '=') << "\n\n";
859
860     std::cout << "DECISION TREE:\n\n";
861
862     std::cout << "    Q1: Is this a real-time or safety-critical system?\n";
863     std::cout << "\n";
864     std::cout << "    YES → AVOID PIMPL (use direct implementation or FastPimpl
865         )\n";
866     std::cout << "                Reason: Non-deterministic, cache-hostile, heap
867         allocation\n";
868     std::cout << "\n";
869     std::cout << "    NO → Continue to Q2\n\n";
870
871     std::cout << "    Q2: Is this a public API/library interface?\n";
872     std::cout << "\n";
873     std::cout << "    YES → Continue to Q3\n";
874     std::cout << "\n";
875     std::cout << "    NO → DON'T USE PIMPL (internal class - direct impl)\n\n";
876
877     std::cout << "    Q3: Do you need ABI (binary) stability?\n";
878     std::cout << "\n";
879     std::cout << "    YES → Continue to Q4\n";
880     std::cout << "\n";
881     std::cout << "    NO → DON'T USE PIMPL (recompilation acceptable)\n\n";
882
883     std::cout << "    Q4: Is the class performance-critical (hot path)?\n";

```

```

882     std::cout << "\n";
883     std::cout << " YES → RECONSIDER Pimpl (profile first, consider
884         FastPimpl)\n";
885     std::cout << "\n";
886     std::cout << " NO → Continue to Q5\n\n";
887
887     std::cout << " Q5: Is the implementation complex/large?\n";
888     std::cout << "\n";
889     std::cout << " YES → USE PIMPL (good candidate)\n";
890     std::cout << "\n";
891     std::cout << " NO → Probably not worth it (overhead > benefit)\n\n";
892
893     std::cout << std::string(80, '-') << "\n\n";
894
895     std::cout << "COMPARISON TABLE:\n\n";
896     std::cout << "                                     \n";
897     std::cout << " CRITERION          NO PIMPL    PIMPL    FAST PIMPL   REAL-
898         TIME OK? \n";
898     std::cout << "                                     \n";
899     std::cout << " Performance        BEST      POOR      GOOD      /   /
900         \n";
900     std::cout << " Cache Locality     BEST      WORST      BEST      /   /
901         \n";
901     std::cout << " Heap Allocation     NO       YES       NO       /   /
902         \n";
902     std::cout << " ABI Stability      NO       YES       PARTIAL   N/A
903         \n";
903     std::cout << " Compile Time        SLOW      FAST      FAST      N/A
904         \n";
904     std::cout << " Information Hiding  NO       YES       YES      N/A
905         \n";
905     std::cout << " Complexity          LOW      MEDIUM    HIGH     N/A
906         \n";
906     std::cout << " Memory Overhead    0 bytes  8 bytes  Impl size  N/A
907         \n";
907     std::cout << "                                     \n\n";
908
909     std::cout << "USE PIMPL WHEN:\n\n";
910     std::cout << "     Shipping shared libraries (ABI stability critical)\n";
911     std::cout << "         Examples: Qt, wxWidgets, system libraries\n\n";
912
913     std::cout << "     Plugin architectures (binary compatibility)\n";
914     std::cout << "         Examples: Audio plugins, game engines\n\n";
915
916     std::cout << "     Large complex implementations (compilation firewall)\n";
917     std::cout << "         Examples: GUI frameworks, network libraries\n\n";
918
919     std::cout << "     Platform-specific code (hide platform details)\n";
920     std::cout << "         Examples: Cross-platform libraries\n\n";
921
922     std::cout << "AVOID PIMPL WHEN:\n\n";
923     std::cout << "     Real-time systems (non-deterministic)\n";
924     std::cout << "         Examples: Control systems, DSP, robotics\n\n";
925

```

```
926     std::cout << "    Performance-critical code (cache-hostile)\n";
927     std::cout << "        Examples: Game engines, HFT, rendering\n\n";
928
929     std::cout << "    Safety-critical systems (heap allocation)\n";
930     std::cout << "        Examples: Automotive (ISO 26262), avionics (DO-178C)\n\n";
931
932     std::cout << "    Small simple classes (overhead > benefit)\n";
933     std::cout << "        Examples: POD types, value types\n\n";
934
935     std::cout << "    Internal implementation classes (not exposed)\n";
936     std::cout << "        Examples: Private helpers, implementation details\n\n";
937
938     std::cout << "    Header-only libraries (templates)\n";
939     std::cout << "        Examples: Template libraries, generic code\n\n";
940
941     std::cout << "    Using C++20 modules (reduces need)\n";
942     std::cout << "        Examples: Modern codebases with module support\n\n";
943
944     std::cout << "FAMOUS LIBRARIES USING PIMPL:\n\n";
945     std::cout << "    • Qt Framework - Extensive use for ABI stability\n";
946     std::cout << "    • Boost.Aasio - Some classes use Pimpl\n";
947     std::cout << "    • Windows API - HWND, HANDLE (opaque pointers)\n";
948     std::cout << "    • OpenSSL - Internal structures hidden\n";
949     std::cout << "    • wxWidgets - Cross-platform abstraction\n\n";
950
951     std::cout << "GOLDEN RULES:\n\n";
952     std::cout << "    1. Pimpl is a DESIGN PATTERN, not a default choice\n";
953     std::cout << "    2. Only use when benefits outweigh performance cost\n";
954     std::cout << "    3. Profile before and after - measure the impact\n";
955     std::cout << "    4. Consider FastPimpl for real-time constraints\n";
956     std::cout << "    5. Never use traditional Pimpl in real-time code\n";
957     std::cout << "    6. C++20 modules may reduce need for Pimpl\n";
958 }
959
960 } // namespace decision_guide
961
962 // =====
963 // MAIN
964 // =====
965
966 int main() {
967     std::cout << "\n" << std::string(80, '=') << "\n";
968     std::cout << "PIMPL IDIOM IN MODERN C++ - STILL RELEVANT?\n";
969     std::cout << "Performance Impact on Real-Time Systems\n";
970     std::cout << std::string(80, '=') << "\n";
971
972     what_is_pimpl::demonstrate();
973     modern_cpp_pimpl::demonstrate();
974     performance_problems::demonstrate();
975     realtime_problems::demonstrate();
976     alternatives::demonstrate();
977     decision_guide::demonstrate();
978 }
```

```
979     std::cout << "\n" << std::string(80, '=') << "\n";
980     std::cout << "FINAL VERDICT\n";
981     std::cout << std::string(80, '=') << "\n\n";
982
983     std::cout << "IS PIMPL STILL RELEVANT IN MODERN C++?\n\n";
984
985     std::cout << " YES, for:\n";
986     std::cout << " • Shared libraries requiring ABI stability\n";
987     std::cout << " • Large projects needing compilation firewalls\n";
988     std::cout << " • Public APIs with evolving implementation\n";
989     std::cout << " • Modern C++ makes it easier (unique_ptr, shared_ptr)\n\n";
990     ";
991
992     std::cout << " NO (AVOID), for:\n";
993     std::cout << " • Real-time systems - NON-DETERMINISTIC\n";
994     std::cout << " • Safety-critical systems - HEAP ALLOCATION\n";
995     std::cout << " • Performance-critical code - CACHE-HOSTILE\n";
996     std::cout << " • Simple classes - OVERHEAD > BENEFIT\n\n";
997
998     std::cout << "WHY PIMPL IS BAD FOR REAL-TIME:\n\n";
999     std::cout << " 1. POINTER INDIRECTNESS - Extra memory access (cache miss)\n";
1000    std::cout << " 2. DESTROYED CACHE LOCALITY - Scattered Impl objects in
1001       heap\n";
1002    std::cout << " 3. HEAP ALLOCATION - Non-deterministic malloc/free\n";
1003    std::cout << " 4. MEMORY JUMPS - CPU prefetcher cannot help\n";
1004    std::cout << " 5. FRAGMENTATION - System degrades over time\n\n";
1005
1006    std::cout << "MITIGATION OPTIONS:\n\n";
1007    std::cout << " FastPimpl (in-object storage) - Zero heap, cache-
1008      friendly\n";
1009    std::cout << " Pre-allocated pools - Bounded allocation during init\n";
1010    std::cout << " No Pimpl - Accept longer compile times for performance\n
1011      \n";
1012
1013    std::cout << "BOTTOM LINE:\n\n";
1014    std::cout << " Pimpl is still relevant for APIs and libraries,\n";
1015    std::cout << " but should be AVOIDED in real-time and performance-
1016      critical code.\n";
1017    std::cout << " The pointer indirection and heap allocation make it\n";
1018    std::cout << " fundamentally incompatible with deterministic real-time
1019      systems.\n\n";
1020
1021    std::cout << std::string(80, '=') << "\n\n";
1022
1023    return 0;
1024 }
```

53 Source Code: ProtobufExample.cpp

File: src/ProtobufExample.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // GOOGLE PROTOCOL BUFFERS (PROTOBUF) EXAMPLE
3 // =====
4 // This example demonstrates Protocol Buffers usage in modern C++.
5 //
6 // TOPICS COVERED:
7 // 1. Creating and populating protobuf messages
8 // 2. Serialization to binary format
9 // 3. Deserialization from binary format
10 // 4. JSON conversion (protobuf v3 feature)
11 // 5. Nested messages and repeated fields
12 // 6. Enums and oneof fields
13 // 7. Performance and memory efficiency
14 // 8. Best practices for embedded systems
15 //
16 // WHAT IS PROTOCOL BUFFERS?
17 // - Language-neutral, platform-neutral serialization format
18 // - Smaller, faster, and simpler than XML/JSON
19 // - Generates code for multiple languages (C++, Python, Java, Go, etc.)
20 // - Backward/forward compatible with schema evolution
21 // - Used by Google, Netflix, Uber, and many others
22 //
23 // WHY USE PROTOBUF?
24 // Efficient: 3-10x smaller than XML, 20-100x faster
25 // Type-safe: Strong typing with generated code
26 // Versioned: Schema evolution with backward compatibility
27 // Cross-language: Same .proto file works for multiple languages
28 // Validated: Automatic validation of message structure
29 //
30 // BUILD REQUIREMENTS:
31 // - Google Protocol Buffers library (libprotobuf-dev)
32 // - protoc compiler to generate C++ code from .proto files
33 //
34 // =====
35
36 #include <iostream>
37 #include <fstream>
38 #include <memory>
39 #include <chrono>
40 #include <iomanip>
41
42 // Include generated protobuf headers
43 // These are generated by protoc from sensor_data.proto
44 // #include "sensor_data.pb.h"
45
46 // Include generated protobuf headers
47 // These are generated by protoc from sensor_data.proto
48 #include "sensor_data.pb.h"
49
```

```
50 // =====
51 // EXAMPLE 1: CREATING AND POPULATING MESSAGES
52 // =====
53
54 void example_create_sensor_reading() {
55     std::cout << "==== Example 1: Creating Sensor Reading ===\n";
56
57     // Create a temperature sensor reading
58     sensors::SensorReading reading;
59
60     // Set basic fields
61     reading.set_type(sensors::TEMPERATURE);
62     reading.set_device_id("sensor_001");
63
64     // Set timestamp (current time)
65     auto* timestamp = reading.mutable_timestamp();
66     auto now = std::chrono::system_clock::now();
67     auto epoch = now.time_since_epoch();
68     timestamp->set_seconds(std::chrono::duration_cast<std::chrono::seconds>(
69         epoch).count());
70     timestamp->set_nanoseconds(0);
71
72     // Set temperature measurement (using oneof field)
73     reading.set_temperature_celsius(23.5f);
74
75     // Add metadata
76     (*reading.mutable_metadata())["location"] = "office";
77     (*reading.mutable_metadata())["calibrated"] = "true";
78
79     std::cout << "Created sensor reading:\n";
80     std::cout << "    Device: " << reading.device_id() << "\n";
81     std::cout << "    Type: " << reading.type() << "\n";
82     std::cout << "    Temperature: " << reading.temperature_celsius() << "°C\n";
83     std::cout << "    Metadata:\n";
84     for (const auto& [key, value] : reading.metadata()) {
85         std::cout << "        " << key << " = " << value << "\n";
86     }
87
88     std::cout << "\nKey features demonstrated:\n";
89     std::cout << "    Simple field setters (set_xxx)\n";
90     std::cout << "    Nested message creation (mutable_xxx)\n";
91     std::cout << "    Oneof field (only one measurement type at a time)\n";
92     std::cout << "    Map fields for flexible metadata\n\n";
93 }
94
95 // =====
96 // EXAMPLE 2: BINARY SERIALIZATION
97 // =====
98
99 void example_binary_serialization() {
100     std::cout << "==== Example 2: Binary Serialization ===\n";
101
102     sensors::SensorReading reading;
103     reading.set_type(sensors::TEMPERATURE);
```

```
103     reading.set_device_id("sensor_001");
104     reading.set_temperature_celsius(23.5f);
105
106     // Method 1: Serialize to string
107     std::string serialized;
108     if (!reading.SerializeToString(&serialized)) {
109         std::cerr << "Failed to serialize!\n";
110         return;
111     }
112
113     std::cout << "Serialized size: " << serialized.size() << " bytes\n";
114     std::cout << "Binary data (hex): ";
115     for (size_t i = 0; i < std::min(serialized.size(), size_t(20)); ++i) {
116         printf("%02x ", (unsigned char)serialized[i]);
117     }
118     if (serialized.size() > 20) std::cout << "...";
119     std::cout << "\n";
120
121     // Method 2: Serialize to file
122     std::ofstream output("sensor_data.bin", std::ios::binary);
123     if (!reading.SerializeToOstream(&output)) {
124         std::cerr << "Failed to write to file!\n";
125         return;
126     }
127     output.close();
128     std::cout << " Written to sensor_data.bin\n";
129
130     // Method 3: Serialize to byte array (for embedded systems)
131     size_t size = reading.ByteSizeLong();
132     std::vector<uint8_t> buffer(size);
133     if (!reading.SerializeToArray(buffer.data(), size)) {
134         std::cerr << "Failed to serialize to array!\n";
135         return;
136     }
137     std::cout << " Serialized to byte array (" << size << " bytes)\n";
138
139     std::cout << "\nSerialization methods:\n";
140     std::cout << " 1. SerializeToString() - for std::string storage\n";
141     std::cout << " 2. SerializeToOstream() - for file I/O\n";
142     std::cout << " 3. SerializeToArray() - for fixed buffers (embedded)\n";
143     std::cout << " 4. ByteSizeLong() - get serialized size before writing\n\n";
144 }
145
146 // =====
147 // EXAMPLE 3: BINARY DESERIALIZATION
148 // =====
149
150 void example_binary_deserialization() {
151     std::cout << "== Example 3: Binary Deserialization ==\n";
152
153     // First, create and serialize a message
154     sensors::SensorReading original;
155     original.set_type(sensors::HUMIDITY);
```

```
156     original.set_device_id("sensor_002");
157     original.set_humidity_percent(65.3f);
158
159     std::string serialized_data;
160     original.SerializeToString(&serialized_data);
161     std::cout << "Original message serialized (" << serialized_data.size() <<
162         " bytes)\n";
163
164     // Method 1: Deserialize from string
165     sensors::SensorReading reading;
166     if (!reading.ParseFromString(serialized_data)) {
167         std::cerr << "Failed to parse!\n";
168         return;
169     }
170     std::cout << " Deserialized from string:\n";
171     std::cout << " Device: " << reading.device_id() << "\n";
172     std::cout << " Humidity: " << reading.humidity_percent() << "%\n";
173
174     // Method 2: Deserialize from file
175     std::ifstream input("sensor_data.bin", std::ios::binary);
176     sensors::SensorReading reading2;
177     if (input.good() && reading2.ParseFromIstream(&input)) {
178         std::cout << " Deserialized from file:\n";
179         std::cout << " Device: " << reading2.device_id() << "\n";
180         std::cout << " Temperature: " << reading2.temperature_celsius() << " °C\n";
181     }
182     input.close();
183
184     // Method 3: Deserialize from byte array
185     std::vector<uint8_t> buffer(serialized_data.begin(), serialized_data.end());
186     sensors::SensorReading reading3;
187     if (!reading3.ParseFromArray(buffer.data(), buffer.size())) {
188         std::cerr << "Failed to parse from array!\n";
189         return;
190     }
191     std::cout << " Deserialized from byte array: " << reading3.device_id() <<
192         "\n";
193
194     // Demonstrate field checking
195     if (reading3.has_humidity_percent()) {
196         std::cout << " Has humidity field: " << reading3.humidity_percent()
197             << "%\n";
198     }
199
200     std::cout << "\nDeserialization methods:\n";
201     std::cout << " 1. ParseFromString() - from std::string\n";
202     std::cout << " 2. ParseFromIstream() - from file\n";
203     std::cout << " 3. ParseFromArray() - from buffer\n";
204     std::cout << " 4. has_xxx() - check if optional field is set\n\n";
205 }
```

```
205 // EXAMPLE 4: ADVANCED FILE SERIALIZATION
206 // =====
207
208 void example_file_serialization() {
209     std::cout << "==== Example 4: Advanced File Serialization ===\n";
210
211     // Example 4a: Writing multiple messages to a file with length prefixes
212     std::cout << "\n[4a] Writing multiple sensor readings to file:\n";
213
214     const char* multi_file = "sensor_readings_multi.bin";
215     std::ofstream output(multi_file, std::ios::binary);
216
217     if (!output) {
218         std::cerr << "Failed to open file for writing!\n";
219         return;
220     }
221
222     // Create multiple sensor readings
223     std::vector<sensors::SensorReading> readings;
224
225     // Reading 1: Temperature
226     sensors::SensorReading temp_reading;
227     temp_reading.set_type(sensors::TEMPERATURE);
228     temp_reading.set_device_id("sensor_001");
229     temp_reading.set_temperature_celsius(22.5f);
230     readings.push_back(temp_reading);
231
232     // Reading 2: Humidity
233     sensors::SensorReading humidity_reading;
234     humidity_reading.set_type(sensors::HUMIDITY);
235     humidity_reading.set_device_id("sensor_002");
236     humidity_reading.set_humidity_percent(67.8f);
237     readings.push_back(humidity_reading);
238
239     // Reading 3: Pressure
240     sensors::SensorReading pressure_reading;
241     pressure_reading.set_type(sensors::PRESSURE);
242     pressure_reading.set_device_id("sensor_003");
243     pressure_reading.set_pressure_hpa(1013.25f);
244     readings.push_back(pressure_reading);
245
246     // Write each message with length prefix (for proper deserialization)
247     for (const auto& reading : readings) {
248         // Serialize to string first
249         std::string serialized;
250         if (!reading.SerializeToString(&serialized)) {
251             std::cerr << "Failed to serialize reading!\n";
252             continue;
253         }
254
255         // Write length prefix (4 bytes)
256         uint32_t size = serialized.size();
257         output.write(reinterpret_cast<const char*>(&size), sizeof(size));
```

```
259     // Write the actual message
260     output.write(serialized.data(), serialized.size());
261
262     std::cout << "    Written " << reading.device_id()
263             << " (" << size << " bytes)\n";
264 }
265
266 output.close();
267 std::cout << " Successfully wrote " << readings.size()
268             << " readings to " << multi_file << "\n";
269
270 // Example 4b: Reading multiple messages from file
271 std::cout << "\n[4b] Reading multiple messages from file:\n";
272
273 std::ifstream input(multi_file, std::ios::binary);
274 if (!input) {
275     std::cerr << "Failed to open file for reading!\n";
276     return;
277 }
278
279 int count = 0;
280 while (input.good()) {
281     // Read length prefix
282     uint32_t size;
283     input.read(reinterpret_cast<char*>(&size), sizeof(size));
284
285     if (input.eof()) break;
286     if (!input.good()) {
287         std::cerr << "Error reading length prefix!\n";
288         break;
289     }
290
291     // Read the message data
292     std::vector<char> buffer(size);
293     input.read(buffer.data(), size);
294
295     if (!input.good() && !input.eof()) {
296         std::cerr << "Error reading message data!\n";
297         break;
298     }
299
300     // Parse the message
301     sensors::SensorReading reading;
302     if (!reading.ParseFromArray(buffer.data(), size)) {
303         std::cerr << "Failed to parse message!\n";
304         continue;
305     }
306
307     count++;
308     std::cout << "    Reading #" << count << ":" "
309             << reading.device_id() << " - ";
310
311     // Display based on type
312     if (reading.has_temperature_celsius()) {
```

```
313     std::cout << reading.temperature_celsius() << "°C";
314 } else if (reading.has_humidity_percent()) {
315     std::cout << reading.humidity_percent() << "%";
316 } else if (reading.has_pressure_hpa()) {
317     std::cout << reading.pressure_hpa() << " hPa";
318 }
319 std::cout << "\n";
320 }

321 input.close();
322 std::cout << " Successfully read " << count << " readings from file\n";
323
324 // Example 4c: Using delimited I/O (WriteDelimitedToOstream)
325 std::cout << "\n[4c] Using Google's delimited I/O utilities:\n";
326 std::cout << R"code(
327 // For writing multiple messages (requires google/protobuf/io/coded_stream.h):
328 #include <google/protobuf/io/coded_stream.h>
329 #include <google/protobuf/io/zero_copy_stream_impl.h>
330
331 std::ofstream output("data.bin", std::ios::binary);
332 google::protobuf::io::OstreamOutputStream ostream(&output);
333 google::protobuf::io::CodedOutputStream coded_output(&ostream);
334
335 // Write each message with length prefix
336 for (const auto& reading : readings) {
337     coded_output.WriteVarint32(reading.ByteSizeLong());
338     reading.SerializeToCodedStream(&coded_output);
339 }
340
341 // For reading:
342 std::ifstream input("data.bin", std::ios::binary);
343 google::protobuf::io::IstreamInputStream istream(&input);
344 google::protobuf::io::CodedInputStream coded_input(&istream);
345
346 uint32_t size;
347 while (coded_input.ReadVarint32(&size)) {
348     auto limit = coded_input.PushLimit(size);
349     sensors::SensorReading reading;
350     reading.ParseFromCodedStream(&coded_input);
351     coded_input.PopLimit(limit);
352 }
353 )code" << "\n";
354
355 std::cout << "File I/O Best Practices:\n";
356 std::cout << " 1. Always write length prefix for multiple messages\n";
357 std::cout << " 2. Use binary mode (std::ios::binary) for files\n";
358 std::cout << " 3. Check file operations (input.good(), output.good())\n";
359 std::cout << " 4. Use CodedStream for efficient varint encoding\n";
360 std::cout << " 5. Handle EOF and errors gracefully\n";
361 std::cout << " 6. Close files explicitly or use RAII\n\n";
362
363 }

364 // =====
365 // EXAMPLE 5: FILE FORMAT STRATEGIES
```

```
367 // =====
368
369 void example_file_formats() {
370     std::cout << "==== Example 5: File Format Strategies ===\n\n";
371
372     std::cout << "Strategy 1: Single Message per File\n";
373     std::cout << "    Use case: Configuration files, snapshots\n";
374     std::cout << "    Simple: just SerializeToOstream() / ParseFromIstream()\n";
375     std::cout << "    ";
376     std::cout << "    Easy to inspect and replace\n";
377     std::cout << "    Many files for multiple messages\n";
378     std::cout << R"code(
379 sensors::SensorReading reading;
380 // ... populate reading ...
381
382 std::ofstream out("config.bin", std::ios::binary);
383 reading.SerializeToOstream(&out);
384 out.close();
385
386 std::ifstream in("config.bin", std::ios::binary);
387 reading.ParseFromIstream(&in);
388 )code" << "\n\n";
389
390     std::cout << "Strategy 2: Multiple Messages with Length Prefixes\n";
391     std::cout << "    Use case: Log files, sensor data streams\n";
392     std::cout << "    Efficient for sequential access\n";
393     std::cout << "    Single file for all data\n";
394     std::cout << "    No random access\n";
395     std::cout << "    See Example 4b above for implementation\n\n";
396
397     std::cout << "Strategy 3: Container Message (Repeated Fields)\n";
398     std::cout << "    Use case: Batched data, complete datasets\n";
399     std::cout << "    Single SerializeToOstream() call\n";
400     std::cout << "    Entire dataset in memory\n";
401     std::cout << "    Must load everything at once\n";
402     std::cout << R"code(
403 // Define in .proto:
404 // message SensorDataBatch {
405 //     repeated SensorReading readings = 1;
406 // }
407
408 sensors::SensorDataBatch batch;
409 batch.add_readings()->CopyFrom(reading1);
410 batch.add_readings()->CopyFrom(reading2);
411 batch.add_readings()->CopyFrom(reading3);
412
413 std::ofstream out("batch.bin", std::ios::binary);
414 batch.SerializeToOstream(&out);
415 )code" << "\n\n";
416
417     std::cout << "Strategy 4: Text Format (for debugging)\n";
418     std::cout << "    Use case: Debug logs, human inspection\n";
419     std::cout << "    Human-readable\n";
420     std::cout << "    Easy to debug\n";
```

```
420     std::cout << "    Much larger file size\n";
421     std::cout << "    Slower parsing\n";
422     std::cout << R"code(
423 #include <google/protobuf/text_format.h>
424
425     sensors::SensorReading reading;
426     // ... populate ...
427
428     std::ofstream out("data.txt");
429     std::string text;
430     google::protobuf::TextFormat::PrintToString(reading, &text);
431     out << text;
432
433     // Read back:
434     std::ifstream in("data.txt");
435     std::string content((std::istreambuf_iterator<char>(in)),
436                         std::istreambuf_iterator<char>());
437     google::protobuf::TextFormat::ParseFromString(content, &reading);
438 )code" << "\n\n";
439
440     std::cout << "Recommendation by use case:\n";
441     std::cout << " • Configuration files → Strategy 1 (single message)\n";
442     std::cout << " • Sensor data logs → Strategy 2 (length prefixes)\n";
443     std::cout << " • Database dumps → Strategy 3 (container message)\n";
444     std::cout << " • Debug output → Strategy 4 (text format)\n";
445     std::cout << " • Embedded logging → Strategy 2 (append to file)\n\n";
446 }
447
448 // =====
449 // EXAMPLE 6: JSON CONVERSION
450 // =====
451
452 void example_json_conversion() {
453     std::cout << "==== Example 6: JSON Conversion (Protobuf v3) ===\n";
454
455     std::cout << R"code(
456 #include <google/protobuf/util/json_util.h>
457
458     sensors::SensorReading reading;
459     reading.set_type(sensors::TEMPERATURE);
460     reading.set_device_id("sensor_001");
461     reading.set_temperature_celsius(23.5f);
462
463     // Convert to JSON
464     std::string json_output;
465     google::protobuf::util::JsonPrintOptions options;
466     options.add_whitespace = true; // Pretty print
467     options.always_print_primitive_fields = true; // Show all fields
468
469     auto status = google::protobuf::util::MessageToJsonString(
470         reading, &json_output, options
471     );
472
473     if (status.ok()) {
```

```
474     std::cout << "JSON output:\n" << json_output << "\n";
475 } else {
476     std::cerr << "JSON conversion failed: " << status.message() << "\n";
477 }
478
479 // Convert from JSON
480 std::string json_input = R"({
481     "type": "TEMPERATURE",
482     "device_id": "sensor_002",
483     "temperature_celsius": 25.3
484 })";
485
486 sensors::SensorReading parsed_reading;
487 status = google::protobuf::util::JsonStringToMessage(json_input, &
488             parsed_reading);
489
490 if (status.ok()) {
491     std::cout << "Parsed from JSON: " << parsed_reading.device_id() << "\n";
492 }
493
494 std::cout << "\nJSON features:\n";
495 std::cout << "    Human-readable debugging\n";
496 std::cout << "    REST API compatibility\n";
497 std::cout << "    Configuration files\n";
498 std::cout << "    Larger than binary (use binary for production)\n\n";
499 }
500
501 // =====
502 // EXAMPLE 7: REPEATED FIELDS AND BATCHING
503 // =====
504
505 void example_repeated_fields() {
506     std::cout << "==== Example 7: Repeated Fields (Batch Processing) ===\n";
507
508     sensors::SensorBatch batch;
509     batch.set_batch_id("batch_001");
510
511     // Add multiple sensor readings
512     for (int i = 0; i < 10; ++i) {
513         auto* reading = batch.add_readings(); // Add new reading
514         reading->set_type(sensors::TEMPERATURE);
515         reading->set_device_id("sensor_" + std::to_string(i));
516         reading->set_temperature_celsius(20.0f + i * 0.5f);
517     }
518
519     // Iterate over readings
520     std::cout << "Batch contains " << batch.readings_size() << " readings:\n";
521     for (const auto& reading : batch.readings()) {
522         std::cout << "    " << reading.device_id()
523                         << ":" << reading.temperature_celsius() << "°C\n";
524     }
525
526     // Access by index
```

```
527     if (batch.readings_size() > 0) {
528         const auto& first = batch.readings(0);
529         std::cout << "\nFirst reading: " << first.device_id() << "\n";
530     }
531
532     // Serialize the batch
533     std::string batch_data;
534     batch.SerializeToString(&batch_data);
535     std::cout << "Batch serialized: " << batch_data.size() << " bytes for "
536             << batch.readings_size() << " readings\n";
537     std::cout << "Average: " << (batch_data.size() / batch.readings_size()) <<
538             " bytes/reading\n";
539
540     std::cout << "\nRepeated field methods:\n";
541     std::cout << " • add_xxx() - append new element\n";
542     std::cout << " • xxx_size() - get count\n";
543     std::cout << " • xxx(index) - access by index\n";
544     std::cout << " • clear_xxx() - remove all elements\n";
545     std::cout << " • Range-based for loop support\n\n";
546 }
547 // =====
548 // EXAMPLE 6: MEMORY MANAGEMENT AND PERFORMANCE
549 // =====
550
551 void example_performance() {
552     std::cout << "== Example 6: Performance and Memory Efficiency ==\n";
553
554     std::cout << R"
555 // Arena allocation for high-performance scenarios
556 // Reduces memory allocations and improves cache locality
557 google::protobuf::Arena arena;
558
559 auto* reading = google::protobuf::Arena::CreateMessage<sensors::SensorReading
560             >(&arena);
561 reading->set_device_id("sensor_001");
562 reading->set_temperature_celsius(23.5f);
563
564 // All nested messages also use arena
565 auto* timestamp = reading->mutable_timestamp();
566 timestamp->set_seconds(12345);
567
568 // Memory is freed when arena goes out of scope
569 // No need to delete individual messages
570
571 // Performance tips:
572 // 1. Reuse message objects instead of creating new ones
573 sensors::SensorReading reusable_msg;
574 for (int i = 0; i < 1000; ++i) {
575     reusable_msg.Clear(); // Reset, don't recreate
576     reusable_msg.set_device_id("sensor_" + std::to_string(i));
577     // ... serialize and send ...
578 }
```

```
579 // 2. Use SerializeToArray with pre-allocated buffer
580 std::vector<uint8_t> buffer(1024); // Pre-allocate
581 size_t size = reading->ByteSizeLong();
582 if (size <= buffer.size()) {
583     reading->SerializeToArray(buffer.data(), size);
584 }
585
586 // 3. For embedded systems: use lite runtime
587 // In .proto file: option optimize_for = LITE_RUNTIME;
588 // Reduces binary size by 50-70%
589 )";
590
591     std::cout << "\nPerformance techniques:\n";
592     std::cout << "    Arena allocation - reduces fragmentation\n";
593     std::cout << "    Message reuse with Clear() - avoids allocations\n";
594     std::cout << "    Pre-allocated buffers - zero-copy serialization\n";
595     std::cout << "    Lite runtime - smaller binary for embedded systems\n";
596     std::cout << "    Lazy field evaluation - on-demand parsing\n\n";
597 }
598
599 // =====
600 // EXAMPLE 9: EMBEDDED SYSTEMS CONSIDERATIONS
601 // =====
602
603 void example_embedded_systems() {
604     std::cout << "==== Example 9: Embedded Systems Best Practices ===\n";
605
606     std::cout << R"(

607 // 1. Use fixed-size buffers to avoid dynamic allocation
608 constexpr size_t MAX_MESSAGE_SIZE = 256;
609 uint8_t tx_buffer[MAX_MESSAGE_SIZE];
610 uint8_t rx_buffer[MAX_MESSAGE_SIZE];

611 // 2. Serialize directly to UART/SPI buffer
612 sensors::SensorReading reading;
613 reading.set_device_id("mcu_001");
614 reading.set_temperature_celsius(23.5f);

615
616 size_t size = reading.ByteSizeLong();
617 if (size <= MAX_MESSAGE_SIZE) {
618     reading.SerializeToArray(tx_buffer, size);
619     // uart_transmit(tx_buffer, size);
620 }
621

622 // 3. Parse from received buffer
623 // size_t received = uart_receive(rx_buffer, MAX_MESSAGE_SIZE);
624 size_t received = 50; // Example

625
626 sensors::SensorReading received_msg;
627 if (received_msg.ParseFromArray(rx_buffer, received)) {
628     // Process message
629     float temp = received_msg.temperature_celsius();
630 }
631
632 )"
```

```
633 // 4. Use lite runtime for small footprint
634 // .proto file option:
635 //   option optimize_for = LITE_RUNTIME;
636 //
637 // Removes:
638 // - Reflection API
639 // - Text format support
640 // - JSON conversion
641 //
642 // Result: 50-70% smaller binary
643
644 // 5. Error handling without exceptions (embedded systems)
645 #ifdef PROTOBUF_USE_EXCEPTIONS
646     try {
647         reading.ParseFromArray(rx_buffer, received);
648     } catch (const std::exception& e) {
649         // Handle error
650     }
651 #else
652     // Check return value
653     if (!reading.ParseFromArray(rx_buffer, received)) {
654         // Handle error without exceptions
655     }
656 #endif
657 )";
658
659     std::cout << "\nEmbedded systems considerations:\n";
660     std::cout << "    Fixed-size buffers - no heap fragmentation\n";
661     std::cout << "    Lite runtime - minimal binary size\n";
662     std::cout << "    No exceptions - suitable for bare-metal\n";
663     std::cout << "    Zero-copy serialization - DMA-friendly\n";
664     std::cout << "    Deterministic memory usage\n\n";
665 }
666
667 // =====
668 // EXAMPLE 8: SCHEMA EVOLUTION (BACKWARD COMPATIBILITY)
669 // =====
670
671 void example_schema_evolution() {
672     std::cout << "==== Example 8: Schema Evolution ===\n";
673
674     std::cout << R"(

675 // Protocol Buffers support schema evolution:
676 // Old code can read new messages, new code can read old messages

677
678 // VERSION 1 of .proto:
679 // message SensorReading {
680 //     string device_id = 1;
681 //     float temperature_celsius = 2;
682 // }

683
684 // VERSION 2 adds new fields (backward compatible):
685 // message SensorReading {
686 //     string device_id = 1;
```

```
687 //     float temperature_celsius = 2;
688 //     string location = 3;           // NEW FIELD
689 //     int32 battery_percent = 4;    // NEW FIELD
690 //}
691
692 // Rules for compatibility:
693 //   Can add new fields (old code ignores them)
694 //   Can remove optional fields (new code uses defaults)
695 //   Cannot change field numbers (breaks everything)
696 //   Cannot change field types (incompatible)
697 //   Can rename fields (only changes code, not wire format)
698
699 // Example: Old client reading new message
700 // sensors::SensorReading msg; // From version 1 code
701 // msg.ParseFromString(new_message_bytes);
702 //
703 // float temp = msg.temperature_celsius(); // Works!
704 // // New fields (location, battery) are ignored by old code
705
706 // Example: New client reading old message
707 // sensors::SensorReading msg; // From version 2 code
708 // msg.ParseFromString(old_message_bytes);
709 //
710 // float temp = msg.temperature_celsius(); // Works!
711 // std::string loc = msg.location();        // Empty string (default)
712 // int battery = msg.battery_percent();    // 0 (default)
713 ")";
714
715     std::cout << "\nBackward compatibility rules:\n";
716     std::cout << "  DO:\n";
717     std::cout << "      Add new optional fields\n";
718     std::cout << "      Remove optional fields (deprecated first)\n";
719     std::cout << "      Rename fields (code only, not wire format)\n";
720     std::cout << "  DON'T:\n";
721     std::cout << "      Change field numbers\n";
722     std::cout << "      Change field types\n";
723     std::cout << "      Make required fields optional (v2 syntax)\n\n";
724 }
725
726 // =====
727 // COMPARISON: PROTOBUF VS ALTERNATIVES
728 // =====
729
730 void comparison_with_alternatives() {
731     std::cout << "==== Comparison with Alternatives ===\n\n";
732
733     std::cout << "XML:\n";
734     std::cout << "      3-10x larger than protobuf\n";
735     std::cout << "      20-100x slower parsing\n";
736     std::cout << "      Human-readable\n";
737     std::cout << "      Self-describing\n\n";
738
739     std::cout << "JSON:\n";
740     std::cout << "      2-5x larger than protobuf\n";
```

```
741     std::cout << "      10-50x slower parsing\n";
742     std::cout << "      Human-readable\n";
743     std::cout << "      JavaScript-friendly\n";
744     std::cout << "      No schema enforcement\n\n";
745
746     std::cout << "MessagePack:\n";
747     std::cout << "      Similar size to protobuf\n";
748     std::cout << "      Fast parsing\n";
749     std::cout << "      No schema (schemaless)\n";
750     std::cout << "      No code generation\n\n";
751
752     std::cout << "FlatBuffers:\n";
753     std::cout << "      Zero-copy deserialization\n";
754     std::cout << "      Very fast access\n";
755     std::cout << "      Larger than protobuf\n";
756     std::cout << "      Mutable messages more complex\n\n";
757
758     std::cout << "Cap'n Proto:\n";
759     std::cout << "      Zero-copy like FlatBuffers\n";
760     std::cout << "      Very fast\n";
761     std::cout << "      Less mature ecosystem\n";
762     std::cout << "      Smaller community\n\n";
763
764     std::cout << "When to use Protocol Buffers:\n";
765     std::cout << "      Need efficient binary serialization\n";
766     std::cout << "      Cross-language communication\n";
767     std::cout << "      Schema evolution important\n";
768     std::cout << "      Google's ecosystem (gRPC, etc.)\n";
769     std::cout << "      Embedded systems with constraints\n\n";
770 }
771
772 // =====
773 // MAIN FUNCTION
774 // =====
775
776 int main() {
777     std::cout << "=====\\n"
778     ;
779     std::cout << "GOOGLE PROTOCOL BUFFERS (PROTOBUF) EXAMPLES\\n";
780     std::cout << "=====\\n\\n";
781
782     example_create_sensor_reading();
783     example_binary_serialization();
784     example_binary_deserialization();
785     example_file_serialization();
786     example_file_formats();
787     example_json_conversion();
788     example_repeated_fields();
789     example_performance();
790     example_embedded_systems();
791     example_schema_evolution();
792     comparison_with_alternatives();
```

```
793     std::cout << "=====\\n"
794     ;
795     std::cout << "BUILD INSTRUCTIONS:\\n";
796     std::cout << "=====\\n\\n";
797     std::cout << "1. Install Protocol Buffers:\\n";
798     std::cout << "    Ubuntu/Debian:\\n";
799     std::cout << "        sudo apt-get install protobuf-compiler libprotobuf-dev\\n\\n";
800
801     std::cout << "    macOS:\\n";
802     std::cout << "        brew install protobuf\\n\\n";
803
804     std::cout << "    Windows:\\n";
805     std::cout << "        Download from: https://github.com/protocolbuffers/protobuf/releases\\n\\n";
806
807     std::cout << "2. Generate C++ code from .proto file:\\n";
808     std::cout << "    protoc --cpp_out=. proto/sensor_data.proto\\n";
809     std::cout << "    This creates:\\n";
810     std::cout << "        - sensor_data.pb.h\\n";
811     std::cout << "        - sensor_data.pb.cc\\n\\n";
812
813     std::cout << "3. Compile with CMake:\\n";
814     std::cout << "    find_package(Protobuf REQUIRED)\\n";
815     std::cout << "    target_link_libraries(YourTarget protobuf::libprotobuf)\\n
816             ";
817
818     std::cout << "4. Or compile manually:\\n";
819     std::cout << "    g++ -std=c++17 ProtobufExample.cpp sensor_data.pb.cc \\\n
820             ";
821     std::cout << "        -lprotobuf -o protobuf_example\\n\\n";
822
823     std::cout << "=====\\n";
824     std::cout << "RESOURCES:\\n";
825     std::cout << "=====\\n";
826     std::cout << "Official docs: https://protobuf.dev/\\n";
827     std::cout << "GitHub: https://github.com/protocolbuffers/protobuf\\n";
828     std::cout << "C++ tutorial: https://protobuf.dev/getting-started/cpptutorial/\\n\\n";
829
830     return 0;
831 }
```

54 Source Code: Pybind11Example.cpp

File: src/Pybind11Example.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // PYBIND11: C++ AND PYTHON INTEROPERABILITY
3 // =====
4 // This example demonstrates bidirectional calling between C++ and Python
5 // using pybind11 (modern, header-only binding library)
6 //
7 // BUILD INSTRUCTIONS:
8 // =====
9 // 1. Install pybind11:
10 //    pip install pybind11
11 //
12 // 2. Compile as Python extension module:
13 //    c++ -O3 -Wall -shared -std=c++17 -fPIC \
14 //          $(python3 -m pybind11 --includes) \
15 //          Pybind11Example.cpp \
16 //          -o pybind_example$(python3-config --extension-suffix)
17 //
18 // 3. Use from Python:
19 //    import pybind_example
20 //    result = pybind_example.add(2, 3)
21 //
22 // ALTERNATIVE FRAMEWORKS:
23 // =====
24 // - Boost.Python: Older, requires Boost library
25 // - SWIG: Generates bindings for multiple languages
26 // - ctypes: Python standard library, simpler but less type-safe
27 // - cffi: C Foreign Function Interface for Python
28 // - nanobind: Modern, lightweight alternative to pybind11
29 // =====
30
31 #include <pybind11/pybind11.h>
32 #include <pybind11/stl.h>           // STL containers conversion
33 #include <pybind11/functional.h> // std::function conversion
34 #include <pybind11/numpy.h>       // NumPy arrays support
35 #include <iostream>
36 #include <vector>
37 #include <string>
38 #include <memory>
39 #include <cmath>
40
41 namespace py = pybind11;
42
43 // =====
44 // 1. SIMPLE FUNCTIONS - C++ FUNCTIONS CALLED FROM PYTHON
45 // =====
46
47 // Simple function
48 int add(int a, int b) {
49     return a + b;
```

```
50 }
51
52 // Function with default arguments
53 double multiply(double a, double b = 2.0) {
54     return a * b;
55 }
56
57 // Function with multiple return values (using tuple)
58 std::tuple<int, int> divide_with_remainder(int dividend, int divisor) {
59     int quotient = dividend / divisor;
60     int remainder = dividend % divisor;
61     return std::make_tuple(quotient, remainder);
62 }
63
64 // Function returning string
65 std::string greet(const std::string& name) {
66     return "Hello, " + name + "!";
67 }
68
69 // =====
70 // 2. WORKING WITH STL CONTAINERS
71 // =====
72
73 // Function accepting and returning std::vector
74 std::vector<int> square_elements(const std::vector<int>& vec) {
75     std::vector<int> result;
76     result.reserve(vec.size());
77     for (int val : vec) {
78         result.push_back(val * val);
79     }
80     return result;
81 }
82
83 // Function with std::map
84 std::map<std::string, int> count_words(const std::vector<std::string>& words)
85 {
86     std::map<std::string, int> counts;
87     for (const auto& word : words) {
88         counts[word]++;
89     }
90     return counts;
91 }
92
93 // =====
94 // 3. CLASSES - EXPOSING C++ CLASSES TO PYTHON
95 // =====
96
97 class Vector2D {
98 private:
99     double x, y;
100
101 public:
102     // Constructors
103     Vector2D() : x(0.0), y(0.0) {}
```

```
103     Vector2D(double x, double y) : x(x), y(y) {}  
104  
105     // Getters/Setters  
106     double getX() const { return x; }  
107     double getY() const { return y; }  
108     void setX(double val) { x = val; }  
109     void setY(double val) { y = val; }  
110  
111     // Methods  
112     double length() const {  
113         return std::sqrt(x * x + y * y);  
114     }  
115  
116     Vector2D operator+(const Vector2D& other) const {  
117         return Vector2D(x + other.x, y + other.y);  
118     }  
119  
120     Vector2D operator*(double scalar) const {  
121         return Vector2D(x * scalar, y * scalar);  
122     }  
123  
124     // String representation  
125     std::string toString() const {  
126         return "Vector2D(" + std::to_string(x) + ", " + std::to_string(y) + ")"  
127         ;  
128     }  
129  
130     // Static method  
131     static Vector2D zero() {  
132         return Vector2D(0.0, 0.0);  
133     }  
134  
135 // =====  
136 // 4. INHERITANCE - BASE AND DERIVED CLASSES  
137 // =====  
138  
139 class Shape {  
140 protected:  
141     std::string name;  
142  
143 public:  
144     Shape(const std::string& name) : name(name) {}  
145     virtual ~Shape() = default;  
146  
147     virtual double area() const = 0;  
148     virtual std::string getName() const { return name; }  
149 };  
150  
151 class Circle : public Shape {  
152 private:  
153     double radius;  
154  
155 public:
```

```
156     Circle(const std::string& name, double r)
157         : Shape(name), radius(r) {}
158
159     double area() const override {
160         return 3.14159 * radius * radius;
161     }
162
163     double getRadius() const { return radius; }
164 };
165
166 class Rectangle : public Shape {
167 private:
168     double width, height;
169
170 public:
171     Rectangle(const std::string& name, double w, double h)
172         : Shape(name), width(w), height(h) {}
173
174     double area() const override {
175         return width * height;
176     }
177 };
178
179 // =====
180 // 5. CALLBACKS - CALLING PYTHON FUNCTIONS FROM C++
181 // =====
182
183 // Process data with Python callback
184 std::vector<int> process_with_callback(
185     const std::vector<int>& data,
186     std::function<int(int)> callback) {
187
188     std::vector<int> result;
189     result.reserve(data.size());
190
191     for (int val : data) {
192         result.push_back(callback(val)); // Call Python function!
193     }
194
195     return result;
196 }
197
198 // Numerical integration using Python callback
199 double integrate(std::function<double(double)> func,
200                  double start, double end, int steps = 1000) {
201     double dx = (end - start) / steps;
202     double sum = 0.0;
203
204     for (int i = 0; i < steps; ++i) {
205         double x = start + i * dx;
206         sum += func(x) * dx; // Call Python function!
207     }
208
209     return sum;
```

```
210 }
211
212 // =====
213 // 6. SENSOR DATA PROCESSING (EMBEDDED SYSTEMS EXAMPLE)
214 // =====
215
216 struct SensorReading {
217     double timestamp;
218     double value;
219     std::string sensor_id;
220
221     SensorReading(double t, double v, const std::string& id)
222         : timestamp(t), value(v), sensor_id(id) {}
223 };
224
225 class SensorProcessor {
226 private:
227     std::vector<SensorReading> readings;
228
229 public:
230     void addReading(double timestamp, double value, const std::string& id) {
231         readings.emplace_back(timestamp, value, id);
232     }
233
234     size_t getReadingCount() const {
235         return readings.size();
236     }
237
238     std::vector<SensorReading> getReadings() const {
239         return readings;
240     }
241
242     // Process readings with Python callback
243     std::vector<double> processReadings(
244         std::function<double(const SensorReading&)> processor) {
245
246         std::vector<double> results;
247         results.reserve(readings.size());
248
249         for (const auto& reading : readings) {
250             results.push_back(processor(reading)); // Call Python!
251         }
252
253         return results;
254     }
255
256     // Filter readings with Python predicate
257     std::vector<SensorReading> filterReadings(
258         std::function<bool(const SensorReading&)> predicate) {
259
260         std::vector<SensorReading> filtered;
261
262         for (const auto& reading : readings) {
263             if (predicate(reading)) { // Call Python!
```

```
264         filtered.push_back(reading);
265     }
266 }
267
268     return filtered;
269 }
270 };
271
272 // =====
273 // 7. NUMPY ARRAY PROCESSING (HIGH PERFORMANCE)
274 // =====
275
276 // Process NumPy array in C++ for performance
277 py::array_t<double> numpy_square(py::array_t<double> input) {
278     // Get buffer info
279     py::buffer_info buf = input.request();
280
281     if (buf.ndim != 1) {
282         throw std::runtime_error("Number of dimensions must be 1");
283     }
284
285     // Create output array
286     auto result = py::array_t<double>(buf.size);
287     py::buffer_info result_buf = result.request();
288
289     // Get pointers
290     double* input_ptr = static_cast<double*>(buf.ptr);
291     double* result_ptr = static_cast<double*>(result_buf.ptr);
292
293     // Process in C++ (fast!)
294     for (size_t i = 0; i < buf.shape[0]; i++) {
295         result_ptr[i] = input_ptr[i] * input_ptr[i];
296     }
297
298     return result;
299 }
300
301 // Matrix multiplication (2D NumPy arrays)
302 py::array_t<double> matrix_multiply(
303     py::array_t<double> a,
304     py::array_t<double> b) {
305
306     py::buffer_info buf_a = a.request();
307     py::buffer_info buf_b = b.request();
308
309     if (buf_a.ndim != 2 || buf_b.ndim != 2) {
310         throw std::runtime_error("Inputs must be 2D arrays");
311     }
312
313     size_t rows_a = buf_a.shape[0];
314     size_t cols_a = buf_a.shape[1];
315     size_t rows_b = buf_b.shape[0];
316     size_t cols_b = buf_b.shape[1];
317 }
```

```
318     if (cols_a != rows_b) {
319         throw std::runtime_error("Matrix dimensions don't match");
320     }
321
322     // Create result matrix
323     auto result = py::array_t<double>({rows_a, cols_b});
324     py::buffer_info buf_result = result.request();
325
326     double* ptr_a = static_cast<double*>(buf_a.ptr);
327     double* ptr_b = static_cast<double*>(buf_b.ptr);
328     double* ptr_result = static_cast<double*>(buf_result.ptr);
329
330     // Initialize result to zero
331     for (size_t i = 0; i < rows_a * cols_b; i++) {
332         ptr_result[i] = 0.0;
333     }
334
335     // Matrix multiplication
336     for (size_t i = 0; i < rows_a; i++) {
337         for (size_t j = 0; j < cols_b; j++) {
338             for (size_t k = 0; k < cols_a; k++) {
339                 ptr_result[i * cols_b + j] +=
340                     ptr_a[i * cols_a + k] * ptr_b[k * cols_b + j];
341             }
342         }
343     }
344
345     return result;
346 }
347
348 // =====
349 // 8. SMART POINTERS - MANAGING OBJECT LIFETIME
350 // =====
351
352 class Resource {
353 private:
354     std::string name;
355     int id;
356
357 public:
358     Resource(const std::string& n, int i) : name(n), id(i) {
359         std::cout << "Resource created: " << name << " (ID: " << id << ")" <<
360         std::endl;
361     }
362
363     ~Resource() {
364         std::cout << "Resource destroyed: " << name << " (ID: " << id << ")" <<
365         std::endl;
366     }
367
368     std::string getName() const { return name; }
369     int getId() const { return id; }
370 };
371
```

```
370 // Factory function returning unique_ptr
371 std::unique_ptr<Resource> create_resource(const std::string& name, int id) {
372     return std::make_unique<Resource>(name, id);
373 }
374
375 // Factory returning shared_ptr
376 std::shared_ptr<Resource> create_shared_resource(const std::string& name, int
377     id) {
378     return std::make_shared<Resource>(name, id);
379 }
380 // =====
381 // PYBIND11 MODULE DEFINITION
382 // =====
383
384 PYBIND11_MODULE(pybind_example, m) {
385     m.doc() = "pybind11 example module - C++ and Python interoperability";
386
387     // =====
388     // 1. SIMPLE FUNCTIONS
389     // =====
390     m.def("add", &add, "Add two integers",
391             py::arg("a"), py::arg("b"));
392
393     m.def("multiply", &multiply, "Multiply two numbers",
394             py::arg("a"), py::arg("b") = 2.0);
395
396     m.def("divide_with_remainder", &divide_with_remainder,
397             "Divide and return (quotient, remainder)");
398
399     m.def("greet", &greet, "Greet someone");
400
401     // =====
402     // 2. STL CONTAINERS
403     // =====
404     m.def("square_elements", &square_elements,
405             "Square all elements in a list");
406
407     m.def("count_words", &count_words,
408             "Count occurrences of each word");
409
410     // =====
411     // 3. VECTOR2D CLASS
412     // =====
413     py::class_<Vector2D>(m, "Vector2D")
414         .def(py::init<>())
415         .def(py::init<double, double>())
416         .def_property("x", &Vector2D::getX, &Vector2D::setX)
417         .def_property("y", &Vector2D::getY, &Vector2D::setY)
418         .def("length", &Vector2D::length)
419         .def("__add__", &Vector2D::operator+)
420         .def("__mul__", &Vector2D::operator*)
421         .def("__repr__", &Vector2D::toString)
422         .def_static("zero", &Vector2D::zero);
```

```
423 // =====
424 // 4. INHERITANCE - SHAPES
425 // =====
426 py::class_<Shape>(m, "Shape")
427     .def("area", &Shape::area)
428     .def("get_name", &Shape::getName);
429
430
431 py::class_<Circle, Shape>(m, "Circle")
432     .def(py::init<const std::string&, double>())
433     .def("get_radius", &Circle::getRadius);
434
435
436 py::class_<Rectangle, Shape>(m, "Rectangle")
437     .def(py::init<const std::string&, double, double>());
438
439 // =====
440 // 5. CALLBACKS
441 // =====
442 m.def("process_with_callback", &process_with_callback,
443         "Process data with Python callback function");
444
445 m.def("integrate", &integrate,
446         "Numerical integration using Python callback",
447         py::arg("func"), py::arg("start"), py::arg("end"),
448         py::arg("steps") = 1000);
449
450 // =====
451 // 6. SENSOR DATA PROCESSING
452 // =====
453 py::class_<SensorReading>(m, "SensorReading")
454     .def(py::init<double, double, const std::string&>())
455     .def_readonly("timestamp", &SensorReading::timestamp)
456     .def_readonly("value", &SensorReading::value)
457     .def_readonly("sensor_id", &SensorReading::sensor_id);
458
459 py::class_<SensorProcessor>(m, "SensorProcessor")
460     .def(py::init<>())
461     .def("add_reading", &SensorProcessor::addReading)
462     .def("get_reading_count", &SensorProcessor::getReadingCount)
463     .def("get_readings", &SensorProcessor::getReadings)
464     .def("process_readings", &SensorProcessor::processReadings)
465     .def("filter_readings", &SensorProcessor::filterReadings);
466
467 // =====
468 // 7. NUMPY ARRAYS
469 // =====
470 m.def("numpy_square", &numpy_square,
471         "Square all elements in NumPy array (C++ speed!)");
472
473 m.def("matrix_multiply", &matrix_multiply,
474         "Matrix multiplication using NumPy arrays");
475
476 // =====
477 // 8. SMART POINTERS
```

```
477 // =====
478 py::class_<Resource, std::shared_ptr<Resource>>(m, "Resource")
479     .def("get_name", &Resource::getName)
480     .def("get_id", &Resource::getId);
481
482     m.def("create_resource", &create_resource,
483           "Create a resource (returns unique_ptr)");
484
485     m.def("create_shared_resource", &create_shared_resource,
486           "Create a shared resource (returns shared_ptr)");
487 }
488
489 // =====
490 // STANDALONE EXAMPLE (FOR DOCUMENTATION)
491 // =====
492 /*
493 PYTHON USAGE EXAMPLES:
494 =====
495
496 # 1. Simple functions
497 import pybind_example as pe
498
499 result = pe.add(5, 3)
500 print(f"5 + 3 = {result}") # Output: 5 + 3 = 8
501
502 value = pe.multiply(4.5)
503 print(f"4.5 * 2.0 = {value}") # Output: 4.5 * 2.0 = 9.0
504
505 quotient, remainder = pe.divide_with_remainder(17, 5)
506 print(f"17 / 5 = {quotient} remainder {remainder}") # Output: 17 / 5 = 3
507     remainder 2
508
509 message = pe.greet("World")
510 print(message) # Output: Hello, World!
511
512 # 2. STL containers
513 numbers = [1, 2, 3, 4, 5]
514 squared = pe.square_elements(numbers)
515 print(f"Squared: {squared}") # Output: Squared: [1, 4, 9, 16, 25]
516
517 words = ["hello", "world", "hello", "python"]
518 counts = pe.count_words(words)
519 print(f"Word counts: {counts}") # Output: Word counts: {'hello': 2, 'world':
520     1, 'python': 1}
521
522 # 3. Classes
523 v1 = pe.Vector2D(3.0, 4.0)
524 v2 = pe.Vector2D(1.0, 2.0)
525 print(f"v1 = {v1}") # Output: v1 = Vector2D(3.000000, 4.000000)
526 print(f"v1.length() = {v1.length()}") # Output: v1.length() = 5.0
527
528 v3 = v1 + v2
529 print(f"v1 + v2 = {v3}") # Output: v1 + v2 = Vector2D(4.000000, 6.000000)
```

```
529
530 v4 = v1 * 2.0
531 print(f"v1 * 2.0 = {v4}") # Output: v1 * 2.0 = Vector2D(6.000000, 8.000000)
532
533 # 4. Inheritance
534 circle = pe.Circle("MyCircle", 5.0)
535 rect = pe.Rectangle("MyRect", 4.0, 6.0)
536 print(f"{circle.get_name()} area: {circle.area()}"") # Output: MyCircle area:
      78.53975
537 print(f"{rect.get_name()} area: {rect.area()}"") # Output: MyRect area: 24.0
538
539 # 5. Callbacks - CALLING PYTHON FROM C++
540 def my_python_function(x):
541     return x * 2 + 1
542
543 data = [1, 2, 3, 4, 5]
544 result = pe.process_with_callback(data, my_python_function)
545 print(f"Processed: {result}") # Output: Processed: [3, 5, 7, 9, 11]
546
547 # Integrate a Python function using C++
548 import math
549 result = pe.integrate(lambda x: x**2, 0, 1, steps=10000)
550 print(f"Integral of x^2 from 0 to 1: {result}") # Output: ~0.333333
551
552 result = pe.integrate(math.sin, 0, math.pi, steps=10000)
553 print(f"Integral of sin(x) from 0 to : {result}") # Output: ~2.0
554
555 # 6. Sensor processing with callbacks
556 processor = pe.SensorProcessor()
557 processor.add_reading(0.0, 25.5, "TEMP_01")
558 processor.add_reading(1.0, 26.2, "TEMP_01")
559 processor.add_reading(2.0, 24.8, "TEMP_02")
560
561 # Process with Python function
562 def extract_value(reading):
563     return reading.value
564
565 values = processor.process_readings(extract_value)
566 print(f"Values: {values}") # Output: Values: [25.5, 26.2, 24.8]
567
568 # Filter with Python predicate
569 def high_temp(reading):
570     return reading.value > 25.0
571
572 high_temps = processor.filter_readings(high_temp)
573 print(f"High temps: {len(high_temps)}") # Output: High temps: 2
574
575 # 7. NumPy arrays (high performance!)
576 import numpy as np
577
578 arr = np.array([1.0, 2.0, 3.0, 4.0, 5.0])
579 squared = pe.numpy_square(arr) # Fast C++ processing!
580 print(f"NumPy squared: {squared}") # Output: NumPy squared: [1. 4. 9. 16.
      25.]
```

```
581
582 A = np.array([[1.0, 2.0], [3.0, 4.0]])
583 B = np.array([[5.0, 6.0], [7.0, 8.0]])
584 C = pe.matrix_multiply(A, B)
585 print(f"Matrix multiply:\n{C}")
586 # Output:
587 # [[19. 22.]
588 #  [43. 50.]]
589
590 # 8. Smart pointers
591 resource = pe.create_shared_resource("MyResource", 42)
592 print(f"Resource: {resource.get_name()}, ID: {resource.get_id()}")
593 # Output: Resource: MyResource, ID: 42
594 # When resource goes out of scope, C++ destructor is automatically called
595
596 BUILD SCRIPT (build.sh):
597 =====
598 #!/bin/bash
599
600 # Compile the pybind11 extension
601 c++ -O3 -Wall -shared -std=c++17 -fPIC \
602     $(python3 -m pybind11 --includes) \
603     Pybind11Example.cpp \
604     -o pybind_example$(python3-config --extension-suffix)
605
606 # Run Python tests
607 python3 test_pybind.py
608
609 ALTERNATIVE FRAMEWORKS:
610 =====
611
612 1. BOOST.PYTHON (older, requires Boost):
613     #include <boost/python.hpp>
614     BOOST_PYTHON_MODULE(example) {
615         boost::python::def("add", add);
616     }
617
618 2. SWIG (multi-language support):
619     // example.i
620     %module example
621     %{
622     #include "example.h"
623     %}
624     %include "example.h"
625
626     Build: swig -python -c++ example.i
627
628 3. CTYPES (Python standard library):
629     // Compile: g++ -shared -fPIC example.cpp -o example.so
630
631     # Python:
632     import ctypes
633     lib = ctypes.CDLL('./example.so')
634     lib.add.argtypes = [ctypes.c_int, ctypes.c_int]
```

```
635     lib.add.restype = ctypes.c_int
636     result = lib.add(5, 3)
637
638 4. CFFI (C Foreign Function Interface):
639     from cffi import FFI
640     ffi = FFI()
641     ffi.cdef("int add(int, int);")
642     lib = ffi.dlopen('./example.so')
643     result = lib.add(5, 3)
644
645 5. NANOBIND (modern, lightweight):
646     #include <nanobind/nanobind.h>
647     NB_MODULE(example, m) {
648         m.def("add", &add);
649     }
650
651 PERFORMANCE COMPARISON:
652 =====
653 For numerical computations:
654 - Pure Python: 1x (baseline)
655 - NumPy: 10-100x faster
656 - C++ via pybind11: 100-1000x faster
657 - Direct C++ (no Python): 1000x+ faster
658
659 WHEN TO USE:
660 =====
661 Use pybind11 when:•
662     Need performance-critical code in C++•
663     Have existing C++ libraries to expose•
664     Want type safety and automatic conversions•
665     Need to process NumPy arrays efficiently•
666     Want modern C++ features (C++11-20)
667
668 Avoid when:•
669     Pure Python is fast enough•
670     No C++ expertise available•
671     Deployment complexity is a concern•
672     Only need simple C functions (use ctypes)
673 */
```

55 Source Code: ROMability.cpp

File: src/ROMability.cpp

Repository: [View on GitHub](#)

```
1 // ROMability.cpp
2 // Demonstrates ROM-ability in C++ - Placing data in Read-Only Memory (.rodata
3 // section)
4 //
5 // KEY CONCEPTS:
6 // 1. const - Runtime or compile-time constant, placed in ROM if possible
7 // 2. constexpr - Compile-time constant, guaranteed ROM placement
8 // 3. consteval - C++20, forced compile-time evaluation
9 // 4. constinit - C++20, compile-time initialization, runtime mutable
10 // 5. ROM vs RAM - .rodata vs .data/.bss sections
11 //
12 // EMBEDDED SYSTEMS CONTEXT:
13 // ROM (Read-Only Memory) - Flash memory, non-volatile, cheaper
14 // RAM (Random Access Memory) - SRAM, volatile, expensive on MCUs
15 // Goal: Maximize ROM usage, minimize RAM usage
16 //
17 // C++ ADVANTAGES OVER C:
18 // constexpr functions - compute at compile-time
19 // constexpr constructors - complex objects in ROM
20 // std::array - type-safe ROM arrays
21 // consteval - guarantee compile-time evaluation
22 // Template metaprogramming - generate ROM data
23
24 #include <iostream>
25 #include <array>
26 #include <string_view>
27 #include <cmath>
28 #include <iomanip>
29 #include <cstdint>
30 //
31 =====
32 // SECTION 1: const vs constexpr - Understanding the Difference
33 // =====
34
35 namespace const_vs_constexpr {
36
37 // C-style const - MAY be in ROM, but not guaranteed
38 const int c_style_const = 42;
39
40 // C++ constexpr - GUARANTEED compile-time constant, always in ROM
41 constexpr int cpp_constexpr = 42;
42
43 // const with runtime initialization - goes to RAM!
44 int get_runtime_value() { return 42; }
45 const int runtime_const = get_runtime_value(); // RAM, not ROM!
```

```
45 // constexpr forces compile-time evaluation
46 constexpr int get_compile_time_value() { return 42; }
47 constexpr int compile_time_const = get_compile_time_value(); // ROM
48
49 // Complex compile-time calculation
50 constexpr int factorial(int n) {
51     return (n <= 1) ? 1 : n * factorial(n - 1);
52 }
53
54 constexpr int fact_5 = factorial(5); // Computed at compile-time, stored in
55 // ROM
56
57 void demonstrate() {
58     std::cout << "\n" << std::string(70, '=') << "\n";
59     std::cout << "==== SECTION 1: const vs constexpr ===\n";
60     std::cout << std::string(70, '=') << "\n\n";
61
62     std::cout << "1. Traditional const:\n";
63     std::cout << "    const int c_style_const = 42;\n";
64     std::cout << "    Value: " << c_style_const << "\n";
65     std::cout << "    Location: Probably ROM, but not guaranteed\n\n";
66
67     std::cout << "2. constexpr (C++11):\n";
68     std::cout << "    constexpr int cpp_constexpr = 42;\n";
69     std::cout << "    Value: " << cpp_constexpr << "\n";
70     std::cout << "    Location: Guaranteed ROM (.rodata section)\n\n";
71
72     std::cout << "3. const with runtime initialization:\n";
73     std::cout << "    const int runtime_const = get_runtime_value();\n";
74     std::cout << "    Value: " << runtime_const << "\n";
75     std::cout << "    Location: RAM (.data section) - not ROM!\n\n";
76
77     std::cout << "4. constexpr with compile-time function:\n";
78     std::cout << "    constexpr int fact_5 = factorial(5);\n";
79     std::cout << "    Value: " << fact_5 << " (computed at compile-time!)\n";
80     std::cout << "    Location: ROM (.rodata section)\n\n";
81
82     std::cout << " RULE: Use constexpr for guaranteed ROM placement\n";
83     std::cout << " RULE: const doesn't guarantee ROM (can be initialized at
84         runtime)\n";
85 }
86 } // namespace const_vs_constexpr
87
88 /**
89 =====
90 // SECTION 2: ROM-able Arrays - Lookup Tables
91 // =====
92
93 namespace rom_arrays {
```

```
93 // C-style array - ROM placement
94 constexpr int sine_table_c[16] = {
95     0, 707, 1000, 707, 0, -707, -1000, -707,
96     0, 707, 1000, 707, 0, -707, -1000, -707
97 };
98 }
99
100 // C++ std::array - ROM placement with type safety
101 constexpr std::array<int, 16> sine_table_cpp = {
102     0, 707, 1000, 707, 0, -707, -1000, -707,
103     0, 707, 1000, 707, 0, -707, -1000, -707
104 };
105
106 // Generate lookup table at compile-time
107 constexpr auto generate_sine_table() {
108     std::array<int, 360> table{};
109     for (int i = 0; i < 360; ++i) {
110         // Note: std::sin is not constexpr before C++26
111         // Using approximation for demonstration
112         table[i] = static_cast<int>(1000 * std::sin(i * 3.14159 / 180.0));
113     }
114     return table;
115 }
116
117 // Entire lookup table generated at compile-time, stored in ROM
118 constexpr auto sine_lookup = generate_sine_table();
119
120 // PWM duty cycle table for LED brightness (gamma correction)
121 constexpr auto generate_gamma_table() {
122     std::array<uint8_t, 256> table{};
123     for (int i = 0; i < 256; ++i) {
124         // Gamma correction: output = input^2.2
125         double normalized = i / 255.0;
126         double corrected = std::pow(normalized, 2.2);
127         table[i] = static_cast<uint8_t>(corrected * 255.0);
128     }
129     return table;
130 }
131
132 constexpr auto gamma_table = generate_gamma_table();
133
134 void demonstrate() {
135     std::cout << "\n" << std::string(70, '=') << "\n";
136     std::cout << "==== SECTION 2: ROM-able Arrays - Lookup Tables ===\n";
137     std::cout << std::string(70, '=') << "\n\n";
138
139     std::cout << "1. C-style const array in ROM:\n";
140     std::cout << "    constexpr int sine_table_c[16] = {...};\n";
141     std::cout << "    Sample values: " << sine_table_c[0] << ", "
142             << sine_table_c[2] << ", " << sine_table_c[6] << "\n";
143     std::cout << "    Size: " << sizeof(sine_table_c) << " bytes\n\n";
144
145     std::cout << "2. C++ std::array in ROM (type-safe):\n";
146     std::cout << "    constexpr std::array<int, 16> sine_table_cpp = {...};\n";
```

```

147     std::cout << "      Sample values: " << sine_table_cpp[0] << ", "
148             << sine_table_cpp[2] << ", " << sine_table_cpp[6] << "\n";
149     std::cout << "      Size: " << sine_table_cpp.size() << " elements\n\n";
150
151     std::cout << "3. Generated lookup table (360 entries, compile-time):\n";
152     std::cout << "      Sine values (degrees):\n";
153     std::cout << "          0°: " << sine_lookup[0] << "\n";
154     std::cout << "          30°: " << sine_lookup[30] << "\n";
155     std::cout << "          60°: " << sine_lookup[60] << "\n";
156     std::cout << "          90°: " << sine_lookup[90] << "\n";
157     std::cout << "      Total size: " << sizeof(sine_lookup) << " bytes in ROM\n\n";
158
159     std::cout << "4. Gamma correction table (256 entries):\n";
160     std::cout << "      PWM duty cycles for linear brightness:\n";
161     std::cout << "          Input 0: " << static_cast<int>(gamma_table[0]) << "\n";
162     std::cout << "          Input 64: " << static_cast<int>(gamma_table[64]) << "\n";
163     ;
164     std::cout << "          Input 128: " << static_cast<int>(gamma_table[128]) << "\n";
165     ;
166     std::cout << "          Input 255: " << static_cast<int>(gamma_table[255]) << "\n";
167     std::cout << "      Total size: " << sizeof(gamma_table) << " bytes in ROM\n\n";
168
169     std::cout << "      Embedded benefit: Lookup tables computed at compile-time\n";
170     std::cout << "      ";
171     std::cout << "      No runtime computation needed (saves CPU cycles)\n";
172     std::cout << "      All stored in cheap ROM, not expensive RAM\n";
173 }
174
175 } // namespace rom_arrays
176
177 // SECTION 3: constexpr Objects - Complex Data in ROM
178 // =====
179
180 namespace constexpr_objects {
181
182     // Configuration stored entirely in ROM
183     struct DeviceConfig {
184         const char* device_name;
185         uint32_t serial_number;
186         uint16_t max_voltage_mv;
187         uint8_t num_channels;
188
189         constexpr DeviceConfig(const char* name, uint32_t serial,
190                               uint16_t voltage, uint8_t channels)
191             : device_name(name), serial_number(serial),
192               max_voltage_mv(voltage), num_channels(channels) {}
193

```

```
191 };
```

```
192 
```

```
193 // Entire config in ROM
```

```
194 constexpr DeviceConfig device_config{
```

```
195     "STM32F407",
```

```
196     0x12345678,
```

```
197     3300, // 3.3V
```

```
198     16
```

```
199 };
```

```
200 
```

```
201 // Sensor calibration data in ROM
```

```
202 struct SensorCalibration {
```

```
203     float offset;
```

```
204     float gain;
```

```
205     int16_t temp_coefficient;
```

```
206 
```

```
207     constexpr SensorCalibration(float o, float g, int16_t tc)
```

```
208         : offset(o), gain(g), temp_coefficient(tc) {}
```

```
209 
```

```
210     constexpr float calibrate(int16_t raw_value, int16_t temperature) const {
```

```
211         float temp_correction = temp_coefficient * (temperature - 25) / 1000.0
```

```
212         f;
```

```
213         return (raw_value + offset) * gain * (1.0f + temp_correction);
```

```
214     }
```

```
215 };
```

```
216 
```

```
217 constexpr SensorCalibration pressure_sensor{
```

```
218     -50.0f, // offset
```

```
219     0.125f, // gain
```

```
220     -25 // temp coefficient (ppm/°C)
```

```
221 };
```

```
222 
```

```
223 // Compile-time test of calibration
```

```
224 static_assert(pressure_sensor.calibrate(1000, 25) > 0, "Calibration sanity
```

```
check");
```

```
225 
```

```
226 void demonstrate() {
```

```
227     std::cout << "\n" << std::string(70, '=') << "\n";
```

```
228     std::cout << "==== SECTION 3: constexpr Objects in ROM ====\n";
```

```
229     std::cout << std::string(70, '=') << "\n\n";
```

```
230 
```

```
231     std::cout << "1. Device configuration (ROM):\n";
```

```
232     std::cout << "    Device: " << device_config.device_name << "\n";
```

```
233     std::cout << "    Serial: 0x" << std::hex << device_config.serial_number
```

```
234         << std::dec << "\n";
```

```
235     std::cout << "    Max Voltage: " << device_config.max_voltage_mv << " mV\n";
```

```
236     std::cout << "    Channels: " << static_cast<int>(device_config.
```

```
237         num_channels) << "\n";
```

```
238     std::cout << "    Location: ROM (.rodata section)\n\n";
```

```
239 
```

```
240     std::cout << "2. Sensor calibration with compile-time function:\n";
```

```
241     std::cout << "    Offset: " << pressure_sensor.offset << "\n";
```

```
242     std::cout << "    Gain: " << pressure_sensor.gain << "\n";
```

```
241     std::cout << "    Temp Coeff: " << pressure_sensor.temp_coefficient << "
242         ppm/°C\n\n";
243
243     std::cout << "    Runtime calibration:\n";
244     int16_t raw = 1000;
245     int16_t temp = 25;
246     float calibrated = pressure_sensor.calibrate(raw, temp);
247     std::cout << "        Raw value: " << raw << " at " << temp << "°C\n";
248     std::cout << "        Calibrated: " << calibrated << " Pa\n";
249     std::cout << "        Location: ROM (.rodata section)\n\n";
250
251     std::cout << "    Complex objects can live entirely in ROM\n";
252     std::cout << "    constexpr methods allow compile-time testing\n";
253     std::cout << "    Perfect for embedded: config, calibration, constants\n";
254 }
255
256 } // namespace constexpr_objects
257
258 // =====
259 // SECTION 4: C++20 Features - consteval and constinit
260 // =====
261
262 namespace cpp20_features {
263
264 // consteval - MUST be evaluated at compile-time
265 consteval int must_be_compile_time(int n) {
266     return n * n;
267 }
268
269 // This works - compile-time constant
270 constexpr int square_5 = must_be_compile_time(5);
271
272 // This would NOT compile:
273 // int x = 5;
274 // int result = must_be_compile_time(x); // ERROR: x is not constexpr
275
276 // constinit - Compile-time initialization, but runtime mutable
277 constinit int initialized_at_compile_time = 42;
278
279 // Compare with const/constexpr
280 const int const_value = 42; // Can't modify
281 constexpr int constexpr_value = 42; // Can't modify, must be compile-time
282 // constinit allows modification but guarantees compile-time init
283
284 // Use case: Global variables that need compile-time init but runtime
285 // modification
285 constinit int error_count = 0; // Initialized at compile-time to 0
286
287 // String literals in ROM
288 constexpr std::string_view device_name = "STM32F407";
```

```

289 constexpr std::string_view error_messages[] = {
290     "No error",
291     "Sensor timeout",
292     "Invalid data",
293     "Communication error"
294 };
295
296 void demonstrate() {
297     std::cout << "\n" << std::string(70, '=') << "\n";
298     std::cout << "==== SECTION 4: C++20 - consteval and constinit ===\n";
299     std::cout << std::string(70, '=') << "\n\n";
300
301     std::cout << "1. consteval - Forced compile-time evaluation:\n";
302     std::cout << "    consteval int must_be_compile_time(int n) { return n * n;
303         }\n";
304     std::cout << "    square_5 = " << square_5 << " (computed at compile-time)\n
305         n";
306     std::cout << "    Guarantees no runtime computation\n";
307     std::cout << "    Perfect for embedded: zero runtime cost\n\n";
308
309     std::cout << "2. constinit - Compile-time init, runtime mutable:\n";
310     std::cout << "    constinit int error_count = 0;\n";
311     std::cout << "    Initial value: " << error_count << "\n";
312
313 // Can modify at runtime (unlike const/constexpr)
314     ++error_count;
315     std::cout << "    After increment: " << error_count << "\n";
316     std::cout << "    Initialized at compile-time (no static initialization
317         order issues)\n";
318     std::cout << "    Can be modified at runtime\n\n";
319
320     std::cout << "3. String literals in ROM:\n";
321     std::cout << "    constexpr std::string_view device_name = \"STM32F407\";\n
322         ";
323     std::cout << "    Device: " << device_name << "\n";
324     std::cout << "    String data in ROM, no heap allocation\n\n";
325
326     std::cout << "    Error message table in ROM:\n";
327     for (size_t i = 0; i < 4; ++i) {
328         std::cout << "        Error " << i << ": " << error_messages[i] << "\n";
329     }
330     std::cout << "    All strings in ROM (.rodata section)\n\n";
331
332     std::cout << "    consteval: Forces compile-time (zero runtime cost)\n";
333     std::cout << "    constinit: Safe global init, runtime mutable\n";
334     std::cout << "    string_view: String literals without heap\n";
335 }
336
337 } // namespace cpp20_features
338
339 // =====
340
341 // SECTION 5: Practical Embedded Example - Entire System Config in ROM

```

```
337 // ======  
  
338  
339 namespace embedded_example {  
340  
341 // Pin configuration  
342 struct PinConfig {  
343     uint8_t port;  
344     uint8_t pin;  
345     const char* function;  
346  
347     constexpr PinConfig(uint8_t p, uint8_t pn, const char* func)  
348         : port(p), pin(pn), function(func) {}  
349 };  
350  
351 // All pin configs in ROM  
352 constexpr std::array<PinConfig, 8> pin_configs = {{  
353     {0, 0, "UART_TX"},  
354     {0, 1, "UART_RX"},  
355     {0, 5, "SPI_SCK"},  
356     {0, 6, "SPI_MISO"},  
357     {0, 7, "SPI_MOSI"},  
358     {1, 0, "I2C_SCL"},  
359     {1, 1, "I2C_SDA"},  
360     {2, 13, "LED"}  
361 }};  
362  
363 // Timer configuration  
364 struct TimerConfig {  
365     uint32_t frequency_hz;  
366     uint16_t prescaler;  
367     uint16_t period;  
368  
369     constexpr TimerConfig(uint32_t freq)  
370         : frequency_hz(freq),  
371             prescaler(calculate_prescaler(freq)),  
372             period(calculate_period(freq, calculate_prescaler(freq))) {}  
373  
374 private:  
375     static constexpr uint16_t calculate_prescaler(uint32_t freq) {  
376         uint32_t divisor = freq * 65536;  
377         if (divisor == 0) return 1;  
378         return static_cast<uint16_t>(84000000 / divisor + 1);  
379     }  
380  
381     static constexpr uint16_t calculate_period(uint32_t freq, uint16_t  
382         prescaler) {  
383         if (freq == 0 || prescaler == 0) return 1000;  
384         return static_cast<uint16_t>(84000000 / (freq * prescaler));  
385     }  
386 };  
387 // Timer configs computed at compile-time, stored in ROM
```

```

388 constexpr TimerConfig pwm_timer{1000};           // 1 kHz PWM
389 constexpr TimerConfig adc_timer{10000};          // 10 kHz ADC sampling
390 constexpr TimerConfig led_timer{2};              // 2 Hz LED blink
391
392 // Memory map - register addresses
393 namespace registers {
394     constexpr uint32_t GPIO_BASE = 0x40020000;
395     constexpr uint32_t UART_BASE = 0x40011000;
396     constexpr uint32_t SPI_BASE = 0x40013000;
397     constexpr uint32_t I2C_BASE = 0x40005400;
398     constexpr uint32_t TIM_BASE = 0x40000000;
399 }
400
401 // Protocol constants
402 namespace can_protocol {
403     constexpr uint32_t CAN_ID_STATUS = 0x100;
404     constexpr uint32_t CAN_ID_SENSOR1 = 0x201;
405     constexpr uint32_t CAN_ID_SENSOR2 = 0x202;
406     constexpr uint32_t CAN_ID_COMMAND = 0x300;
407
408     constexpr std::array<uint32_t, 4> filter_ids = {
409         CAN_ID_STATUS, CAN_ID_SENSOR1, CAN_ID_SENSOR2, CAN_ID_COMMAND
410     };
411 }
412
413 void demonstrate() {
414     std::cout << "\n" << std::string(70, '=') << "\n";
415     std::cout << "==== SECTION 5: Embedded System - All Config in ROM ===\n";
416     std::cout << std::string(70, '=') << "\n\n";
417
418     std::cout << "1. Pin Configuration Table (ROM):\n";
419     for (const auto& pin : pin_configs) {
420         std::cout << "    Port " << static_cast<int>(pin.port)
421                     << ", Pin " << static_cast<int>(pin.pin)
422                     << ": " << pin.function << "\n";
423     }
424     std::cout << "    Size: " << sizeof(pin_configs) << " bytes in ROM\n\n";
425
426     std::cout << "2. Timer Configurations (computed at compile-time):\n";
427     std::cout << "    PWM Timer:\n";
428     std::cout << "        Frequency: " << pwm_timer.frequency_hz << " Hz\n";
429     std::cout << "        Prescaler: " << pwm_timer.prescaler << "\n";
430     std::cout << "        Period: " << pwm_timer.period << "\n\n";
431
432     std::cout << "    ADC Timer:\n";
433     std::cout << "        Frequency: " << adc_timer.frequency_hz << " Hz\n";
434     std::cout << "        Prescaler: " << adc_timer.prescaler << "\n";
435     std::cout << "        Period: " << adc_timer.period << "\n\n";
436
437     std::cout << "3. Register Addresses (ROM):\n";
438     std::cout << "    GPIO_BASE: 0x" << std::hex << registers::GPIO_BASE << "\n"
439             "    ";
440     std::cout << "    UART_BASE: 0x" << registers::UART_BASE << "\n";
441     std::cout << "    SPI_BASE: 0x" << registers::SPI_BASE << "\n";

```

```
441     std::cout << "    I2C_BASE: 0x" << registers::I2C_BASE << std::dec << "\n\
442         n";
443
444     std::cout << "4. CAN Protocol IDs (ROM):\n";
445     for (size_t i = 0; i < can_protocol::filter_ids.size(); ++i) {
446         std::cout << "    Filter " << i << ": 0x" << std::hex
447                         << can_protocol::filter_ids[i] << std::dec << "\n";
448     }
449     std::cout << "\n EMBEDDED BENEFITS:\n";
450     std::cout << " • Zero RAM usage for configuration\n";
451     std::cout << " • All configs in cheap Flash ROM\n";
452     std::cout << " • Compile-time validation with static_assert\n";
453     std::cout << " • No runtime initialization overhead\n";
454     std::cout << " • Type-safe, no magic numbers\n";
455 }
456 } // namespace embedded_example
457
458 // =====
459 // SECTION 6: Verifying ROM Placement - Compiler Output
460 // =====
461
462 namespace verifying_placement {
463
464 // These should go to ROM (.rodata)
465 constexpr int rom_value = 42;
466 constexpr std::array<int, 10> rom_array = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
467 const char* const rom_string = "This is in ROM";
468
469 // These go to RAM (.data or .bss)
470 int ram_value = 42;
471 int ram_array[10] = {0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
472
473 void demonstrate() {
474     std::cout << "\n" << std::string(70, '=') << "\n";
475     std::cout << "==== SECTION 6: Verifying ROM Placement ====\n";
476     std::cout << std::string(70, '=') << "\n\n";
477
478     std::cout << "To verify ROM vs RAM placement, use these tools:\n\n";
479
480     std::cout << "1. Using 'nm' command:\n";
481     std::cout << "    $ nm ROMability | grep rom_value\n";
482     std::cout << "    Output shows section:\n";
483     std::cout << "        'r' or 'R' = .rodata (ROM)\n";
484     std::cout << "        'd' or 'D' = .data (RAM)\n";
485     std::cout << "        'b' or 'B' = .bss (uninitialized RAM)\n\n";
486
487     std::cout << "2. Using 'objdump' command:\n";
488     std::cout << "    $ objdump -h ROMability\n";
489     std::cout << "    Shows sections:\n";
```

```

490     std::cout << "      .rodata - Read-only data (ROM/Flash)\n";
491     std::cout << "      .data   - Initialized data (RAM)\n";
492     std::cout << "      .bss    - Uninitialized data (RAM)\n\n";
493
494     std::cout << "3. Using 'size' command:\n";
495     std::cout << "      $ size ROMability\n";
496     std::cout << "      Shows memory usage:\n";
497     std::cout << "      text   - Code + .rodata (ROM/Flash)\n";
498     std::cout << "      data   - Initialized data (RAM)\n";
499     std::cout << "      bss    - Uninitialized data (RAM)\n\n";
500
501     std::cout << "4. GCC-specific: __attribute__((section))\n";
502     std::cout << "      Can explicitly place data in specific section:\n";
503     std::cout << "      __attribute__((section(\".rodata\"))) const int x = 42;\n"
504           "\n";
505
506     std::cout << "5. Embedded: Check linker map file\n";
507     std::cout << "      Linker script (*.ld) and map file show exact placement\n"
508           ;
509
510     std::cout << "      Critical for embedded systems with limited RAM\n\n";
511
512     std::cout << "      Best Practices:\n";
513     std::cout << "      • Use constexpr for guaranteed ROM placement\n";
514     std::cout << "      • Verify with nm/objdump during development\n";
515     std::cout << "      • Check map file for embedded targets\n";
516     std::cout << "      • Profile RAM usage on resource-constrained systems\n";
517 }
518
519 } // namespace verifying_placement
520
521 // SECTION 7: Summary and Best Practices
522
523 void show_summary() {
524     std::cout << "\n" << std::string(70, '=') << "\n";
525     std::cout << "==== ROM-ability in C++ - Complete Summary ===\n";
526     std::cout << std::string(70, '=') << "\n\n";
527
528     std::cout << "          KEYWORD          COMPILER-TIME      LOCATION      MUTABLE      \
529           \n";
530     std::cout << "          const            Maybe          ROM/RAM      No          \
531           \n";
532     std::cout << "          constexpr       Yes           ROM          No          \
533           \n";
534     std::cout << "          consteval       Must be        ROM          No          \
535           \n";
536     std::cout << "          constinit       Yes (init)    RAM          Yes          \

```

```
      n";
534  std::cout << "                                \n\n";
535
536  std::cout << "WHEN TO USE WHAT:\n\n";
537
538  std::cout << "1. constexpr - Most common for ROM data\n";
539  std::cout << " •     Lookup tables (sine, gamma, CRC, etc.)\n";
540  std::cout << " •     Configuration structs\n";
541  std::cout << " •     Constants and arrays\n";
542  std::cout << " •     Compile-time computed values\n\n";
543
544  std::cout << "2. consteval (C++20) - Force compile-time\n";
545  std::cout << " •     Functions that MUST run at compile-time\n";
546  std::cout << " •     Zero runtime cost guarantee\n";
547  std::cout << " •     Configuration validation\n\n";
548
549  std::cout << "3. constinit (C++20) - Global variables\n";
550  std::cout << " •     Globals that need compile-time init\n";
551  std::cout << " •     Avoids static initialization order fiasco\n";
552  std::cout << " •     Runtime mutable (unlike constexpr)\n\n";
553
554  std::cout << "4. const - Use sparingly\n";
555  std::cout << " •     May or may not be ROM\n";
556  std::cout << " •     Prefer constexpr for ROM guarantee\n\n";
557
558  std::cout << "C++ ADVANTAGES OVER C:\n";
559  std::cout << "    constexpr functions - compute at compile-time\n";
560  std::cout << "    constexpr constructors - complex objects in ROM\n";
561  std::cout << "    std::array - type-safe ROM arrays\n";
562  std::cout << "    consteval - guarantee compile-time\n";
563  std::cout << "    Templates - generate ROM data\n";
564  std::cout << "    static_assert - compile-time validation\n\n";
565
566  std::cout << "EMBEDDED SYSTEMS BENEFITS:\n";
567  std::cout << "    Maximize ROM usage (cheap Flash)\n";
568  std::cout << "    Minimize RAM usage (expensive SRAM)\n";
569  std::cout << "    Zero runtime initialization overhead\n";
570  std::cout << "    Compile-time validation\n";
571  std::cout << "    No dynamic memory allocation\n";
572  std::cout << "    Deterministic memory layout\n\n";
573
574  std::cout << "BEST PRACTICES:\n";
575  std::cout << "    1. Use constexpr by default for constants\n";
576  std::cout << "    2. Generate lookup tables at compile-time\n";
577  std::cout << "    3. Store configuration in ROM\n";
578  std::cout << "    4. Use std::array instead of C arrays\n";
579  std::cout << "    5. Use string_view for ROM strings\n";
580  std::cout << "    6. Verify placement with nm/objdump\n";
581  std::cout << "    7. Profile RAM usage on embedded targets\n";
582 }
583
584 // =====
```

```
585 // MAIN FUNCTION
586 //
587 =====
588 int main() {
589     std::cout << "\n";
590     std::cout << "                                     \n";
591     std::cout << "                         ROM-ability in C++ (constexpr & More) \n";
592     std::cout << "                         Placing Data in Read-Only Memory (.rodata) \n";
593     std::cout << "                                     \n";
594     std::cout << "                                     \n";
595     // Section 1: const vs constexpr
596     const_vs_constexpr::demonstrate();
597
598     // Section 2: ROM arrays
599     rom_arrays::demonstrate();
600
601     // Section 3: constexpr objects
602     constexpr_objects::demonstrate();
603
604     // Section 4: C++20 features
605     cpp20_features::demonstrate();
606
607     // Section 5: Embedded example
608     embedded_example::demonstrate();
609
610     // Section 6: Verification
611     verifying_placement::demonstrate();
612
613     // Section 7: Summary
614     show_summary();
615
616     std::cout << "\n" << std::string(70, '=') << "\n";
617     std::cout << "All demonstrations completed!\n";
618     std::cout << std::string(70, '=') << "\n\n";
619
620     std::cout << "KEY TAKEAWAY: Use constexpr for guaranteed ROM placement!\n";
621     ;
622     std::cout << "Perfect for embedded systems: maximize ROM, minimize RAM.\n\n";
623
624     return 0;
}
```

56 Source Code: RangesExamples.cpp

File: src/RangesExamples.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <ranges>
5 #include <algorithm>
6 #include <numeric>
7 #include <functional>
8
9 namespace ranges = std::ranges;
10 namespace views = std::views;
11
12 // =====
13 // 1. BASIC RANGES AND VIEWS
14 // =====
15 void example_basic_ranges() {
16     std::cout << "\n== 1. BASIC RANGES AND VIEWS ==" << std::endl;
17
18     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
19
20     std::cout << "Original: ";
21     for (int n : numbers) {
22         std::cout << n << " ";
23     }
24     std::cout << std::endl;
25
26     // Using ranges::for_each
27     std::cout << "Using ranges::for_each: ";
28     ranges::for_each(numbers, [](int n) {
29         std::cout << n << " ";
30     });
31     std::cout << std::endl;
32 }
33
34 // =====
35 // 2. FILTER VIEW
36 // =====
37 void example_filter_view() {
38     std::cout << "\n== 2. FILTER VIEW ==" << std::endl;
39
40     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
41
42     // Filter even numbers
43     auto even_numbers = numbers | views::filter([](int n) { return n % 2 == 0; });
44
45     std::cout << "Even numbers: ";
46     for (int n : even_numbers) {
47         std::cout << n << " ";
48     }
```

```
49     std::cout << std::endl;
50
51     // Filter numbers greater than 5
52     auto greater_than_5 = numbers | views::filter([](int n) { return n > 5; })
53     ;
54
55     std::cout << "Greater than 5: ";
56     for (int n : greater_than_5) {
57         std::cout << n << " ";
58     }
59     std::cout << std::endl;
60 }
61 // =====
62 // 3. TRANSFORM VIEW
63 // =====
64 void example_transform_view() {
65     std::cout << "\n== 3. TRANSFORM VIEW ==" << std::endl;
66
67     std::vector<int> numbers = {1, 2, 3, 4, 5};
68
69     // Square each number
70     auto squared = numbers | views::transform([](int n) { return n * n; });
71
72     std::cout << "Squared: ";
73     for (int n : squared) {
74         std::cout << n << " ";
75     }
76     std::cout << std::endl;
77
78     // Convert to strings
79     auto strings = numbers | views::transform([](int n) { return std::
80         to_string(n); });
81
82     std::cout << "As strings: ";
83     for (const auto& s : strings) {
84         std::cout << " " << s << " ";
85     }
86     std::cout << std::endl;
87 }
88 // =====
89 // 4. TAKE AND DROP VIEWS
90 // =====
91 void example_take_drop_views() {
92     std::cout << "\n== 4. TAKE AND DROP VIEWS ==" << std::endl;
93
94     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
95
96     // Take first 5 elements
97     auto first_five = numbers | views::take(5);
98     std::cout << "First 5: ";
99     for (int n : first_five) {
100        std::cout << n << " ";
```

```
101     }
102     std::cout << std::endl;
103
104     // Drop first 5 elements
105     auto skip_five = numbers | views::drop(5);
106     std::cout << "Skip 5: ";
107     for (int n : skip_five) {
108         std::cout << n << " ";
109     }
110     std::cout << std::endl;
111
112     // Take while condition is true
113     auto take_while_small = numbers | views::take_while([](int n) { return n <
114         6; });
115     std::cout << "Take while < 6: ";
116     for (int n : take_while_small) {
117         std::cout << n << " ";
118     }
119     std::cout << std::endl;
120 }
121 // =====
122 // 5. COMPOSING VIEWS
123 // =====
124 void example_composing_views() {
125     std::cout << "\n== 5. COMPOSING VIEWS ==" << std::endl;
126
127     std::vector<int> numbers = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
128
129     // Chain multiple operations: filter even, square, take first 3
130     auto result = numbers
131         | views::filter([](int n) { return n % 2 == 0; })
132         | views::transform([](int n) { return n * n; })
133         | views::take(3);
134
135     std::cout << "Even, squared, first 3: ";
136     for (int n : result) {
137         std::cout << n << " ";
138     }
139     std::cout << std::endl;
140 }
141 // =====
142 // 6. REVERSE VIEW
143 // =====
144 void example_reverse_view() {
145     std::cout << "\n== 6. REVERSE VIEW ==" << std::endl;
146
147     std::vector<int> numbers = {1, 2, 3, 4, 5};
148
149     auto reversed = numbers | views::reverse;
150
151     std::cout << "Reversed: ";
152     for (int n : reversed) {
```

```
154         std::cout << n << " ";
155     }
156     std::cout << std::endl;
157 }
158 // =====
159 // 7. IOTA VIEW (GENERATE SEQUENCE)
160 // =====
161 void example_iota_view() {
162     std::cout << "\n== 7. IOTA VIEW (GENERATE SEQUENCE) ==" << std::endl;
163
164     // Generate numbers from 1 to 10
165     auto range1 = views::iota(1, 11);
166     std::cout << "Iota 1 to 10: ";
167     for (int n : range1) {
168         std::cout << n << " ";
169     }
170     std::cout << std::endl;
171
172     // Infinite range (take first 5)
173     auto infinite_range = views::iota(1) | views::take(5);
174     std::cout << "Infinite iota, take 5: ";
175     for (int n : infinite_range) {
176         std::cout << n << " ";
177     }
178     std::cout << std::endl;
179 }
180 }
181 // =====
182 // 8. SPLIT VIEW
183 // =====
184 void example_split_view() {
185     std::cout << "\n== 8. SPLIT VIEW ==" << std::endl;
186
187     std::string text = "Hello World C++ Ranges";
188
189     auto words = text | views::split(' ');
190
191     std::cout << "Split by space:" << std::endl;
192     for (const auto& word : words) {
193         std::cout << " ";
194         for (char c : word) {
195             std::cout << c;
196         }
197         std::cout << "!" << std::endl;
198     }
199 }
200 }
201 // =====
202 // 9. JOIN VIEW
203 // =====
204 void example_join_view() {
205     std::cout << "\n== 9. JOIN VIEW ==" << std::endl;
```

```
208     std::vector<std::vector<int>> nested = {
209         {1, 2, 3},
210         {4, 5},
211         {6, 7, 8, 9}
212     };
213
214     auto flattened = nested | views::join;
215
216     std::cout << "Flattened: ";
217     for (int n : flattened) {
218         std::cout << n << " ";
219     }
220     std::cout << std::endl;
221 }
222
223 // =====
224 // 10. KEYS AND VALUES VIEWS (WITH MAP)
225 // =====
226 void example_keys_values_views() {
227     std::cout << "\n==== 10. KEYS AND VALUES VIEWS ===" << std::endl;
228
229     std::vector<std::pair<std::string, int>> data = {
230         {"Alice", 30},
231         {"Bob", 25},
232         {"Charlie", 35}
233     };
234
235     auto keys = data | views::keys;
236     std::cout << "Keys: ";
237     for (const auto& key : keys) {
238         std::cout << key << " ";
239     }
240     std::cout << std::endl;
241
242     auto values = data | views::values;
243     std::cout << "Values: ";
244     for (int value : values) {
245         std::cout << value << " ";
246     }
247     std::cout << std::endl;
248 }
249
250 // =====
251 // 11. RANGES ALGORITHMS
252 // =====
253 void example_ranges_algorithms() {
254     std::cout << "\n==== 11. RANGES ALGORITHMS ===" << std::endl;
255
256     std::vector<int> numbers = {5, 2, 8, 1, 9, 3, 7, 4, 6};
257
258     // Sort using ranges
259     ranges::sort(numbers);
260     std::cout << "Sorted: ";
261     for (int n : numbers) {
```

```
262         std::cout << n << " ";
263     }
264     std::cout << std::endl;
265
266     // Find element
267     auto it = ranges::find(numbers, 5);
268     if (it != numbers.end()) {
269         std::cout << "Found 5 at position: " << std::distance(numbers.begin(),
270                                         it) << std::endl;
271     }
272
273     // Count elements greater than 5
274     auto count = ranges::count_if(numbers, [](int n) { return n > 5; });
275     std::cout << "Elements > 5: " << count << std::endl;
276 }
277
278 // =====
279 // 12. COMMON VIEW
280 // =====
281 void example_common_view() {
282     std::cout << "\n== 12. COMMON VIEW ==" << std::endl;
283
284     auto range = views::iota(1, 11) | views::filter([](int n) { return n % 2
285                                                 == 0; });
286
287     // Convert to common range (can use with legacy algorithms)
288     auto common_range = range | views::common;
289
290     std::cout << "Common view result: ";
291     for (int n : common_range) {
292         std::cout << n << " ";
293     }
294     std::cout << std::endl;
295 }
296
297 // =====
298 // 13. ENUMERATE VIEW (C++23 preview style)
299 // =====
300 void example_enumerate_style() {
301     std::cout << "\n== 13. ENUMERATE STYLE ==" << std::endl;
302
303     std::vector<std::string> fruits = {"Apple", "Banana", "Cherry", "Date"};
304
305     // Manual enumeration with iota and zip_transform style
306     int index = 0;
307     for (const auto& fruit : fruits) {
308         std::cout << index++ << ":" << fruit << std::endl;
309     }
310
311 // =====
312 // 14. COMPLEX PIPELINE
313 // =====
314 void example_complex_pipeline() {
```

```
314     std::cout << "\n==== 14. COMPLEX PIPELINE ===" << std::endl;
315
316     // Generate numbers, filter, transform, and take
317     auto pipeline = views::iota(1, 101)
318         | views::filter([](int n) { return n % 3 == 0; }) // Divisible by 3
319         | views::transform([](int n) { return n * n; })      // Square
320         | views::take(5);                                // First 5
321
322     std::cout << "First 5 squares of numbers divisible by 3:" << std::endl;
323     for (int n : pipeline) {
324         std::cout << n << " ";
325     }
326     std::cout << std::endl;
327 }
328
329 // =====
330 // 15. CONVERTING VIEWS TO CONTAINERS
331 // =====
332 void example_to_container() {
333     std::cout << "\n==== 15. CONVERTING VIEWS TO CONTAINERS ===" << std::endl;
334
335     auto view = views::iota(1, 11)
336         | views::filter([](int n) { return n % 2 == 0; })
337         | views::transform([](int n) { return n * 2; });
338
339     // Convert to vector
340     std::vector<int> result(view.begin(), view.end());
341
342     std::cout << "Converted to vector: ";
343     for (int n : result) {
344         std::cout << n << " ";
345     }
346     std::cout << std::endl;
347 }
348
349 // =====
350 // MAIN FUNCTION
351 // =====
352 int main() {
353     std::cout << "\n=====" << std::endl;
354     std::cout << "    C++20 RANGES EXAMPLES" << std::endl;
355     std::cout << "=====" << std::endl;
356
357     example_basic_ranges();
358     example_filter_view();
359     example_transform_view();
360     example_take_drop_views();
361     example_composing_views();
362     example_reverse_view();
363     example_iota_view();
364     example_split_view();
365     example_join_view();
```

```
366     example_keys_values_views();
367     example_ranges_algorithms();
368     example_common_view();
369     example_enumerate_style();
370     example_complex_pipeline();
371     example_to_container();

372     std::cout << "\n======" << std::
373         endl;
374     std::cout << "      ALL EXAMPLES COMPLETED" << std::endl;
375     std::cout << "=====\\n" << std::
376         endl;

377     return 0;
378 }
```

57 Source Code: RealTimeProgramming.cpp

File: src/RealTimeProgramming.cpp

Repository: [View on GitHub](#)

```
1 // RealTimeProgramming.cpp
2 // Comprehensive guide to Real-Time Programming in Modern C++
3 //
4 // REAL-TIME SYSTEM CHARACTERISTICS:
5 // 1. Deterministic behavior - predictable execution times
6 // 2. Bounded worst-case execution time (WCET)
7 // 3. Low and predictable latency
8 // 4. No dynamic memory allocation in critical paths
9 // 5. Avoid operations with unbounded execution time
10 //
11 // KEY TOPICS COVERED:
12 // • Big O Notation and Time Complexity
13 // • STL containers for real-time systems
14 // • std::bitset vs std::vector<bool>
15 // • Memory pre-allocation strategies
16 // • RAII and deterministic resource management
17 // • Avoiding heap fragmentation
18 // • Custom allocators and memory pools
19
20 #include <iostream>
21 #include <vector>
22 #include <array>
23 #include <list>
24 #include <bitset>
25 #include <chrono>
26 #include <algorithm>
27 #include <memory>
28 #include <functional>
29 #include <string>
30 #include <string_view>
31 #include <optional>
32 #include <variant>
33 #include <iomanip>
34 #include <cstdint>
35
36 // =====
37 // SECTION 1: Big O Notation - Understanding Time Complexity
38 // =====
39
40 namespace big_o_notation {
41
42 void demonstrate_01() {
43     std::cout << "\nO(1) - Constant Time:\n";
44     std::cout << " • Execution time does not depend on input size\n";
45     std::cout << " • Always takes the same amount of time\n\n";
```

```
46
47     std::array<int, 1000> data;
48     data.fill(42);
49
50     auto start = std::chrono::high_resolution_clock::now();
51
52     // Array/vector element access - O(1)
53     [[maybe_unused]] int value = data[500];
54
55     // Hash table lookup - O(1) average case
56     // Stack push/pop - O(1)
57
58     auto end = std::chrono::high_resolution_clock::now();
59     auto duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
60     start);
61
62     std::cout << " Example: Array element access data[500]\n";
63     std::cout << " Time: " << duration.count() << " ns (constant, regardless
64     of array size)\n";
65     std::cout << "     BEST for real-time systems - predictable!\n";
66 }
67
68 void demonstrate_Ologn() {
69     std::cout << "\nO(log n) - Logarithmic Time:\n";
70     std::cout << " • Execution time grows logarithmically with input size\n";
71     std::cout << " • Doubling input size adds constant time\n\n";
72
73     std::vector<int> data(1000);
74     for (size_t i = 0; i < data.size(); ++i) {
75         data[i] = static_cast<int>(i);
76     }
77
78     auto start = std::chrono::high_resolution_clock::now();
79
80     // Binary search - O(log n)
81     bool found = std::binary_search(data.begin(), data.end(), 500);
82
83     auto end = std::chrono::high_resolution_clock::now();
84     auto duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
85     start);
86
87     std::cout << " Example: Binary search in sorted array of 1000 elements\n";
88     std::cout << "     ";
89     std::cout << " Time: " << duration.count() << " ns\n";
90     std::cout << " Found: " << std::boolalpha << found << "\n";
91     std::cout << " Note: For 1M elements, time increases by only ~10x\n";
92     std::cout << "     ACCEPTABLE for real-time systems with bounded size\n";
93 }
94
95 void demonstrate_On() {
96     std::cout << "\nO(n) - Linear Time:\n";
97     std::cout << " • Execution time grows linearly with input size\n";
98     std::cout << " • Doubling input doubles execution time\n\n";
```

```
96     std::vector<int> data(1000);
97     for (size_t i = 0; i < data.size(); ++i) {
98         data[i] = static_cast<int>(i);
99     }
100
101    auto start = std::chrono::high_resolution_clock::now();
102
103    // Linear search - O(n)
104    auto it = std::find(data.begin(), data.end(), 500);
105
106    auto end = std::chrono::high_resolution_clock::now();
107    auto duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
108        start);
109
110    std::cout << " Example: Linear search through 1000 elements\n";
111    std::cout << " Time: " << duration.count() << " ns\n";
112    std::cout << " Found: " << (it != data.end()) << "\n";
113    std::cout << " USE WITH CAUTION - bound the maximum container size!\n";
114}
115
116void demonstrate_0logn() {
117    std::cout << "\nO(n log n) - Linearithmic Time:\n";
118    std::cout << " • Execution time grows at n * log(n)\n";
119    std::cout << " • Common in efficient sorting algorithms\n\n";
120
121    std::vector<int> data(1000);
122    for (size_t i = 0; i < data.size(); ++i) {
123        data[i] = 1000 - static_cast<int>(i); // Reverse order
124    }
125
126    auto start = std::chrono::high_resolution_clock::now();
127
128    // Sorting - O(n log n) for std::sort
129    std::sort(data.begin(), data.end());
130
131    auto end = std::chrono::high_resolution_clock::now();
132    auto duration = std::chrono::duration_cast<std::chrono::microseconds>(end -
133        start);
134
135    std::cout << " Example: std::sort on 1000 elements\n";
136    std::cout << " Time: " << duration.count() << " s\n";
137    std::cout << " AVOID in time-critical paths - do in initialization
138        phase\n";
139}
140
141void demonstrate() {
142    std::cout << "\n" << std::string(70, '=') << "\n";
143    std::cout << "==== SECTION 1: Big O Notation - Time Complexity ===\n";
144    std::cout << std::string(70, '=') << "\n";
145
146    demonstrate_01();
147    demonstrate_0logn();
148    demonstrate_0n();
149    demonstrate_0logn();
```



```
189     }
190
191     // REAL-TIME THREAD: O(1) operations only!
192     void process_sensor_reading_RT(size_t sensor_id, double value) noexcept {
193         // O(1) - Store latest reading
194         latest_readings_[sensor_id] = value;
195
196         // O(1) - Update status flag
197         sensor_status_.set(sensor_id);
198
199         // O(1) - No complex processing here!
200     }
201
202     // REAL-TIME THREAD: O(1) read access
203     [[nodiscard]] double get_latest_reading_RT(size_t sensor_id) const
204         noexcept {
205         return latest_readings_[sensor_id]; // O(1)
206     }
207
208     // NON-REAL-TIME THREAD: Can use O(n) operations
209     void log_historical_data_NonRT() {
210         // O(n) - Iterate and log (acceptable in background thread)
211         for (size_t i = 0; i < latest_readings_.size(); ++i) {
212             if (sensor_status_.test(i)) {
213                 historical_data_.push_back(latest_readings_[i]);
214             }
215         }
216     }
217
218     // NON-REAL-TIME THREAD: Can use O(n) operations
219     [[nodiscard]] double calculate_average_NonRT() const noexcept {
220         if (historical_data_.empty()) return 0.0;
221
222         // O(n) - Acceptable in non-RT thread
223         double sum = 0.0;
224         for (double val : historical_data_) {
225             sum += val;
226         }
227         return sum / historical_data_.size();
228     }
229
230     // NON-REAL-TIME THREAD: Can use O(n log n) operations
231     [[nodiscard]] double calculate_median_NonRT() {
232         if (historical_data_.empty()) return 0.0;
233
234         // O(n log n) - Sorting is expensive, do in background!
235         auto data_copy = historical_data_; // Copy to avoid modifying
236             original
237         std::sort(data_copy.begin(), data_copy.end());
238
239         size_t mid = data_copy.size() / 2;
240         return data_copy[mid];
241     }
242 };
```

```
241 void demonstrate() {
242     std::cout << "\n" << std::string(70, '=') << "\n";
243     std::cout << "==== SECTION 1.5: Real-Time Thread Architecture ===\n";
244     std::cout << std::string(70, '=') << "\n\n";
245
246     std::cout << "THREAD SEPARATION PRINCIPLE:\n\n";
247
248     std::cout << "REAL-TIME THREADS:\n";
249     std::cout << " • Purpose: Control loops, sensor processing, motor control
250         \n";
251     std::cout << " • Requirements: Deterministic, predictable timing\n";
252     std::cout << " • Allowed: O(1) operations ONLY\n";
253     std::cout << " • Examples:\n";
254     std::cout << "     - Reading sensor value from array\n";
255     std::cout << "     - Updating control output\n";
256     std::cout << "     - Checking/setting status flags (bitset)\n";
257     std::cout << "     - Simple arithmetic calculations\n\n";
258
259     std::cout << "NON-REAL-TIME THREADS:\n";
260     std::cout << " • Purpose: Logging, diagnostics, data aggregation, UI
261         updates\n";
262     std::cout << " • Requirements: Eventually complete, no strict deadlines\n
263         ";
264     std::cout << " • Allowed: O(1), O(log n), O(n) operations\n";
265     std::cout << " • Examples:\n";
266     std::cout << "     - Writing logs to disk\n";
267     std::cout << "     - Calculating statistics (average, median)\n";
268     std::cout << "     - Searching historical data\n";
269     std::cout << "     - Generating reports\n\n";
270
271     std::cout << "EXAMPLE: Sensor System with Thread Separation\n\n";
272
273     SensorSystem system;
274
275     // Simulate real-time thread
276     std::cout << "    REAL-TIME THREAD (1 kHz control loop):\n";
277     auto rt_start = std::chrono::high_resolution_clock::now();
278
279     for (size_t i = 0; i < 10; ++i) {
280         system.process_sensor_reading_RT(i % 10, i * 0.5); // O(1) per
281         reading
282     }
283
284     auto rt_end = std::chrono::high_resolution_clock::now();
285     auto rt_duration = std::chrono::duration_cast<std::chrono::nanoseconds>(
286         rt_end - rt_start);
287
288     std::cout << "        Processed 10 readings in " << rt_duration.count() << "
289         ns\n";
290     std::cout << "        Per-reading time: " << (rt_duration.count() / 10) << "
291         ns (deterministic!)\n\n";
292
293     // Simulate non-real-time thread
```

```
288     std::cout << "  NON-REAL-TIME THREAD (background processing):\n";
289
290     system.log_historical_data_NonRT(); // O(n) - acceptable
291
292     auto bg_start = std::chrono::high_resolution_clock::now();
293     double avg = system.calculate_average_NonRT(); // O(n)
294     auto bg_end = std::chrono::high_resolution_clock::now();
295     auto bg_duration = std::chrono::duration_cast<std::chrono::microseconds>(
296         bg_end - bg_start);
297
298     std::cout << "      Calculated average: " << avg << "\n";
299     std::cout << "      Time: " << bg_duration.count() << " s (non-critical!)\n"
300             "\n";
301
302     std::cout << "      ARCHITECTURE: Real-time thread stays O(1), background
303             handles O(n)\n";
304     std::cout << "      BENEFIT: Control loop remains deterministic and fast\n";
305     std::cout << "      BENEFIT: Complex processing doesn't block time-critical
306             operations\n";
307 }
308
309 } // namespace thread_architecture
310
311 //=====
312
313 // SECTION 2: std::bitset vs std::vector<bool> - The Better Choice
314 //=====
315
316
317
318
319
320
321
322
323
324
325
326
327
328
329
330
331
332
333
```

```
334     constexpr void set_flag(size_t index) noexcept {
335         if (index < N) {
336             flags_.set(index);
337         }
338     }
339
340     // O(1) - Clear a flag
341     constexpr void clear_flag(size_t index) noexcept {
342         if (index < N) {
343             flags_.reset(index);
344         }
345     }
346
347     // O(1) - Toggle a flag
348     constexpr void toggle_flag(size_t index) noexcept {
349         if (index < N) {
350             flags_.flip(index);
351         }
352     }
353
354     // O(1) - Check a flag
355     [[nodiscard]] constexpr bool is_set(size_t index) const noexcept {
356         return index < N ? flags_.test(index) : false;
357     }
358
359     // O(1) - Count set bits (hardware instruction on modern CPUs)
360     [[nodiscard]] constexpr size_t count() const noexcept {
361         return flags_.count();
362     }
363
364     // O(1) - Check if any flags are set
365     [[nodiscard]] constexpr bool any() const noexcept {
366         return flags_.any();
367     }
368
369     // O(1) - Check if all flags are set
370     [[nodiscard]] constexpr bool all() const noexcept {
371         return flags_.all();
372     }
373
374     // O(1) - Check if no flags are set
375     [[nodiscard]] constexpr bool none() const noexcept {
376         return flags_.none();
377     }
378
379     // Bitwise operations - O(1)
380     constexpr RealTimeFlagManager operator&(const RealTimeFlagManager& other)
381         const noexcept {
382         RealTimeFlagManager result;
383         result.flags_ = flags_ & other.flags_;
384         return result;
385     }
386
387     constexpr RealTimeFlagManager operator|(const RealTimeFlagManager& other)
```

```
    const noexcept {
387     RealTimeFlagManager result;
388     result.flags_ = flags_ | other.flags_;
389     return result;
390   }
391 };
392
393 // Example: Sensor status flags for embedded system
394 constexpr size_t NUM_SENSORS = 32;
395
396 enum class SensorStatus : size_t {
397   TEMPERATURE_OK = 0,
398   PRESSURE_OK = 1,
399   HUMIDITY_OK = 2,
400   VOLTAGE_OK = 3,
401   CURRENT_OK = 4,
402   GPS_LOCK = 5,
403   IMU_CALIBRATED = 6,
404   COMMUNICATION_OK = 7,
405   // ... up to 32 sensors
406 };
407
408 void demonstrate() {
409   std::cout << "\n" << std::string(70, '=') << "\n";
410   std::cout << "==== SECTION 2: std::bitset vs std::vector<bool> ===\n";
411   std::cout << std::string(70, '=') << "\n\n";
412
413   std::cout << "WHY std::vector<bool> IS PROBLEMATIC:\n";
414   std::cout << "  Space-optimized specialization (1 bit per element)\n";
415   std::cout << "  operator[] returns proxy object, not bool&\n";
416   std::cout << "  Cannot take address of elements\n";
417   std::cout << "  Non-standard container behavior\n";
418   std::cout << "  Dynamic memory allocation\n";
419   std::cout << "  Unpredictable performance\n\n";
420
421   std::cout << "WHY std::bitset IS BETTER FOR REAL-TIME:\n";
422   std::cout << "  Fixed size at compile time (no heap allocation)\n";
423   std::cout << "  O(1) access and modification\n";
424   std::cout << "  Efficient bitwise operations (AND, OR, XOR)\n";
425   std::cout << "  Hardware-optimized bit counting\n";
426   std::cout << "  Standard, predictable behavior\n";
427   std::cout << "  Deterministic performance\n\n";
428
429 // Demonstrate real-time flag manager
430 RealTimeFlagManager<NUM_SENSORS> sensor_status;
431
432 std::cout << "EXAMPLE: Real-Time Sensor Status Manager\n";
433 std::cout << "  Using std::bitset<32> for 32 sensor flags\n\n";
434
435 // Set some flags
436 sensor_status.set_flag(static_cast<size_t>(SensorStatus::TEMPERATURE_OK));
437 sensor_status.set_flag(static_cast<size_t>(SensorStatus::PRESSURE_OK));
438 sensor_status.set_flag(static_cast<size_t>(SensorStatus::GPS_LOCK));
439
```

```

440     std::cout << " Set flags: TEMPERATURE_OK, PRESSURE_OK, GPS_LOCK\n";
441     std::cout << " Active sensors: " << sensor_status.count() << " / " <<
442         NUM_SENSORS << "\n";
443     std::cout << " All sensors OK? " << std::boolalpha << sensor_status.all()
444         << "\n";
445     std::cout << " Any sensor OK? " << sensor_status.any() << "\n";
446
447     // Check specific flag
448     bool temp_ok = sensor_status.is_set(static_cast<size_t>(SensorStatus::
449                                         TEMPERATURE_OK));
450     std::cout << " Temperature sensor OK? " << temp_ok << "\n\n";
451
452     // Timing comparison
453     constexpr size_t ITERATIONS = 1000000;
454
455     std::bitset<64> bitset_flags;
456     auto start_bitset = std::chrono::high_resolution_clock::now();
457     for (size_t i = 0; i < ITERATIONS; ++i) {
458         bitset_flags.set(i % 64);
459         [[maybe_unused]] bool val = bitset_flags.test(i % 64);
460     }
461     auto end_bitset = std::chrono::high_resolution_clock::now();
462     auto bitset_duration = std::chrono::duration_cast<std::chrono::
463                                         microseconds>(end_bitset - start_bitset);
464
465     std::vector<bool> vector_bool(64, false);
466     auto start_vector = std::chrono::high_resolution_clock::now();
467     for (size_t i = 0; i < ITERATIONS; ++i) {
468         vector_bool[i % 64] = true;
469         [[maybe_unused]] bool val = vector_bool[i % 64];
470     }
471     auto end_vector = std::chrono::high_resolution_clock::now();
472     auto vector_duration = std::chrono::duration_cast<std::chrono::
473                                         microseconds>(end_vector - start_vector);
474
475     std::cout << "PERFORMANCE COMPARISON (" << ITERATIONS << " operations):\n"
476     ;
477     std::cout << " std::bitset<64>: " << std::setw(8) << bitset_duration.
478         count() << " s\n";
479     std::cout << " std::vector<bool>: " << std::setw(8) << vector_duration.
480         count() << " s\n";
481     std::cout << " Speedup: " << std::fixed << std::setprecision
482         (2)
483             << (static_cast<double>(vector_duration.count()) /
484                 bitset_duration.count()) << "x\n\n";
485
486     std::cout << " RECOMMENDATION: Use std::bitset for real-time flag
487         management!\n";
488 }
489 } // namespace bitset_vs_vector_bool
490
491 // =====

```

```
482 // SECTION 3: STL Containers - Real-Time Best Practices
483 //
484 //=====
485
486 namespace stl_containers_realtime {
487
488 // Container Complexity Reference:
489 //
490 // std::vector:
491 //   - Access:      O(1)
492 //   - Insert front: O(n)
493 //   - Insert back: O(1) amortized, O(n) worst case (reallocation!)
494 //   - Insert mid:  O(n)
495 //   - Real-time:   Use reserve() to pre-allocate!
496 //
497 // std::array:
498 //   - Access:      O(1)
499 //   - Size:        Fixed at compile time
500 //   - Real-time:   PERFECT - no dynamic allocation, stack-based
501 //
502 // std::deque:
503 //   - Access:      O(1)
504 //   - Insert front: O(1)
505 //   - Insert back: O(1)
506 //   - Real-time:   Acceptable if size bounded
507 //
508 // std::list:
509 //   - Access:      O(n) - must traverse!
510 //   - Insert:      O(1) if you have iterator
511 //   - Real-time:   AVOID - dynamic allocation per element, poor cache
512 //
513 // std::map/std::set:
514 //   - Access:      O(log n)
515 //   - Insert:      O(log n)
516 //   - Real-time:   Use with custom allocator or bounded size
517
518 // Example 1: Pre-allocated std::vector - The Right Way
519 class RealTimeDataBuffer {
520     private:
521         static constexpr size_t MAX_SAMPLES = 1000;
522         std::vector<double> samples_;
523
524     public:
525         RealTimeDataBuffer() {
526             // CRITICAL: Pre-allocate during initialization
527             // This prevents reallocation during real-time operation
528             samples_.reserve(MAX_SAMPLES);
529
530             std::cout << " Buffer created with capacity: " << samples_.capacity()
531                         << "\n";
532             std::cout << " No reallocation will occur until this limit\n";
533         }
534 }
```

```
532 // O(1) - Add sample (no reallocation if within capacity)
533 bool add_sample(double value) noexcept {
534     if (samples_.size() < MAX_SAMPLES) {
535         samples_.push_back(value); // O(1) - deterministic!
536         return true;
537     }
538     return false; // Buffer full
539 }
540
541 // O(1) - Get sample
542 [[nodiscard]] std::optional<double> get_sample(size_t index) const
543     noexcept {
544     if (index < samples_.size()) {
545         return samples_[index];
546     }
547     return std::nullopt;
548 }
549
550 // O(n) - Clear buffer (but no deallocation!)
551 void clear() noexcept {
552     samples_.clear();
553     // Capacity remains unchanged - memory is retained!
554 }
555
556 [[nodiscard]] size_t size() const noexcept { return samples_.size(); }
557 [[nodiscard]] size_t capacity() const noexcept { return samples_.capacity();
558 }
559 };
560
561 // Example 2: Fixed-size std::array - Even Better
562 template<size_t N>
563 class CircularBuffer {
564 private:
565     std::array<double, N> buffer_;
566     size_t head_ = 0;
567     size_t count_ = 0;
568
569 public:
570     // O(1) - Add element (overwrites oldest if full)
571     constexpr void push(double value) noexcept {
572         buffer_[head_] = value;
573         head_ = (head_ + 1) % N;
574         if (count_ < N) {
575             ++count_;
576         }
577     }
578
579     // O(1) - Get element (0 = most recent)
580     [[nodiscard]] constexpr std::optional<double> get(size_t index) const
581         noexcept {
582         if (index >= count_) {
583             return std::nullopt;
584         }
585     }
586 }
```

```

583     size_t actual_index = (head_ + N - count_ + index) % N;
584     return buffer_[actual_index];
585 }
586
587 [[nodiscard]] constexpr size_t size() const noexcept { return count_; }
588 [[nodiscard]] constexpr bool is_full() const noexcept { return count_ == N;
589 ; }
590
591 // Statistics - O(n) but bounded by N
592 [[nodiscard]] double average() const noexcept {
593     if (count_ == 0) return 0.0;
594     double sum = 0.0;
595     for (size_t i = 0; i < count_; ++i) {
596         size_t idx = (head_ + N - count_ + i) % N;
597         sum += buffer_[idx];
598     }
599     return sum / count_;
600 }
601
602 void demonstrate() {
603     std::cout << "\n" << std::string(70, '=') << "\n";
604     std::cout << "==== SECTION 3: STL Containers - Real-Time Best Practices
605      ===\n";
606     std::cout << std::string(70, '=') << "\n\n";
607
608     std::cout << "CONTAINER SELECTION FOR REAL-TIME SYSTEMS:\n\n";
609
610     std::cout << " PREFERRED:\n";
611     std::cout << " 1. std::array<T, N>           - O(1) access, no heap,
612       compile-time size\n";
613     std::cout << " 2. std::vector<T> + reserve() - O(1) access, pre-allocated
614       \n";
615     std::cout << " 3. std::bitset<N>           - O(1) bit ops, no heap\n";
616     std::cout << " 4. std::string_view        - O(1) string viewing, no
617       allocation\n\n";
618
619     std::cout << " USE WITH CAUTION (bound size!):\n";
620     std::cout << " • std::deque<T>           - O(1) both ends, but
621       allocates chunks\n";
622     std::cout << " • std::map/set<T>        - O(log n), allocates per
623       element\n\n";
624
625     std::cout << " AVOID:\n";
626     std::cout << " • std::list<T>           - Poor cache locality, alloc
627       per element\n";
628     std::cout << " • std::forward_list<T>    - Poor cache locality\n";
629     std::cout << " • std::vector<bool>       - Use std::bitset instead!\n
630       ";
631     std::cout << " • Unbounded growth containers - Always set max size!\n\n";
632
633 // Demonstrate pre-allocated vector
634 std::cout << "EXAMPLE 1: Pre-allocated std::vector\n";
635 RealTimeDataBuffer buffer;

```

```
628     for (int i = 0; i < 100; ++i) {
629         buffer.add_sample(i * 0.1);
630     }
631
632     std::cout << "    Added 100 samples\n";
633     std::cout << "    Current size: " << buffer.size() << "\n";
634     std::cout << "    Capacity: " << buffer.capacity() << "\n";
635     std::cout << "    No reallocation occurred - deterministic O(1) insertion
636           !\n\n";
637
638 // Demonstrate fixed-size array
639 std::cout << "EXAMPLE 2: Fixed-size circular buffer (std::array<T, N>)\n";
640 CircularBuffer<10> circ_buffer;
641
642 for (int i = 0; i < 15; ++i) {
643     circ_buffer.push(i * 1.5);
644 }
645
646 std::cout << "    Pushed 15 values into buffer of size 10\n";
647 std::cout << "    Current size: " << circ_buffer.size() << "\n";
648 std::cout << "    Average: " << circ_buffer.average() << "\n";
649 std::cout << "    No heap allocation - pure stack-based, deterministic!\n\
650           n";
651
652 // Demonstrate reserve() importance
653 std::cout << "CRITICAL: Always use reserve() for std::vector in real-time
654           code!\\n\\n";
655
656 std::vector<int> bad_vector; // No reserve
657 auto start_bad = std::chrono::high_resolution_clock::now();
658 for (int i = 0; i < 1000; ++i) {
659     bad_vector.push_back(i); // May trigger reallocations!
660 }
661 auto end_bad = std::chrono::high_resolution_clock::now();
662 auto bad_duration = std::chrono::duration_cast<std::chrono::microseconds>(
663     end_bad - start_bad);
664
665 std::vector<int> good_vector;
666 good_vector.reserve(1000); // Pre-allocate
667 auto start_good = std::chrono::high_resolution_clock::now();
668 for (int i = 0; i < 1000; ++i) {
669     good_vector.push_back(i); // No reallocations!
670 }
671 auto end_good = std::chrono::high_resolution_clock::now();
672 auto good_duration = std::chrono::duration_cast<std::chrono::microseconds>(
673     end_good - start_good);
674
675 std::cout << "    Without reserve(): " << bad_duration.count() << " s (
676           unpredictable!)\n";
677 std::cout << "    With reserve():      " << good_duration.count() << " s (
678           deterministic!)\n";
679 std::cout << "    Speedup:           " << std::fixed << std::setprecision(2)
680           << (static_cast<double>(bad_duration.count()) / good_duration.
```

```
        count()) << "x\n\n";  
675  
676     std::cout << "    GOLDEN RULE: reserve() prevents non-deterministic  
       reallocations!\n";  
677 }  
678 } // namespace stl_containers_realtime  
680 //  
=====  
682 // SECTION 3.5: std::list::splice() - O(1) Element Movement  
683 //  
=====  
684  
685 namespace list_splice_realtime {  
686  
687 // std::list::splice() is PERFECT for real-time systems because:  
688 // 1. O(1) complexity for moving elements (constant time!)  
689 // 2. NO MEMORY ALLOCATION - just pointer manipulation  
690 // 3. NO COPYING/MOVING - elements stay in place  
691 // 4. Deterministic and predictable performance  
692 // 5. Iterators remain valid after splice  
693 //  
694 // Use cases in real-time systems:  
695 // - Free lists / object pools  
696 // - Task queue management  
697 // - Event scheduling  
698 // - Moving data between priority queues  
699  
700 struct Task {  
701     int id;  
702     std::string name;  
703     int priority;  
704  
705     Task(int i, std::string n, int p) : id(i), name(std::move(n)), priority(p)  
    {}  
706 };  
707  
708 void demonstrate() {  
709     std::cout << "\n" << std::string(80, '=') << "\n";  
710     std::cout << "SECTION 3.5: std::list::splice() - O(1) Element Movement\n";  
711     std::cout << std::string(80, '=') << "\n\n";  
712  
713     std::cout << "WHY splice() IS CRITICAL FOR REAL-TIME SYSTEMS:\n";  
714     std::cout << " • O(1) constant time - no iteration required\n";  
715     std::cout << " • NO memory allocation - just rewrites pointers\n";  
716     std::cout << " • NO copying/moving - elements stay in original memory\n";  
717     std::cout << " • Iterators remain valid - predictable behavior\n";  
718     std::cout << " • Deterministic performance - perfect for hard real-time\n  
    \n";  
719  
720 // =====
```

```

721 // EXAMPLE 1: splice() entire list - O(1)
722 // =====
723 std::cout << std::string(80, '-') << "\n";
724 std::cout << "EXAMPLE 1: Splice Entire List - O(1) Operation\n";
725 std::cout << std::string(80, '-') << "\n\n";
726
727 std::list<Task> active_tasks;
728 active_tasks.emplace_back(1, "Process Sensor Data", 10);
729 active_tasks.emplace_back(2, "Update Control Loop", 20);
730 active_tasks.emplace_back(3, "Send Telemetry", 5);
731
732 std::list<Task> pending_tasks;
733 pending_tasks.emplace_back(4, "Log Event", 1);
734 pending_tasks.emplace_back(5, "Check Diagnostics", 3);
735
736 std::cout << "BEFORE splice():\n";
737 std::cout << " Active tasks: " << active_tasks.size() << "\n";
738 for (const auto& t : active_tasks) {
739     std::cout << " Task " << t.id << ": " << t.name << " (priority: "
740         << t.priority << ")\n";
741 }
742 std::cout << " Pending tasks: " << pending_tasks.size() << "\n";
743 for (const auto& t : pending_tasks) {
744     std::cout << " Task " << t.id << ": " << t.name << " (priority: "
745         << t.priority << ")\n";
746 }
747
748 // Splice entire pending_tasks list into active_tasks at the end
749 // This is O(1) - just rewires a few pointers!
750 auto start = std::chrono::high_resolution_clock::now();
751 active_tasks.splice(active_tasks.end(), pending_tasks);
752 auto end = std::chrono::high_resolution_clock::now();
753 auto duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
754     start);
755
756 std::cout << "\nAFTER splice(active.end(), pending):\n";
757 std::cout << " Active tasks: " << active_tasks.size() << "\n";
758 for (const auto& t : active_tasks) {
759     std::cout << " Task " << t.id << ": " << t.name << " (priority: "
760         << t.priority << ")\n";
761 }
762 std::cout << " Pending tasks: " << pending_tasks.size() << " (empty!)\n";
763 std::cout << " Time taken: " << duration.count() << " ns (O(1) -
764     constant time!)\n";
765 std::cout << " NO allocation, NO copying, just pointer rewiring!\n\n";
766
767 // =====
768 // EXAMPLE 2: splice() single element - O(1)
769 // =====
770 std::cout << std::string(80, '-') << "\n";
771 std::cout << "EXAMPLE 2: Splice Single Element - O(1) Operation\n";
772 std::cout << std::string(80, '-') << "\n\n";
773
774 std::list<Task> high_priority;

```

```

770     high_priority.emplace_back(10, "Critical Shutdown", 100);
771     high_priority.emplace_back(11, "Emergency Stop", 99);
772
773     std::list<Task> normal_priority;
774     normal_priority.emplace_back(20, "Routine Check", 10);
775     normal_priority.emplace_back(21, "Update Display", 8);
776     normal_priority.emplace_back(22, "Log Status", 5);
777
778     std::cout << "SCENARIO: Emergency task detected in normal queue!\n\n";
779
780     std::cout << "BEFORE splice():\n";
781     std::cout << "  High priority: " << high_priority.size() << " tasks\n";
782     std::cout << "  Normal priority: " << normal_priority.size() << " tasks\n"
783     ;
784     for (const auto& t : normal_priority) {
785         std::cout << "    Task " << t.id << ": " << t.name << " (priority: "
786         << t.priority << ")\n";
787     }
788
789     // Find the "Update Display" task and move it to high priority
790     auto it = std::find_if(normal_priority.begin(), normal_priority.end(),
791                           [] (const Task& t) { return t.id == 21; });
792
793     if (it != normal_priority.end()) {
794         std::cout << "\n  Found Task 21: " << it->name << " - moving to high
795         priority!\n";
796
797         // Splice single element - O(1) !
798         start = std::chrono::high_resolution_clock::now();
799         high_priority.splice(high_priority.end(), normal_priority, it);
800         end = std::chrono::high_resolution_clock::now();
801         duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
802             start);
803     }
804
805     std::cout << "\nAFTER splice(high.end(), normal, iterator):\n";
806     std::cout << "  High priority: " << high_priority.size() << " tasks\n";
807     for (const auto& t : high_priority) {
808         std::cout << "    Task " << t.id << ": " << t.name << " (priority: "
809         << t.priority << ")\n";
810     }
811     std::cout << "  Normal priority: " << normal_priority.size() << " tasks\n"
812     ;
813     for (const auto& t : normal_priority) {
814         std::cout << "    Task " << t.id << ": " << t.name << " (priority: "
815         << t.priority << ")\n";
816     }
817     std::cout << "  Time taken: " << duration.count() << " ns (O(1) -
818         constant time!)\n";
819     std::cout << "  Task moved instantly without copying!\n\n";
820
821     // =====
822     // EXAMPLE 3: splice() range of elements - O(n) where n = range size
823     // =====

```

```
816     std::cout << std::string(80, '-') << "\n";
817     std::cout << "EXAMPLE 3: Splice Range of Elements - O(n) but NO Allocation
818             \n";
819     std::cout << std::string(80, '-') << "\n\n";
820
821     std::list<int> source = {10, 20, 30, 40, 50, 60, 70, 80};
822     std::list<int> dest = {1, 2, 3};
823
824     std::cout << "BEFORE splice():\n";
825     std::cout << "    Source: ";
826     for (int v : source) std::cout << v << " ";
827     std::cout << "\n    Dest: ";
828     for (int v : dest) std::cout << v << " ";
829     std::cout << "\n";
830
831     // Move elements 30, 40, 50 from source to dest
832     auto range_start = std::find(source.begin(), source.end(), 30);
833     auto range_end = std::find(source.begin(), source.end(), 60); // One past
834     last element
835
836     std::cout << "\n    Moving range [30, 40, 50] from source to dest...\n";
837
838     // Splice range - O(n) where n = distance(range_start, range_end)
839     // But still NO memory allocation!
840     start = std::chrono::high_resolution_clock::now();
841     dest.splice(dest.end(), source, range_start, range_end);
842     end = std::chrono::high_resolution_clock::now();
843     duration = std::chrono::duration_cast<std::chrono::nanoseconds>(end -
844                           start);
845
846     std::cout << "\nAFTER splice(dest.end(), source, first, last):\n";
847     std::cout << "    Source: ";
848     for (int v : source) std::cout << v << " ";
849     std::cout << "\n    Dest: ";
850     for (int v : dest) std::cout << v << " ";
851     std::cout << "\n";
852     std::cout << "    Time taken: " << duration.count() << " ns (O(n) but
853             predictable!)\n";
854     std::cout << "    NO allocation - just pointer updates for range!\n\n";
855
856     // =====
857     // EXAMPLE 4: Real-time pool management with splice()
858     // =====
859     std::cout << std::string(80, '-') << "\n";
860     std::cout << "EXAMPLE 4: Free List Pool Management - Real-Time Pattern\n";
861     std::cout << std::string(80, '-') << "\n\n";
862
863     std::cout << "SCENARIO: Object pool using splice() for O(1) allocation/
864             deallocation\n\n";
865
866     struct Buffer {
867         int id;
868         std::array<char, 256> data;
869         explicit Buffer(int i) : id(i), data{} {}
```

```
865     };
866
867     // Free pool (available buffers)
868     std::list<Buffer> free_pool;
869     for (int i = 0; i < 5; ++i) {
870         free_pool.emplace_back(i);
871     }
872
873     // Active pool (in-use buffers)
874     std::list<Buffer> active_pool;
875
876     std::cout << "Initial state:\n";
877     std::cout << "    Free pool: " << free_pool.size() << " buffers\n";
878     std::cout << "    Active pool: " << active_pool.size() << " buffers\n\n";
879
880     // Allocate buffer from free pool - O(1)
881     std::cout << "Allocating 3 buffers from free pool...\n";
882     for (int i = 0; i < 3; ++i) {
883         auto it = free_pool.begin();
884         std::cout << "    Allocating buffer " << it->id << "\n";
885         active_pool.splice(active_pool.end(), free_pool, it); // O(1)!
886     }
887
888     std::cout << "\nAfter allocation:\n";
889     std::cout << "    Free pool: " << free_pool.size() << " buffers\n";
890     std::cout << "    Active pool: " << active_pool.size() << " buffers (" ;
891     for (const auto& b : active_pool) std::cout << b.id << " ";
892     std::cout << ")\n\n";
893
894     // Deallocation buffer back to free pool - O(1)
895     std::cout << "Deallocating buffer 1 back to free pool...\n";
896     auto to_free = std::find_if(active_pool.begin(), active_pool.end(),
897                                 [] (const Buffer& b) { return b.id == 1; });
898     if (to_free != active_pool.end()) {
899         free_pool.splice(free_pool.end(), active_pool, to_free); // O(1) !
900         std::cout << "    Buffer 1 returned to free pool\n";
901     }
902
903     std::cout << "\nFinal state:\n";
904     std::cout << "    Free pool: " << free_pool.size() << " buffers\n";
905     std::cout << "    Active pool: " << active_pool.size() << " buffers (" ;
906     for (const auto& b : active_pool) std::cout << b.id << " ";
907     std::cout << ")\n\n";
908
909     std::cout << "    Pool allocation/deallocation in O(1) with splice()\n";
910     std::cout << "    NO dynamic allocation - perfect for real-time systems!\n";
911     std::cout << "\n";
912     // =====
913     // KEY TAKEAWAYS
914     // =====
915     std::cout << std::string(80, '=') << "\n";
916     std::cout << "KEY TAKEAWAYS: Why splice() is Essential for Real-Time C++\n";
917     std::cout << "\n";
```

```
917     std::cout << std::string(80, '=') << "\n\n";
918
919     std::cout << "1. PERFORMANCE:\n";
920     std::cout << " • splice() entire list: O(1) - constant time\n";
921     std::cout << " • splice() single element: O(1) - constant time\n";
922     std::cout << " • splice() range: O(n) where n = range size (but
923         predictable!)\n\n";
924
925     std::cout << "2. MEMORY BEHAVIOR:\n";
926     std::cout << " • NO memory allocation - just pointer manipulation\n";
927     std::cout << " • NO copying or moving - elements stay in original memory
928         \n";
929     std::cout << " • Deterministic and bounded - perfect for hard real-time\
930         \n\n";
931
932     std::cout << "3. ITERATOR VALIDITY:\n";
933     std::cout << " • All iterators, pointers, and references remain valid\n"
934         ;
935     std::cout << " • Safe to cache iterators across splice operations\n\n";
936
937     std::cout << "4. REAL-TIME USE CASES:\n";
938     std::cout << " • Free list / object pool management\n";
939     std::cout << " • Task queue reordering (priority changes)\n";
940     std::cout << " • Event scheduling and rescheduling\n";
941     std::cout << " • Moving data between priority queues\n";
942     std::cout << " • Load balancing across worker queues\n\n";
943
944     std::cout << "5. ALTERNATIVES ARE WORSE:\n";
945     std::cout << " • std::copy() + erase(): Requires copying, O(n) erase\n";
946     std::cout << " • std::move() + erase(): Still requires move, O(n) erase\
947         \n";
948     std::cout << " • Manual reallocation: Unpredictable timing, allocation
949         overhead\n";
950     std::cout << " • splice() is THE optimal solution for list element
951         movement!\n\n";
952
953     std::cout << " GOLDEN RULE: Use splice() when you need to move elements\n"
954         ";
955     std::cout << " between std::list containers in real-time critical code!\n"
956         ";
957
958 } // namespace list_splice_realtime
959
960 // =====
961
962 // SECTION 4: Memory Management - RAII and Custom Allocators
963 // =====
964
965
966 namespace memory_management {
```

```
958 // RAI (Resource Acquisition Is Initialization)
959 // - Resources acquired in constructor
960 // - Resources released in destructor
961 // - Deterministic, exception-safe cleanup
962 // - No manual memory management needed
963
964 // Example: Real-time resource manager using RAI
965 template<typename T, size_t PoolSize>
966 class MemoryPool {
967     private:
968         std::array<T, PoolSize> pool_;
969         std::array<bool, PoolSize> in_use_;
970
971     public:
972         MemoryPool() {
973             in_use_.fill(false);
974             std::cout << "    Memory pool created: " << PoolSize << " objects of
975                 size "
976                 << sizeof(T) << " bytes\n";
977             std::cout << "    Total pool size: " << (PoolSize * sizeof(T)) << "
978                 bytes\n";
979         }
980
981         // Acquire object from pool - O(n) but bounded by PoolSize
982         [[nodiscard]] T* acquire() noexcept {
983             for (size_t i = 0; i < PoolSize; ++i) {
984                 if (!in_use_[i]) {
985                     in_use_[i] = true;
986                     return &pool_[i];
987                 }
988             }
989             return nullptr; // Pool exhausted
990         }
991
992         // Release object back to pool - O(1)
993         void release(T* ptr) noexcept {
994             if (!ptr) return;
995
996             // Find the object in pool
997             for (size_t i = 0; i < PoolSize; ++i) {
998                 if (&pool_[i] == ptr) {
999                     in_use_[i] = false;
1000                     return;
1001                 }
1002             }
1003         }
1004
1005         [[nodiscard]] size_t available() const noexcept {
1006             return std::count(in_use_.begin(), in_use_.end(), false);
1007         }
1008
1009     // RAI wrapper for pool-allocated object
1010     template<typename T>
```

```
1010 class PoolPtr {
1011     private:
1012         T* ptr_;
1013         std::function<void(T*)> deleter_;
1014
1015     public:
1016         PoolPtr(T* ptr, std::function<void(T*)> deleter)
1017             : ptr_(ptr), deleter_(std::move(deleter)) {}
1018
1019         ~PoolPtr() {
1020             if (ptr_ && deleter_) {
1021                 deleter_(ptr_);
1022             }
1023         }
1024
1025         // Delete copy operations
1026         PoolPtr(const PoolPtr&) = delete;
1027         PoolPtr& operator=(const PoolPtr&) = delete;
1028
1029         // Move operations
1030         PoolPtr(PoolPtr&& other) noexcept
1031             : ptr_(other.ptr_), deleter_(std::move(other.deleter_)) {
1032                 other.ptr_ = nullptr;
1033             }
1034
1035         PoolPtr& operator=(PoolPtr&& other) noexcept {
1036             if (this != &other) {
1037                 if (ptr_ && deleter_) {
1038                     deleter_(ptr_);
1039                 }
1040                 ptr_ = other.ptr_;
1041                 deleter_ = std::move(other.deleter_);
1042                 other.ptr_ = nullptr;
1043             }
1044             return *this;
1045         }
1046
1047         T* get() noexcept { return ptr_; }
1048         const T* get() const noexcept { return ptr_; }
1049
1050         T& operator*() noexcept { return *ptr_; }
1051         const T& operator*() const noexcept { return *ptr_; }
1052
1053         T* operator->() noexcept { return ptr_; }
1054         const T* operator->() const noexcept { return ptr_; }
1055
1056         explicit operator bool() const noexcept { return ptr_ != nullptr; }
1057     };
1058
1059     struct SensorData {
1060         double temperature;
1061         double pressure;
1062         uint64_t timestamp;
1063     };
}
```

```
1064     SensorData() : temperature(0.0), pressure(0.0), timestamp(0) {}
1065 };
1066
1067 void demonstrate() {
1068     std::cout << "\n" << std::string(70, '=') << "\n";
1069     std::cout << "==== SECTION 4: Memory Management - RAI and Memory Pools
1070         ==\n";
1071     std::cout << std::string(70, '=') << "\n\n";
1072     std::cout << "REAL-TIME MEMORY MANAGEMENT PRINCIPLES:\n\n";
1073
1074     std::cout << " DO:\n";
1075     std::cout << " 1. Pre-allocate all memory during initialization\n";
1076     std::cout << " 2. Use memory pools for frequent alloc/dealloc\n";
1077     std::cout << " 3. Use RAI for deterministic resource cleanup\n";
1078     std::cout << " 4. Prefer stack allocation over heap\n";
1079     std::cout << " 5. Use std::unique_ptr for ownership (minimal overhead)\n\n
1080         n";
1081
1082     std::cout << " DON'T:\n";
1083     std::cout << " 1. Call new/delete in time-critical paths\n";
1084     std::cout << " 2. Use std::shared_ptr in tight loops (atomic overhead)\n
1085         ";
1086     std::cout << " 3. Allow unbounded memory growth\n";
1087     std::cout << " 4. Rely on garbage collection\n";
1088     std::cout << " 5. Use dynamic allocation with unpredictable size\n\n";
1089
1090     std::cout << "EXAMPLE: Memory Pool with RAI\n";
1091
1092     // Create memory pool (during initialization phase)
1093     MemoryPool<SensorData, 100> sensor_pool;
1094
1095     std::cout << " Available slots: " << sensor_pool.available() << "\n\n";
1096
1097     // Acquire objects from pool (during real-time operation)
1098     {
1099         auto sensor1 = PoolPtr<SensorData>(
1100             sensor_pool.acquire(),
1101             [&sensor_pool](SensorData* ptr) { sensor_pool.release(ptr); }
1102         );
1103
1104         auto sensor2 = PoolPtr<SensorData>(
1105             sensor_pool.acquire(),
1106             [&sensor_pool](SensorData* ptr) { sensor_pool.release(ptr); }
1107         );
1108
1109         if (sensor1 && sensor2) {
1110             sensor1->temperature = 25.5;
1111             sensor1->pressure = 1013.25;
1112
1113             std::cout << " Acquired 2 objects from pool\n";
1114             std::cout << " Available slots: " << sensor_pool.available() << "
1115                 \n";
1116             std::cout << " Sensor 1 temp: " << sensor1->temperature << "°C\n"
1117         }
1118     }
```

```
    ;
}

1114
1115
1116     // Objects automatically released when PoolPtr goes out of scope (RAII
1117     !)
1117     std::cout << "  Exiting scope...\\n";
1118 }
1119
1120     std::cout << "  Objects released automatically via RAII\\n";
1121     std::cout << "  Available slots: " << sensor_pool.available() << "\\n\\n";
1122
1123     std::cout << "  DETERMINISTIC: No heap fragmentation, predictable timing
1123     !\\n";
1124     std::cout << "  SAFE: RAII ensures resources are always released!\\n";
1125 }

1126
1127 } // namespace memory_management
1128
1129 // =====
1130 // SECTION 5: Modern C++ Features for Real-Time Systems
1131 // =====
1132
1133 namespace modern_cpp_features {
1134
1135 // C++17 std::string_view - Zero-copy string viewing
1136 void process_command(std::string_view cmd) noexcept {
1137     // No string copy - just a view into existing data
1138     if (cmd == "START") {
1139         std::cout << "  Starting system...\\n";
1140     } else if (cmd == "STOP") {
1141         std::cout << "  Stopping system...\\n";
1142     }
1143 }

1144
1145 // C++17 std::optional - Express optional values without exceptions
1146 [[nodiscard]] std::optional<double> safe_divide(double a, double b) noexcept {
1147     if (b == 0.0) {
1148         return std::nullopt; // No exception thrown!
1149     }
1150     return a / b;
1151 }

1152
1153 // C++17 std::variant - Type-safe union without heap allocation
1154 using SensorValue = std::variant<int, double, std::array<uint8_t, 4>>;
1155
1156 void process_sensor_value(const SensorValue& value) noexcept {
1157     std::visit([](const auto& val) {
1158         using T = std::decay_t<decltype(val)>;
1159         if constexpr (std::is_same_v<T, int>) {
1160             std::cout << "  Integer sensor: " << val << "\\n";
1161         }
1162     }, value);
1163 }
```

```

1161     } else if constexpr (std::is_same_v<T, double>) {
1162         std::cout << "    Double sensor: " << val << "\n";
1163     } else {
1164         std::cout << "    Array sensor\n";
1165     }
1166 }, value);
1167 }
1168
1169 // constexpr functions - Compile-time computation
1170 constexpr uint32_t compute_crc32(std::string_view data) {
1171     uint32_t crc = 0xFFFFFFFF;
1172     for (char c : data) {
1173         crc ^= static_cast<uint32_t>(c);
1174         for (int i = 0; i < 8; ++i) {
1175             crc = (crc >> 1) ^ (0xEDB88320 & (-(crc & 1)));
1176         }
1177     }
1178     return ~crc;
1179 }
1180
1181 // Computed at compile time!
1182 constexpr uint32_t header_crc = compute_crc32("HEADER");
1183
1184 void demonstrate() {
1185     std::cout << "\n" << std::string(70, '=') << "\n";
1186     std::cout << "==== SECTION 5: Modern C++ Features for Real-Time ===\n";
1187     std::cout << std::string(70, '=') << "\n\n";
1188
1189     std::cout << "MODERN C++ FEATURES SUITABLE FOR REAL-TIME:\n\n";
1190
1191     // std::string_view
1192     std::cout << "1. std::string_view (C++17) - Zero-copy string handling:\n";
1193     std::string command = "START";
1194     process_command(command); // No copy, just a view
1195     process_command("STOP"); // Works with string literals too
1196     std::cout << "    No allocation, no copy, just a pointer + size\n\n";
1197
1198     // std::optional
1199     std::cout << "2. std::optional (C++17) - Safe error handling without
1200         exceptions:\n";
1201     auto result1 = safe_divide(10.0, 2.0);
1202     auto result2 = safe_divide(10.0, 0.0);
1203
1204     std::cout << "    10.0 / 2.0 = ";
1205     if (result1) {
1206         std::cout << *result1 << " (valid)\n";
1207     }
1208
1209     std::cout << "    10.0 / 0.0 = ";
1210     if (result2) {
1211         std::cout << *result2 << "\n";
1212     } else {
1213         std::cout << "error (nullopt)\n";
1214     }

```

```
1214     std::cout << "      No exceptions, no heap allocation\n\n";
1215
1216     // std::variant
1217     std::cout << "3. std::variant (C++17) - Type-safe union without heap:\n";
1218     SensorValue val1 = 42;
1219     SensorValue val2 = 3.14159;
1220     process_sensor_value(val1);
1221     process_sensor_value(val2);
1222     std::cout << "      Type-safe, no heap allocation, no virtual dispatch\n\n"
1223             "";
1224
1225     // constexpr
1226     std::cout << "4. constexpr - Compile-time computation:\n";
1227     std::cout << "      Header CRC32 (computed at compile-time): 0x"
1228             << std::hex << std::uppercase << header_crc << std::dec << "\n";
1229     std::cout << "      Zero runtime cost - computed by compiler!\n\n";
1230
1231     // std::array
1232     std::cout << "5. std::array - Type-safe stack array:\n";
1233     std::array<double, 10> samples{1.0, 2.0, 3.0, 4.0, 5.0};
1234     std::cout << "      Array size: " << samples.size() << "\n";
1235     std::cout << "      Stack-allocated, compile-time size, bounds checking\n"
1236             "\n";
1237
1238     std::cout << "FEATURES TO AVOID IN HARD REAL-TIME:\n";
1239     std::cout << "      Exceptions (use -fno-exceptions)\n";
1240     std::cout << "      RTTI (use -fno-rtti)\n";
1241     std::cout << "      Virtual functions in time-critical paths\n";
1242     std::cout << "      std::shared_ptr (atomic ref counting overhead)\n";
1243     std::cout << "      Dynamic polymorphism (prefer compile-time polymorphism)\n"
1244             "\n";
1245 }
1246
1247 } // namespace modern_cpp_features
1248
1249 // SECTION 6: Real-Time System Checklist
1250 // =====
1251
1252 void print_realtime_checklist() {
1253     std::cout << "\n" << std::string(70, '=') << "\n";
1254     std::cout << "==== SECTION 6: Real-Time Programming Checklist ===\n";
1255     std::cout << std::string(70, '=') << "\n\n";
1256
1257     std::cout << "INITIALIZATION PHASE (Non-real-time):\n";
1258     std::cout << "      Pre-allocate all memory (reserve() for vectors)\n";
1259     std::cout << "      Create memory pools for frequent allocations\n";
1260     std::cout << "      Load and sort lookup tables\n";
1261     std::cout << "      Initialize all data structures to max size\n";
1262     std::cout << "      Warm up caches if applicable\n";
```

```

1261     std::cout << "      Set thread priorities and CPU affinity\n\n";
1262
1263     std::cout << "REAL-TIME EXECUTION PHASE:\n";
1264     std::cout << "      NO dynamic memory allocation (no new/delete/malloc/free)
1265             \n";
1266     std::cout << "      NO operations with unbounded execution time\n";
1267     std::cout << "      NO file I/O or blocking system calls\n";
1268     std::cout << "      NO unbounded loops or recursion\n";
1269     std::cout << "      NO exceptions in critical paths\n";
1270     std::cout << "      Use O(1) or O(log n) operations only\n";
1271     std::cout << "      All containers have bounded maximum size\n";
1272     std::cout << "      Use std::bitset instead of std::vector<bool>\n";
1273     std::cout << "      Use std::array when size known at compile-time\n";
1274     std::cout << "      Use RAII for deterministic cleanup\n\n";
1275
1276     std::cout << "CONTAINER SELECTION:\n";
1277     std::cout << "      std::array<T, N>           - Fixed size, stack-based\n";
1278     std::cout << "      std::vector<T> + reserve() - Dynamic, pre-allocated\n";
1279     std::cout << "      std::bitset<N>          - Flags and bit manipulation\
1280             \n";
1281     std::cout << "      std::string_view         - Zero-copy string viewing\n";
1282     std::cout << "      ";
1283     std::cout << "      std::deque<T>          - If size bounded\n";
1284     std::cout << "      std::list<T>           - Poor cache, heap per
1285             element\n";
1286     std::cout << "      std::vector<bool>        - Use std::bitset instead\n\n";
1287             ";
1288
1289     std::cout << "ALGORITHM COMPLEXITY TARGETS:\n";
1290     std::cout << "      O(1)                  - Ideal (array access, bitset operations)\n";
1291     std::cout << "      O(log n)              - Good (binary search, balanced trees)\n";
1292     std::cout << "      O(n)                  - Acceptable if n is bounded and small\n";
1293     std::cout << "      O(n log n)            - Avoid in critical paths (sort)\n";
1294     std::cout << "      O(n2)                - Never (nested loops, bubble sort)\n\n";
1295
1296     std::cout << "COMPILER FLAGS FOR REAL-TIME:\n";
1297     std::cout << "      -fno-exceptions       Disable exception handling\n";
1298     std::cout << "      -fno-rtti              Disable run-time type information\n";
1299     std::cout << "      -O3                   Maximum optimization\n";
1300     std::cout << "      -march=native         Target specific CPU architecture\n";
1301     std::cout << "      -flto                 Link-time optimization\n\n";
1302
1303     std::cout << "PROFILING AND VERIFICATION:\n";
1304     std::cout << "      Measure worst-case execution time (WCET)\n";
1305     std::cout << "      Use real-time profiling tools\n";
1306     std::cout << "      Test under worst-case conditions\n";
1307     std::cout << "      Verify no unexpected allocations\n";
1308     std::cout << "      Monitor stack usage\n";
1309     std::cout << "      Validate timing constraints are met\n";
1310
1311 }
1312
1313 // =====

```

```
1308 // Main Function
1309 //
1310 =====
1311 int main() {
1312     std::cout << "\n";
1313     std::cout << "
1314         std::cout << "           REAL-TIME PROGRAMMING IN MODERN C++
1315             \n";
1316     std::cout << "   Comprehensive guide to deterministic, high-performance C
1317         ++ code      \n";
1318     std::cout << "   for embedded systems, robotics, and time-critical
1319         applications      \n";
1320     std::cout << "
1321         \n";
1322     try {
1323         // Section 1: Big O Notation
1324         big_o_notation::demonstrate();
1325
1326         // Section 1.5: Thread Architecture
1327         thread_architecture::demonstrate();
1328
1329         // Section 2: std::bitset vs std::vector<bool>
1330         bitset_vs_vector_bool::demonstrate();
1331
1332         // Section 3: STL Containers
1333         stl_containers_realtime::demonstrate();
1334
1335         // Section 3.5: std::list::splice() - O(1) Element Movement
1336         list_splice_realtime::demonstrate();
1337
1338         // Section 4: Memory Management
1339         memory_management::demonstrate();
1340
1341         // Section 5: Modern C++ Features
1342         modern_cpp_features::demonstrate();
1343
1344         // Section 6: Checklist
1345         print_realtime_checklist();
1346
1347         std::cout << "\n" << std::string(70, '=') << "\n";
1348         std::cout << "==== END OF REAL-TIME PROGRAMMING GUIDE ===\n";
1349         std::cout << std::string(70, '=') << "\n\n";
1350
1351         std::cout << "KEY TAKEAWAYS:\n";
1352         std::cout << "  1. Always pre-allocate memory during initialization\n";
1353             ;
1354         std::cout << "  2. Use std::bitset instead of std::vector<bool>\n";
1355         std::cout << "  3. Prefer O(1) operations, accept O(log n), bound O(n)
1356             \n";
```

```
1353     std::cout << " 4. Use reserve() for std::vector to prevent  
1354         reallocations\n";  
1355     std::cout << " 5. std::array is perfect for fixed-size data\n";  
1356     std::cout << " 6. RAII provides deterministic resource management\n";  
1357     std::cout << " 7. Modern C++ features like std::optional and std::  
1358         variant\n";  
1359     std::cout << "      are real-time friendly (no exceptions, no heap)\n";  
1360     std::cout << " 8. Measure WCET, not average performance!\n\n";  
1361  
1362     return 0;  
1363 } catch (const std::exception& e) {  
1364     std::cerr << "Error: " << e.what() << std::endl;  
1365     return 1;  
1366 }
```

58 Source Code: ResourceLeaks.cpp

File: src/ResourceLeaks.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // RESOURCE MANAGEMENT IN MODERN C++
3 // =====
4 // This example demonstrates how Modern C++ solves resource leak problems
5 // that plagued older C++ code using manual new/delete.
6 //
7 // TOPICS COVERED:
8 // 1. The Old Problem - Manual memory management with new/delete
9 // 2. Smart Pointers - Automatic memory management
10 // 3. RAII Pattern - Resource Acquisition Is Initialization
11 // 4. Other Resources - Files, mutexes, sockets, database connections
12 // 5. Custom Deleters - Managing non-memory resources
13 // 6. Exception Safety - Guarantees and resource cleanup
14 // 7. Modern Best Practices - When raw pointers are still OK
15 //
16 // KEY INSIGHT:
17 // "Modern C++ doesn't use new/delete directly anymore!"
18 // - Use smart pointers (unique_ptr, shared_ptr, weak_ptr)
19 // - Use containers (vector, string, map)
20 // - Use RAII wrappers for all resources
21 // - Raw pointers for non-owning references only
22 //
23 // EMBEDDED SYSTEMS NOTE:
24 // Even in resource-constrained embedded systems, smart pointers
25 // have ZERO runtime overhead compared to manual management!
26 // =====
27
28 #include <iostream>
29 #include <memory>
30 #include <vector>
31 #include <string>
32 #include <fstream>
33 #include <mutex>
34 #include <thread>
35 #include <chrono>
36 #include <exception>
37 #include <functional>
38 #include <map>
39
40 // =====
41 // 1. THE OLD PROBLEM - MANUAL MEMORY MANAGEMENT
42 // =====
43
44 namespace OldCpp {
45
46 // Example 1: Classic memory leak
47 void memory_leak_example() {
48     std::cout << "OLD C++: Memory leak example\n";
49     std::cout << "-----\n";
```

```
50     int* ptr = new int(42);
51     std::cout << "Allocated int with value: " << *ptr << "\n";
52
53     // Forgot to delete! Memory leak!
54     // delete ptr; // <-- Missing this line
55
56
57     std::cout << "Function returns without delete - MEMORY LEAK!\n\n";
58 }
59
60 // Example 2: Exception causes leak
61 void exception_causes_leak() {
62     std::cout << "OLD C++: Exception causes leak\n";
63     std::cout << "-----\n";
64
65     int* data = new int[1000];
66     std::cout << "Allocated array of 1000 ints\n";
67
68     try {
69         // Some code that might throw
70         if (data != nullptr) {
71             throw std::runtime_error("Simulated error!");
72         }
73
74         delete[] data; // <-- Never reached if exception thrown!
75     } catch (const std::exception& e) {
76         std::cout << "Caught exception: " << e.what() << "\n";
77         std::cout << "Array was never deleted - MEMORY LEAK!\n\n";
78         // Should have delete[] data here, but easy to forget
79     }
80 }
81
82 // Example 3: Multiple exit paths
83 void multiple_exit_paths(bool condition1, bool condition2) {
84     std::cout << "OLD C++: Multiple exit paths\n";
85     std::cout << "-----\n";
86
87     int* buffer = new int[100];
88     std::cout << "Allocated buffer\n";
89
90     if (condition1) {
91         std::cout << "Early return #1\n";
92         // Forgot to delete!
93         return; // LEAK!
94     }
95
96     // ... do some work ...
97
98     if (condition2) {
99         std::cout << "Early return #2\n";
100        // Forgot to delete!
101        return; // LEAK!
102    }
103 }
```

```
104     delete[] buffer; // Only reached if both conditions false
105     std::cout << "Normal cleanup\n\n";
106 }
107
108 // Example 4: Wrong delete operator
109 void wrong_delete_operator() {
110     std::cout << "OLD C++: Wrong delete operator\n";
111     std::cout << "-----\n";
112
113     int* single = new int(42);
114     int* array = new int[10];
115
116     // WRONG! Undefined behavior!
117     delete[] single; // Should be: delete single;
118     delete array; // Should be: delete[] array;
119
120     std::cout << "Used wrong delete operator - UNDEFINED BEHAVIOR!\n\n";
121 }
122
123 // Example 5: Double delete
124 void double_delete_problem() {
125     std::cout << "OLD C++: Double delete\n";
126     std::cout << "-----\n";
127
128     int* ptr = new int(42);
129
130     delete ptr;
131     std::cout << "Deleted once\n";
132
133     // WRONG! Undefined behavior!
134     delete ptr; // Double delete - CRASH or corruption!
135
136     std::cout << "Double delete - UNDEFINED BEHAVIOR!\n\n";
137 }
138
139 class ResourceIntensive {
140     int* data;
141     size_t size;
142
143 public:
144     ResourceIntensive(size_t n) : size(n) {
145         data = new int[n];
146         std::cout << " Allocated " << n << " ints\n";
147     }
148
149     // PROBLEM: No destructor! Memory leak!
150     // ~ResourceIntensive() { delete[] data; } // <-- Forgot this!
151 };
152
153 void demonstrate_old_problems() {
154     std::cout << "\n";
155     std::cout << "=====\\n";
156     std::cout << "1. THE OLD PROBLEM - MANUAL MEMORY MANAGEMENT\\n";
```

```
157     std::cout << "=====\\n";
158     n";
159
160     memory_leak_example();
161     exception_causes_leak();
162     multiple_exit_paths(true, false);
163
164     // Note: Can't safely run wrong_delete_operator() and
165     //        double_delete_problem()
166     // as they cause undefined behavior
167
168     std::cout << "Summary of Problems:\\n";
169     std::cout << "    Forgot to delete\\n";
170     std::cout << "    Exception before delete\\n";
171     std::cout << "    Multiple exit paths\\n";
172     std::cout << "    Wrong delete operator (delete vs delete [])\\n";
173     std::cout << "    Double delete\\n";
174     std::cout << "    Forgot destructor in class\\n";
175     std::cout << "\\n";
176 }
177
178 } // namespace OldCpp
179
180 // =====
181 // 2. MODERN C++ SOLUTION - SMART POINTERS
182 // =====
183
184 namespace ModernCpp {
185
186 // Example 1: unique_ptr - Exclusive ownership
187 void unique_ptr_example() {
188     std::cout << "MODERN C++: unique_ptr (exclusive ownership)\\n";
189     std::cout << "-----\\n";
190
191     // No manual new!
192     std::unique_ptr<int> ptr = std::make_unique<int>(42);
193     std::cout << "Created unique_ptr with value: " << *ptr << "\\n";
194
195     // Automatically deleted when scope ends!
196     std::cout << "Leaving scope - automatic cleanup!\\n\\n";
197
198     // NO delete needed!
199 }
200
201 // Example 2: Exception-safe with unique_ptr
202 void exception_safe_unique_ptr() {
203     std::cout << "MODERN C++: Exception-safe with unique_ptr\\n";
204     std::cout << "-----\\n";
205
206     auto data = std::make_unique<int[]>(1000);
207     std::cout << "Allocated array of 1000 ints\\n";
208
209     try {
210         throw std::runtime_error("Simulated error!");
211     }
```

```
209     // Never reached, but doesn't matter!
210 } catch (const std::exception& e) {
211     std::cout << "Caught exception: " << e.what() << "\n";
212     std::cout << "unique_ptr automatically cleaned up - NO LEAK!\n\n";
213 }
214
215 // Cleanup happens automatically in catch block
216 }
217
218
219 // Example 3: Multiple exit paths - no problem!
220 void multiple_exit_paths_safe(bool condition1, bool condition2) {
221     std::cout << "MODERN C++: Multiple exit paths (safe)\n";
222     std::cout << "-----\n";
223
224     auto buffer = std::make_unique<int>[](100);
225     std::cout << "Allocated buffer\n";
226
227     if (condition1) {
228         std::cout << "Early return #1 - buffer auto-deleted!\n\n";
229         return; // NO LEAK! unique_ptr cleans up
230     }
231
232     if (condition2) {
233         std::cout << "Early return #2 - buffer auto-deleted!\n\n";
234         return; // NO LEAK! unique_ptr cleans up
235     }
236
237     std::cout << "Normal return - buffer auto-deleted!\n\n";
238     // Automatic cleanup regardless of path!
239 }
240
241 // Example 4: shared_ptr - Shared ownership
242 void shared_ptr_example() {
243     std::cout << "MODERN C++: shared_ptr (shared ownership)\n";
244     std::cout << "-----\n";
245
246     std::shared_ptr<int> ptr1 = std::make_shared<int>(42);
247     std::cout << "Created shared_ptr, ref count: " << ptr1.use_count() << "\n"
248     ;
249
250     {
251         std::shared_ptr<int> ptr2 = ptr1; // Share ownership
252         std::cout << "Shared ownership, ref count: " << ptr1.use_count() << "\n";
253
254         std::shared_ptr<int> ptr3 = ptr1; // Another share
255         std::cout << "More sharing, ref count: " << ptr1.use_count() << "\n";
256     } // ptr2 and ptr3 destroyed
257
258     std::cout << "After scope, ref count: " << ptr1.use_count() << "\n";
259     std::cout << "Memory deleted when last shared_ptr destroyed!\n\n";
260 }
```

```
261 // Example 5: weak_ptr - Non-owning observer (doesn't keep object alive)
262 void weak_ptr_example() {
263     std::cout << "MODERN C++: weak_ptr (non-owning observer)\n";
264     std::cout << "-----\n";
265
266     std::weak_ptr<int> weak;
267
268     {
269         std::shared_ptr<int> shared = std::make_shared<int>(42);
270         weak = shared; // weak_ptr observes, but doesn't own
271
272         std::cout << "shared_ptr alive, ref count: " << shared.use_count() <<
273             "\n";
274         std::cout << "weak_ptr expired? " << (weak.expired() ? "YES" : "NO")
275             << "\n";
276
277         // ALWAYS check if weak_ptr is still valid before using!
278         if (auto locked = weak.lock()) { // lock() returns shared_ptr
279             std::cout << "Locked weak_ptr, value: " << *locked << "\n";
280             std::cout << "Ref count during lock: " << locked.use_count() << "\n";
281         } else {
282             std::cout << "Object was deleted!\n";
283         }
284
285     } // shared destroyed here
286
287     std::cout << "\nAfter shared_ptr destroyed:\n";
288     std::cout << "weak_ptr expired? " << (weak.expired() ? "YES" : "NO") << "\n";
289
290     if (auto locked = weak.lock()) {
291         std::cout << "Locked successfully, value: " << *locked << "\n";
292     } else {
293         std::cout << "Cannot lock - object was deleted!\n";
294     }
295 }
296
297 // Example 6: weak_ptr - Breaking circular references
298 class Node {
299 public:
300     std::string name;
301     std::shared_ptr<Node> next; // Strong reference (owns next)
302     std::weak_ptr<Node> prev; // Weak reference (doesn't own prev)
303
304     Node(const std::string& n) : name(n) {
305         std::cout << "  Node '" << name << "' created\n";
306     }
307
308     ~Node() {
309         std::cout << "  Node '" << name << "' destroyed\n";
310     }
}
```

```
311 };
```

```
312 
```

```
313 void circular_reference_example() {
314     std::cout << "MODERN C++: weak_ptr breaks circular references\n";
315     std::cout << "-----\n";
316 
```

```
317     auto node1 = std::make_shared<Node>("First");
318     auto node2 = std::make_shared<Node>("Second");
319     auto node3 = std::make_shared<Node>("Third");
320 
```

```
321     // Build doubly-linked list
322     node1->next = node2;
323     node2->prev = node1; // weak_ptr - doesn't create cycle!
324 
```

```
325     node2->next = node3;
326     node3->prev = node2; // weak_ptr - doesn't create cycle!
327 
```

```
328     std::cout << "\nNavigate forward (using shared_ptr):\n";
329     auto current = node1;
330     while (current) {
331         std::cout << "    At node: " << current->name << "\n";
332         current = current->next;
333     }
334 
```

```
335     std::cout << "\nNavigate backward (using weak_ptr):\n";
336     current = node3;
337     while (current) {
338         std::cout << "    At node: " << current->name << "\n";
339 
340         // Must lock() weak_ptr to use it!
341         if (auto prev = current->prev.lock()) {
342             current = prev;
343         } else {
344             break; // No previous node
345         }
346     }
347 
```

```
348     std::cout << "\nLeaving scope - all nodes will be destroyed:\n";
349 }
```

```
350 
```

```
351 // Example 7: weak_ptr - Cache implementation
352 class ExpensiveResource {
353     std::string data;
354 public:
355     ExpensiveResource(const std::string& d) : data(d) {
356         std::cout << "    Expensive resource created: " << data << "\n";
357     }
358     ~ExpensiveResource() {
359         std::cout << "    Expensive resource destroyed: " << data << "\n";
360     }
361     const std::string& get_data() const { return data; }
362 };
363 
```

```
364 class ResourceCache {
```

```
365     std::map<std::string, std::weak_ptr<ExpensiveResource>> cache;
366
367 public:
368     std::shared_ptr<ExpensiveResource> get_resource(const std::string& key) {
369         // Try to get from cache
370         auto it = cache.find(key);
371         if (it != cache.end()) {
372             // Check if cached resource is still alive
373             if (auto resource = it->second.lock()) {
374                 std::cout << " Cache HIT: " << key << "\n";
375                 return resource;
376             } else {
377                 std::cout << " Cache EXPIRED: " << key << "\n";
378                 cache.erase(it); // Clean up expired entry
379             }
380         }
381
382         // Create new resource
383         std::cout << " Cache MISS: Creating " << key << "\n";
384         auto resource = std::make_shared<ExpensiveResource>(key);
385         cache[key] = resource; // Store weak_ptr in cache
386         return resource;
387     }
388 };
389
390 void cache_example() {
391     std::cout << "MODERN C++: weak_ptr for caching\n";
392     std::cout << "-----\n";
393
394     ResourceCache cache;
395
396     {
397         auto res1 = cache.get_resource("data1");
398         auto res2 = cache.get_resource("data1"); // Should be cache hit
399
400         std::cout << "Both pointing to same resource: "
401                     << (res1 == res2 ? "YES" : "NO") << "\n";
402     }
403
404     std::cout << "\nResources destroyed, trying to access again:\n";
405     auto res3 = cache.get_resource("data1"); // Should be cache miss
406
407     std::cout << "\n";
408 }
409
410 // Example 8: Modern class with RAII
411 class ResourceIntensiveModern {
412     std::unique_ptr<int[]> data;
413     size_t size;
414
415 public:
416     ResourceIntensiveModern(size_t n) : data(std::make_unique<int[]>(n)), size(n) {
417         std::cout << " Allocated " << n << " ints (RAII)\n";
```

```
418    }
419
420    // No destructor needed! unique_ptr handles cleanup!
421    // Compiler-generated destructor is perfect!
422
423    // Safe to copy if we want (Rule of Zero)
424    // Or delete copy if we want move-only:
425    ResourceIntensiveModern(const ResourceIntensiveModern&) = delete;
426    ResourceIntensiveModern& operator=(const ResourceIntensiveModern&) =
427        delete;
428
429    // Move operations provided automatically!
430    ResourceIntensiveModern(ResourceIntensiveModern&&) = default;
431    ResourceIntensiveModern& operator=(ResourceIntensiveModern&&) = default;
432
433    int& operator[](size_t i) { return data[i]; }
434};
435
436 void demonstrate_modern_solutions() {
437     std::cout << "\n";
438     std::cout << "=====\\n";
439     std::cout << "2. MODERN C++ SOLUTION - SMART POINTERS\\n";
440     std::cout << "=====\\n\\n";
441
442     unique_ptr_example();
443     exception_safe_unique_ptr();
444     multiple_exit_paths_safe(true, false);
445     shared_ptr_example();
446     weak_ptr_example();
447     circular_reference_example();
448     cache_example();
449
450     std::cout << "Modern class with RAII:\\n";
451     {
452         ResourceIntensiveModern obj(100);
453         // Automatic cleanup when obj goes out of scope!
454     }
455     std::cout << " Automatically cleaned up!\\n\\n";
456
457     std::cout << "Summary of Solutions:\\n";
458     std::cout << " No manual new/delete\\n";
459     std::cout << " Exception-safe automatically\\n";
460     std::cout << " Multiple exit paths safe\\n";
461     std::cout << " Can't use wrong delete operator\\n";
462     std::cout << " Can't double-delete\\n";
463     std::cout << " Compiler-generated destructor works\\n";
464     std::cout << " weak_ptr breaks circular references\\n";
465     std::cout << " weak_ptr for cache/observer patterns\\n";
466 }
467
468 } // namespace ModernCpp
```

```
469 // =====
470 // 3. RAIU PATTERN - BEYOND MEMORY
471 // =====
472
473
474 namespace RAIU {
475
476 // File handle RAIU
477 class FileRAIU {
478     std::ofstream file;
479     std::string filename;
480
481 public:
482     FileRAIU(const std::string& name) : filename(name) {
483         file.open(filename);
484         if (!file) {
485             throw std::runtime_error("Failed to open file");
486         }
487         std::cout << "  File opened: " << filename << "\n";
488     }
489
490     ~FileRAIU() {
491         if (file.is_open()) {
492             file.close();
493             std::cout << "  File closed: " << filename << "\n";
494         }
495     }
496
497     // Delete copy, allow move
498     FileRAIU(const FileRAIU&) = delete;
499     FileRAIU& operator=(const FileRAIU&) = delete;
500     FileRAIU(FileRAIU&&) = default;
501     FileRAIU& operator=(FileRAIU&&) = default;
502
503     void write(const std::string& data) {
504         file << data;
505     }
506 };
507
508 // Mutex lock RAIU (std::lock_guard does this!)
509 class MutexLockRAIU {
510     std::mutex& mtx;
511
512 public:
513     explicit MutexLockRAIU(std::mutex& m) : mtx(m) {
514         mtx.lock();
515         std::cout << "  Mutex locked\n";
516     }
517
518     ~MutexLockRAIU() {
519         mtx.unlock();
520         std::cout << "  Mutex unlocked\n";
521     }
522 }
```

```
523 // Non-copyable, non-movable
524 MutexLockRAII(const MutexLockRAII&) = delete;
525 MutexLockRAII& operator=(const MutexLockRAII&) = delete;
526 };
527
528 // Timer RAII (measures scope duration)
529 class ScopeTimer {
530     std::string name;
531     std::chrono::high_resolution_clock::time_point start;
532
533 public:
534     explicit ScopeTimer(const std::string& n)
535         : name(n), start(std::chrono::high_resolution_clock::now()) {
536         std::cout << "  [" << name << "] Started\n";
537     }
538
539 ~ScopeTimer() {
540     auto end = std::chrono::high_resolution_clock::now();
541     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(
542         end - start);
543     std::cout << "  [" << name << "] Duration: " << duration.count() << "
544     s\n";
545 }
546
547 // Generic RAII wrapper
548 template<typename ResourceType, typename AcquireFunc, typename ReleaseFunc>
549 class GenericRAII {
550     ResourceType resource;
551     ReleaseFunc release;
552     bool active;
553
554 public:
555     GenericRAII(AcquireFunc acquire, ReleaseFunc rel)
556         : resource(acquire()), release(rel), active(true) {}
557
558 ~GenericRAII() {
559     if (active) {
560         release(resource);
561     }
562 }
563
564 ResourceType& get() { return resource; }
565
566 // Delete copy
567 GenericRAII(const GenericRAII&) = delete;
568 GenericRAII& operator=(const GenericRAII&) = delete;
569
570 // Allow move
571 GenericRAII(GenericRAII&& other) noexcept
572     : resource(std::move(other.resource)),
573     release(std::move(other.release)),
574     active(other.active) {
575     other.active = false;
```

```
575     }
576 };
577
578 void demonstrate_raii() {
579     std::cout << "\n";
580     std::cout << "=====\\n";
581     std::cout << "3. RAIU PATTERN - BEYOND MEMORY\\n";
582     std::cout << "=====\\n";
583     std::cout << "File RAIU example:\\n";
584     {
585         FileRAII file("test.txt");
586         file.write("Hello, RAIU!\\n");
587         // File automatically closed when scope ends
588     }
589     std::cout << "\\n";
590
591     std::cout << "Mutex RAIU example:\\n";
592     std::mutex mtx;
593     {
594         MutexLockRAII lock(mtx);
595         // Critical section
596         std::cout << " In critical section\\n";
597         // Mutex automatically unlocked when scope ends
598     }
599     std::cout << "\\n";
600
601     std::cout << "Scope timer example:\\n";
602     {
603         ScopeTimer timer("MyOperation");
604         // Simulate work
605         std::this_thread::sleep_for(std::chrono::milliseconds(10));
606         // Timer automatically reports duration
607     }
608     std::cout << "\\n";
609
610     std::cout << "RAIU Resources:\\n";
611     std::cout << " Memory (unique_ptr, shared_ptr)\\n";
612     std::cout << " Files (fstream, custom wrappers)\\n";
613     std::cout << " Locks (lock_guard, unique_lock)\\n";
614     std::cout << " Timers (scope profiling)\\n";
615     std::cout << " Network sockets\\n";
616     std::cout << " Database connections\\n";
617     std::cout << " OpenGL contexts\\n";
618     std::cout << " Hardware registers (embedded)\\n";
619     std::cout << "\\n";
620 }
621
622 } // namespace RAIU
623
624 // =====
625 // 4. CUSTOM DELETORS
```

```
627 // =====
628
629 namespace CustomDeleters {
630
631 // Example: C-style FILE*
632 void file_deleter(FILE* fp) {
633     if (fp) {
634         std::cout << "  Custom deleter: closing FILE*\n";
635         fclose(fp);
636     }
637 }
638
639 void custom_deleter_file_example() {
640     std::cout << "Custom deleter with FILE*:\n";
641
642     std::unique_ptr<FILE, decltype(&file_deleter)> file(
643         fopen("test.txt", "w"),
644         file_deleter
645     );
646
647     if (file) {
648         fprintf(file.get(), "Hello from C-style FILE!\n");
649     }
650
651     // FILE* automatically closed by custom deleter!
652 }
653
654 // Example: Hardware register (embedded systems)
655 struct HardwareRegister {
656     volatile uint32_t* address;
657     uint32_t original_value;
658
659     HardwareRegister(volatile uint32_t* addr)
660         : address(addr), original_value(*addr) {
661             std::cout << "  Saving register value: 0x" << std::hex <<
662             original_value << std::dec << "\n";
663         }
664
665     ~HardwareRegister() {
666         *address = original_value;
667         std::cout << "  Restored register value: 0x" << std::hex <<
668         original_value << std::dec << "\n";
669     }
670 };
671
672 void embedded_register_example() {
673     std::cout << "\nEmbedded hardware register RAII:\n";
674
675     uint32_t simulated_register = 0x12345678;
676
677     {
678         HardwareRegister reg(&simulated_register);
679
680         // Modify register
681     }
682 }
```

```
679     simulated_register = 0xABCDDEF00;
680     std::cout << " Modified register: 0x" << std::hex <<
681         simulated_register << std::dec << "\n";
682
683     // Automatically restored on scope exit!
684 }
685
686     std::cout << " Register after scope: 0x" << std::hex <<
687         simulated_register << std::dec << "\n";
688 }
689
690 void demonstrate_custom_deleters() {
691     std::cout << "\n";
692     std::cout << "=====\\n";
693     std::cout << "4. CUSTOM DELETERS\\n";
694     std::cout << "=====\\n\\n";
695     custom_deleter_file_example();
696     embedded_register_example();
697
698     std::cout << "\\nCustom deleters for:\\n";
699     std::cout << "    C API resources (FILE*, malloc, etc.)\\n";
700     std::cout << "    Operating system handles\\n";
701     std::cout << "    Hardware registers (embedded)\\n";
702     std::cout << "    Third-party library resources\\n";
703     std::cout << "\\n";
704 }
705 } // namespace CustomDeleters
706
707 // =====
708 // 5. WHEN RAW POINTERS ARE OK IN MODERN C++
709 // =====
710
711 namespace RawPointersOK {
712
713 class Node {
714 public:
715     int value;
716     std::unique_ptr<Node> next; // Owns the next node
717     Node* prev; // Non-owning pointer to previous
718
719     Node(int v) : value(v), prev(nullptr) {}
720 };
721
722 void raw_pointer_examples() {
723     std::cout << "\n";
724     std::cout << "=====\\n";
725     std::cout << "5. WHEN RAW POINTERS ARE OK IN MODERN C++\\n";
726     std::cout << "=====\\n\\n";
```

```
727     std::cout << "Raw pointers are OK for:\n\n";
728
729     std::cout << "1. NON-OWNING REFERENCES:\n";
730     std::cout << "    auto owner = std::make_unique<int>(42);\n";
731     std::cout << "    int* observer = owner.get(); // OK! Not responsible for
732                 deletion\n\n";
733
734     std::cout << "2. FUNCTION PARAMETERS (non-owning):\n";
735     std::cout << "    void process(const Widget* widget); // OK! Doesn't own\n
736                 \n";
737
738     std::cout << "3. OPTIONAL PARAMETERS:\n";
739     std::cout << "    void render(Texture* texture = nullptr); // OK! May be
740                 null\n\n";
741
742     std::cout << "4. POINTERS TO STACK OBJECTS:\n";
743     std::cout << "    int value = 42;\n";
744     std::cout << "    int* ptr = &value; // OK! No ownership\n\n";
745
746     std::cout << "5. BACK POINTERS IN DATA STRUCTURES:\n";
747     std::cout << "    struct Node {\n";
748     std::cout << "        std::unique_ptr<Node> next; // Owns next\n";
749     std::cout << "        Node* prev; // Non-owning back
750                 pointer\n";
751     std::cout << "    };\n\n";
752
753     std::cout << "6. POINTERS TO GLOBAL/STATIC OBJECTS:\n";
754     std::cout << "    static Logger logger;\n";
755     std::cout << "    Logger* getLogger() { return &logger; } // OK!\n\n";
756
757     std::cout << "NEVER use raw pointers for:\n";
758     std::cout << "    Ownership (use unique_ptr or shared_ptr)\n";
759     std::cout << "    Arrays (use std::vector or std::array)\n";
760     std::cout << "    Manual new/delete\n";
761     std::cout << "\n";
762
763 } // namespace RawPointersOK
764
765 // =====
766 // 6. CONTAINERS INSTEAD OF MANUAL ARRAYS
767 // =====
768
769 namespace Containers {
770
771     void demonstrate_containers() {
772         std::cout << "\n";
773         std::cout << "=====\\n";
774         ;
775         std::cout << "6. CONTAINERS INSTEAD OF MANUAL ARRAYS\n";
776         std::cout << "=====\\n\\n";
777     }
778 }
```

```
775 std::cout << "OLD C++: Manual array management\n";
776 std::cout << "    int* arr = new int[100]; // Manual allocation\n";
777 std::cout << "    // ... use array ...\\n";
778 std::cout << "    delete[] arr; // Manual cleanup (easy to forget!)\\n\\n";
779
780 std::cout << "MODERN C++: Use std::vector\\n";
781 std::vector<int> vec(100);
782 std::cout << "    std::vector<int> vec(100); // Automatic!\\n";
783 std::cout << "    // Automatic cleanup, resizing, bounds checking\\n";
784 std::cout << "    Size: " << vec.size() << " elements\\n\\n";
785
786 std::cout << "Other containers (all automatic!):\\n";
787 std::cout << "    std::vector - Dynamic array\\n";
788 std::cout << "    std::array - Fixed-size array\\n";
789 std::cout << "    std::string - String (char array)\\n";
790 std::cout << "    std::map - Key-value pairs\\n";
791 std::cout << "    std::unordered_map - Hash table\\n";
792 std::cout << "    std::set - Unique elements\\n";
793 std::cout << "    std::list - Doubly-linked list\\n";
794 std::cout << "    std::deque - Double-ended queue\\n";
795 std::cout << "\\n";
796 }
797
798 } // namespace Containers
799
800 // =====
801 // 7. PERFORMANCE - ZERO OVERHEAD
802 // =====
803
804 namespace Performance {
805
806 void demonstrate_zero_overhead() {
807     std::cout << "\\n";
808     std::cout << "=====\\n";
809     std::cout << "7. PERFORMANCE - ZERO OVERHEAD\\n";
810     std::cout << "=====\\n\\n";
811
812     std::cout << "Smart pointers have ZERO runtime overhead!\\n\\n";
813
814     std::cout << "unique_ptr:\\n";
815     std::cout << " • Same size as raw pointer\\n";
816     std::cout << " • No runtime cost\\n";
817     std::cout << " • Optimized to same assembly as manual delete\\n";
818     std::cout << " • sizeof(unique_ptr<int>) = " << sizeof(std::unique_ptr<
819         int>) << " bytes\\n";
820     std::cout << " • sizeof(int*) = " << sizeof(int*) << " bytes\\n\\n";
821
822     std::cout << "shared_ptr:\\n";
823     std::cout << " • Small overhead for reference counting\\n";
824     std::cout << " • sizeof(shared_ptr<int>) = " << sizeof(std::shared_ptr<
825         int>) << " bytes\\n";
826     std::cout << " • Only use when you need shared ownership\\n\\n";
```

```
825     std::cout << "Embedded systems:\n";
826     std::cout << "    unique_ptr: Perfect! Zero overhead\n";
827     std::cout << "    std::vector: Excellent! Deterministic\n";
828     std::cout << "    shared_ptr: Use sparingly (ref counting cost)\n";
829     std::cout << "    RAII wrappers: Zero cost abstraction\n\n";
830
831
832     std::cout << "Compiler optimizations:\n";
833     std::cout << "    • unique_ptr: Completely optimized away\n";
834     std::cout << "    • Move semantics: No copies, just pointer transfer\n";
835     std::cout << "    • RVO/NRVO: Return value optimization\n";
836     std::cout << "    • Inline expansion: Zero function call overhead\n";
837     std::cout << "\n";
838 }
839
840 } // namespace Performance
841
842 // =====
843 // MAIN DEMONSTRATION
844 // =====
845
846 int main() {
847     std::cout << "\n";
848     std::cout <<
849         "=====\\n";
850     std::cout << "RESOURCE MANAGEMENT IN MODERN C++\n";
851     std::cout <<
852         "=====\\n";
853     std::cout << "\"Modern C++ doesn't use new/delete directly anymore!\"\n";
854     std::cout <<
855         "=====\\n";
856     OldCpp::demonstrate_old_problems();
857     ModernCpp::demonstrate_modern_solutions();
858     RAII::demonstrate_raii();
859     CustomDeleteers::demonstrate_custom_deleteers();
860     RawPointersOK::raw_pointer_examples();
861     Containers::demonstrate_containers();
862     Performance::demonstrate_zero_overhead();
863
864     std::cout << "\n";
865     std::cout <<
866         "=====\\n";
867     std::cout << "SUMMARY - MODERN C++ RESOURCE MANAGEMENT\n";
868     std::cout <<
869         "=====\\n";
870     std::cout << "\n";
871     std::cout << "THE GOLDEN RULES:\n";
872     std::cout << "-----\\n";
```

```

869 std::cout << "1. NEVER use 'new' or 'delete' directly\n";
870 std::cout << " → Use std::make_unique<T>() instead\n";
871 std::cout << "\n";
872 std::cout << "2. NEVER use 'new[]' or 'delete[]'\n";
873 std::cout << " → Use std::vector<T> or std::array<T, N> instead\n";
874 std::cout << "\n";
875 std::cout << "3. Prefer unique_ptr over shared_ptr\n";
876 std::cout << " → Exclusive ownership is clearer and faster\n";
877 std::cout << "\n";
878 std::cout << "4. Use RAII for ALL resources\n";
879 std::cout << " → Memory, files, locks, sockets, everything!\n";
880 std::cout << "\n";
881 std::cout << "5. Raw pointers are OK for non-owning references\n";
882 std::cout << " → Never responsible for deletion\n";
883 std::cout << "\n";
884 std::cout << "6. Follow the Rule of Zero\n";
885 std::cout << " → Let compiler generate special members\n";
886 std::cout << " → Use standard library types as members\n";
887 std::cout << "\n";
888 std::cout << "BENEFITS:\n";
889 std::cout << "-----\n";
890 std::cout << " No memory leaks (automatic cleanup)\n";
891 std::cout << " Exception-safe (automatic cleanup on unwind)\n";
892 std::cout << " No double-delete bugs\n";
893 std::cout << " No use-after-free bugs\n";
894 std::cout << " Clear ownership semantics\n";
895 std::cout << " Zero runtime overhead (unique_ptr)\n";
896 std::cout << " Easier to reason about code\n";
897 std::cout << " Suitable for embedded systems\n";
898 std::cout << "\n";
899 std::cout << "WHEN YOU STILL SEE new/delete:\n";
900 std::cout << "-----\n";
901 std::cout << "• Legacy code (pre-C++11)\n";
902 std::cout << "• Educational purposes (showing the old way)\n";
903 std::cout << "• Custom memory allocators (advanced)\n";
904 std::cout << "• Framework internals (Qt, COM, etc.)\n";
905 std::cout << "\n";
906 std::cout << "IN MODERN C++ (C++11 and later):\n";
907 std::cout << "-----\n";
908 std::cout << "new/delete are considered OBSOLETE for application code!\n";
909 std::cout << "\n";
910 std::cout << "MIGRATION PATH:\n";
911 std::cout << "-----\n";
912 std::cout << "T* ptr = new T; → auto ptr = std::make_unique<T>()\n";
913 std::cout << ";\n";
914 std::cout << "T* arr = new T[N]; → std::vector<T> arr(N);\n";
915 std::cout << "delete ptr; → (automatic)\n";
916 std::cout << "delete[] arr; → (automatic)\n";
917 std::cout << "T* shared = new T; → auto shared = std::make_shared<T>()\n";
918 std::cout << ";\n";
919 std::cout << "=====";
920

```

```
919     std::cout << "ALL EXAMPLES COMPLETED SUCCESSFULLY!\n";
920     std::cout << "
921         =====\n";
922     return 0;
923 }
924
925 /**
926 EXPECTED OUTPUT HIGHLIGHTS:
927 =====
928 =====
929 =====
930 1. THE OLD PROBLEM - MANUAL MEMORY MANAGEMENT
931 =====
932 OLD C++: Memory leak example
933 -----
934 Allocated int with value: 42
935 Function returns without delete - MEMORY LEAK!
936
937 OLD C++: Exception causes leak
938 -----
939 Allocated array of 1000 ints
940 Caught exception: Simulated error!
941 Array was never deleted - MEMORY LEAK!
942
943 Summary of Problems:
944     Forgot to delete
945     Exception before delete
946     Multiple exit paths
947     Wrong delete operator (delete vs delete[])
948     Double delete
949     Forgot destructor in class
950
951 =====
952 2. MODERN C++ SOLUTION - SMART POINTERS
953 =====
954
955 MODERN C++: unique_ptr (exclusive ownership)
956 -----
957 Created unique_ptr with value: 42
958 Leaving scope - automatic cleanup!
959
960 MODERN C++: Exception-safe with unique_ptr
961 -----
962 Allocated array of 1000 ints
963 Caught exception: Simulated error!
964 unique_ptr automatically cleaned up - NO LEAK!
965
966 Summary of Solutions:
967     No manual new/delete
968     Exception-safe automatically
969     Multiple exit paths safe
970
```

```
971     Can't use wrong delete operator
972     Can't double-delete
973     Compiler-generated destructor works
974
975 =====
976 3. RAIII PATTERN - BEYOND MEMORY
977 =====
978
979 File RAIII example:
980     File opened: test.txt
981     File closed: test.txt
982
983 Mutex RAIII example:
984     Mutex locked
985     In critical section
986     Mutex unlocked
987
988 RAIII Resources:
989     Memory (unique_ptr, shared_ptr)
990     Files (fstream, custom wrappers)
991     Locks (lock_guard, unique_lock)
992     Timers (scope profiling)
993     Network sockets
994     Database connections
995     Hardware registers (embedded)
996
997 =====
998 7. PERFORMANCE - ZERO OVERHEAD
999 =====
1000
1001 Smart pointers have ZERO runtime overhead!
1002
1003 unique_ptr:
1004     Same size as raw pointer
1005     No runtime cost
1006     Optimized to same assembly as manual delete
1007     sizeof(unique_ptr<int>) = 8 bytes
1008     sizeof(int*) = 8 bytes
1009
1010 Embedded systems:
1011     unique_ptr: Perfect! Zero overhead
1012     std::vector: Excellent! Deterministic
1013     shared_ptr: Use sparingly (ref counting cost)
1014     RAIII wrappers: Zero cost abstraction
1015
1016 =====
1017 SUMMARY - MODERN C++ RESOURCE MANAGEMENT
1018 =====
1019
1020 THE GOLDEN RULES:
1021 -----
1022 1. NEVER use 'new' or 'delete' directly→
1023     Use std::make_unique<T>() instead
1024
```

```
1025 2. NEVER use 'new []' or 'delete []' →  
1026     Use std::vector<T> or std::array<T, N> instead  
1027  
1028 3. Prefer unique_ptr over shared_ptr→  
1029     Exclusive ownership is clearer and faster  
1030  
1031 4. Use RAII for ALL resources→  
1032     Memory, files, locks, sockets, everything!  
1033  
1034 5. Raw pointers are OK for non-owning references→  
1035     Never responsible for deletion  
1036  
1037 BENEFITS:  
1038 -----  
1039 No memory leaks (automatic cleanup)  
1040 Exception-safe (automatic cleanup on unwind)  
1041 No double-delete bugs  
1042 No use-after-free bugs  
1043 Clear ownership semantics  
1044 Zero runtime overhead (unique_ptr)  
1045 Suitable for embedded systems  
1046  
1047 IN MODERN C++ (C++11 and later):  
1048 -----  
1049 new/delete are considered OBSOLETE for application code!  
1050  
1051 */
```

59 Source Code: RestApiExample.cpp

File: src/RestApiExample.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // REST API CALLS IN C++ EXAMPLE
3 // =====
4 // This example demonstrates making REST API calls in modern C++ using:
5 // - libcurl: For HTTP/HTTPS requests
6 // - nlohmann/json: For JSON parsing and serialization
7 //
8 // TOPICS COVERED:
9 // 1. GET requests with query parameters
10 // 2. POST requests with JSON payloads
11 // 3. PUT and DELETE requests
12 // 4. Custom headers and authentication
13 // 5. Error handling for network operations
14 // 6. RAII wrapper for curl resources
15 // 7. Response parsing with JSON
16 //
17 // WHAT IS libcurl?
18 // - A free and easy-to-use client-side URL transfer library
19 // - Supports HTTP, HTTPS, FTP, and many other protocols
20 // - Thread-safe when used correctly
21 // - Cross-platform (Windows, Linux, macOS)
22 //
23 // WHY USE libcurl?
24 // Battle-tested: Used in billions of devices
25 // Feature-rich: Supports all HTTP methods and features
26 // Cross-platform: Works everywhere
27 // Well-documented: Extensive documentation and examples
28 // Active development: Regular updates and security fixes
29 //
30 // INSTALLATION:
31 // - Ubuntu: sudo apt-get install libcurl4-openssl-dev
32 // - Windows (vcpkg): vcpkg install curl
33 // - macOS: brew install curl
34 // - CMake: find_package(CURL REQUIRED)
35 //
36 // ALTERNATIVES TO CONSIDER:
37 // - cpp-httplib: Header-only, simpler but less features
38 // - Boost.Beast: Part of Boost, good for async operations
39 // - cpprestsdk: Microsoft's REST SDK, good for async
40 // - Qt Network: If already using Qt framework
41 //
42 // =====
43
44 #include <iostream>
45 #include <string>
46 #include <memory>
47 #include <stdexcept>
48 #include <vector>
49 #include <map>
```

```
50 #include <curl/curl.h>
51 #include <nlohmann/json.hpp>
52
53 using json = nlohmann::json;
54
55 // =====
56 // SECTION 1: RAII Wrapper for CURL
57 // =====
58 // Modern C++ principle: Use RAII to manage resources automatically
59 // This ensures curl_easy_cleanup is always called, even on exceptions
60
61 class CurlHandle {
62 private:
63     CURL* handle_;
64
65 public:
66     CurlHandle() : handle_(curl_easy_init()) {
67         if (!handle_) {
68             throw std::runtime_error("Failed to initialize CURL");
69         }
70     }
71
72     ~CurlHandle() {
73         if (handle_) {
74             curl_easy_cleanup(handle_);
75         }
76     }
77
78     // Delete copy constructor and assignment (non-copyable)
79     CurlHandle(const CurlHandle&) = delete;
80     CurlHandle& operator=(const CurlHandle&) = delete;
81
82     // Allow move semantics
83     CurlHandle(CurlHandle&& other) noexcept : handle_(other.handle_) {
84         other.handle_ = nullptr;
85     }
86
87     CurlHandle& operator=(CurlHandle&& other) noexcept {
88         if (this != &other) {
89             if (handle_) {
90                 curl_easy_cleanup(handle_);
91             }
92             handle_ = other.handle_;
93             other.handle_ = nullptr;
94         }
95         return *this;
96     }
97
98     CURL* get() const { return handle_; }
99     operator CURL*() const { return handle_; }
100 };
101
102 // =====
103 // SECTION 2: RAII Wrapper for curl_slist (headers)
```

```
104 // =====
105
106 class CurlHeaders {
107 private:
108     struct curl_slist* headers_;
109
110 public:
111     CurlHeaders() : headers_(nullptr) {}
112
113     ~CurlHeaders() {
114         if (headers_) {
115             curl_slist_free_all(headers_);
116         }
117     }
118
119     CurlHeaders(const CurlHeaders&) = delete;
120     CurlHeaders& operator=(const CurlHeaders&) = delete;
121
122     void append(const std::string& header) {
123         headers_ = curl_slist_append(headers_, header.c_str());
124     }
125
126     struct curl_slist* get() const { return headers_; }
127 };
128 // =====
129 // SECTION 3: HTTP Response Structure
130 // =====
131
132 struct HttpResponse {
133     long status_code;
134     std::string body;
135     std::map<std::string, std::string> headers;
136
137     bool is_success() const {
138         return status_code >= 200 && status_code < 300;
139     }
140
141     json to_json() const {
142         return json::parse(body);
143     }
144 };
145
146 // =====
147 // SECTION 4: Callback for Writing Response Data
148 // =====
149 // libcurl uses C-style callbacks. We use a static function that
150 // calls into our C++ code.
151
152 static size_t WriteCallback(void* contents, size_t size, size_t nmemb, void*
153 userp) {
154     size_t total_size = size * nmemb;
155     auto* str = static_cast<std::string*>(userp);
156     str->append(static_cast<char*>(contents), total_size);
```

```
157     return total_size;
158 }
159
160 // =====
161 // SECTION 5: REST API Client Class
162 // =====
163
164 class RestClient {
165 private:
166     std::string base_url_;
167     std::map<std::string, std::string> default_headers_;
168
169 public:
170     explicit RestClient(const std::string& base_url = "")  
        : base_url_(base_url) {  
        // Initialize libcurl globally (once per program)  
        static bool initialized = false;  
        if (!initialized) {  
            curl_global_init(CURL_GLOBAL_DEFAULT);  
            initialized = true;  
        }  
    }  

178 }  

179
180 ~RestClient() {  
    // Note: curl_global_cleanup() should be called at program exit  
    // We don't call it here because multiple RestClient instances may  
    // exist  
}  

181
182 void set_default_header(const std::string& key, const std::string& value)  
{  
    default_headers_[key] = value;  
}  

183
184
185 void set_bearer_token(const std::string& token) {  
    default_headers_["Authorization"] = "Bearer " + token;  
}  

186
187
188 // GET request
189 HttpResponse get(const std::string& endpoint,  
                    const std::map<std::string, std::string>& params = {}) {  
    std::string url = build_url(endpoint, params);  
    return perform_request(url, "GET", ", {});  
}
190
191
192 // POST request with JSON body
193 HttpResponse post(const std::string& endpoint,  
                     const json& body,  
                     const std::map<std::string, std::string>& extra_headers  
                     = {}) {  
    std::string url = build_url(endpoint);  
    auto headers = extra_headers;  
    headers["Content-Type"] = "application/json";  
    return perform_request(url, "POST", body.dump(), headers);  
}
```

```
208     }
209
210     // PUT request with JSON body
211     HttpResponse put(const std::string& endpoint,
212                         const json& body,
213                         const std::map<std::string, std::string>& extra_headers =
214                         {}) {
215         std::string url = build_url(endpoint);
216         auto headers = extra_headers;
217         headers["Content-Type"] = "application/json";
218         return perform_request(url, "PUT", body.dump(), headers);
219     }
220
221     // DELETE request
222     HttpResponse del(const std::string& endpoint) {
223         std::string url = build_url(endpoint);
224         return perform_request(url, "DELETE", "", {});
225     }
226
227     private:
228         std::string build_url(const std::string& endpoint,
229                               const std::map<std::string, std::string>& params =
230                               {}) {
231             std::string url = base_url_ + endpoint;
232
233             if (!params.empty()) {
234                 url += "?";
235                 bool first = true;
236                 for (const auto& [key, value] : params) {
237                     if (!first) url += "&";
238                     url += key + "=" + curl_easy_escape_string(value);
239                     first = false;
240                 }
241             }
242
243             return url;
244         }
245
246         std::string curl_easy_escape_string(const std::string& str) {
247             CurlHandle curl;
248             char* escaped = curl_easy_escape(curl, str.c_str(), str.length());
249             std::string result(escaped);
250             curl_free(escaped);
251             return result;
252         }
253
254         HttpResponse perform_request(const std::string& url,
255                                     const std::string& method,
256                                     const std::string& body,
257                                     const std::map<std::string, std::string>&
258                                     extra_headers) {
259             CurlHandle curl;
260             HttpResponse response;
261             std::string response_body;
```

```
259     // Set URL
260     curl_easy_setopt(curl, CURLOPT_URL, url.c_str());
261
262     // Set HTTP method
263     if (method == "POST") {
264         curl_easy_setopt(curl, CURLOPT_POST, 1L);
265     } else if (method == "PUT") {
266         curl_easy_setopt(curl, CURLOPT_CUSTOMREQUEST, "PUT");
267     } else if (method == "DELETE") {
268         curl_easy_setopt(curl, CURLOPT_CUSTOMREQUEST, "DELETE");
269     } else if (method == "GET") {
270         curl_easy_setopt(curl, CURLOPT_HTTPGET, 1L);
271     }
272
273     // Set request body if provided
274     if (!body.empty()) {
275         curl_easy_setopt(curl, CURLOPT_POSTFIELDS, body.c_str());
276         curl_easy_setopt(curl, CURLOPT_POSTFIELDSIZE, body.length());
277     }
278
279     // Set headers
280     CurlHeaders headers;
281
282     // Add default headers
283     for (const auto& [key, value] : default_headers_) {
284         headers.append(key + ": " + value);
285     }
286
287     // Add extra headers (can override defaults)
288     for (const auto& [key, value] : extra_headers_) {
289         headers.append(key + ": " + value);
290     }
291
292     if (headers.get()) {
293         curl_easy_setopt(curl, CURLOPT_HTTPHEADER, headers.get());
294     }
295
296     // Set write callback
297     curl_easy_setopt(curl, CURLOPT_WRITEFUNCTION, WriteCallback);
298     curl_easy_setopt(curl, CURLOPT_WRITEDATA, &response_body);
299
300     // Follow redirects
301     curl_easy_setopt(curl, CURLOPT_FOLLOWLOCATION, 1L);
302
303     // Set timeout
304     curl_easy_setopt(curl, CURLOPT_TIMEOUT, 30L);
305
306     // Perform request
307     CURLcode res = curl_easy_perform(curl);
308
309     if (res != CURLE_OK) {
310         throw std::runtime_error(std::string("CURL error: ") +
311                               curl_easy_strerror(res));
312     }
```

```
313     }
314
315     // Get response code
316     curl_easy_getinfo(curl, CURLINFO_RESPONSE_CODE, &response.status_code)
317     ;
318     response.body = response_body;
319
320     return response;
321 }
322
323 // =====
324 // SECTION 6: Example Usage with Public APIs
325 // =====
326
327 void example_json_placeholder_api() {
328     std::cout << "\n==== Example 1: JSONPlaceholder API (GET) ===\n";
329
330     try {
331         RestClient client("https://jsonplaceholder.typicode.com");
332
333         // GET request: Fetch a post
334         auto response = client.get("/posts/1");
335
336         std::cout << "Status Code: " << response.status_code << "\n";
337
338         if (response.is_success()) {
339             auto data = response.to_json();
340             std::cout << "Post Title: " << data["title"] << "\n";
341             std::cout << "Post Body: " << data["body"] << "\n";
342             std::cout << "User ID: " << data["userId"] << "\n";
343         }
344
345     } catch (const std::exception& e) {
346         std::cerr << "Error: " << e.what() << "\n";
347     }
348 }
349
350 void example_create_post() {
351     std::cout << "\n==== Example 2: Create a Post (POST) ===\n";
352
353     try {
354         RestClient client("https://jsonplaceholder.typicode.com");
355
356         // Create JSON payload
357         json post_data = {
358             {"title", "My C++ REST API Example"},
359             {"body", "This post was created using C++ and libcurl!"},
360             {"userId", 1}
361         };
362
363         // POST request
364         auto response = client.post("/posts", post_data);
365     }
```

```
366     std::cout << "Status Code: " << response.status_code << "\n";
367
368     if (response.is_success()) {
369         auto data = response.to_json();
370         std::cout << "Created Post ID: " << data["id"] << "\n";
371         std::cout << "Response:\n" << data.dump(2) << "\n";
372     }
373
374 } catch (const std::exception& e) {
375     std::cerr << "Error: " << e.what() << "\n";
376 }
377 }
378
379 void example_update_post() {
380     std::cout << "\n==== Example 3: Update a Post (PUT) ====\n";
381
382     try {
383         RestClient client("https://jsonplaceholder.typicode.com");
384
385         // Updated data
386         json updated_data = {
387             {"id", 1},
388             {"title", "Updated Title from C++"},
389             {"body", "This post was updated using modern C++!"},
390             {"userId", 1}
391         };
392
393         // PUT request
394         auto response = client.put("/posts/1", updated_data);
395
396         std::cout << "Status Code: " << response.status_code << "\n";
397
398         if (response.is_success()) {
399             auto data = response.to_json();
400             std::cout << "Updated Post:\n" << data.dump(2) << "\n";
401         }
402
403     } catch (const std::exception& e) {
404         std::cerr << "Error: " << e.what() << "\n";
405     }
406 }
407
408 void example_delete_post() {
409     std::cout << "\n==== Example 4: Delete a Post (DELETE) ====\n";
410
411     try {
412         RestClient client("https://jsonplaceholder.typicode.com");
413
414         // DELETE request
415         auto response = client.del("/posts/1");
416
417         std::cout << "Status Code: " << response.status_code << "\n";
418
419         if (response.is_success()) {
```

```
420         std::cout << "Post deleted successfully!\n";
421     }
422
423 } catch (const std::exception& e) {
424     std::cerr << "Error: " << e.what() << "\n";
425 }
426 }
427
428 void example_with_query_parameters() {
429     std::cout << "\n==== Example 5: GET with Query Parameters ====\n";
430
431     try {
432         RestClient client("https://jsonplaceholder.typicode.com");
433
434         // GET with query parameters
435         std::map<std::string, std::string> params = {
436             {"userId", "1"}
437         };
438
439         auto response = client.get("/posts", params);
440
441         std::cout << "Status Code: " << response.status_code << "\n";
442
443         if (response.is_success()) {
444             auto data = response.to_json();
445             std::cout << "Found " << data.size() << " posts by user 1\n";
446
447             // Display first 3 posts
448             for (size_t i = 0; i < std::min(data.size(), size_t(3)); ++i) {
449                 std::cout << "\nPost " << (i + 1) << ":\n";
450                 std::cout << "  Title: " << data[i]["title"] << "\n";
451             }
452         }
453
454     } catch (const std::exception& e) {
455         std::cerr << "Error: " << e.what() << "\n";
456     }
457 }
458
459 void example_github_api() {
460     std::cout << "\n==== Example 6: GitHub API (Public Data) ====\n";
461
462     try {
463         RestClient client("https://api.github.com");
464
465         // GitHub requires User-Agent header
466         client.set_default_header("User-Agent", "ModernCppExamples/1.0");
467
468         // GET user information
469         auto response = client.get("/users/torvalds");
470
471         std::cout << "Status Code: " << response.status_code << "\n";
472
473         if (response.is_success()) {
```

```
474     auto data = response.to_json();
475     std::cout << "GitHub User Info:\n";
476     std::cout << "  Name: " << data.value("name", "N/A") << "\n";
477     std::cout << "  Login: " << data["login"] << "\n";
478     std::cout << "  Public Repos: " << data["public_repos"] << "\n";
479     std::cout << "  Followers: " << data["followers"] << "\n";
480 }
481
482 } catch (const std::exception& e) {
483     std::cerr << "Error: " << e.what() << "\n";
484 }
485 }
486
487 void example_error_handling() {
488     std::cout << "\n==== Example 7: Error Handling ===\n";
489
490     try {
491         RestClient client("https://jsonplaceholder.typicode.com");
492
493         // Try to access a non-existent resource (404)
494         auto response = client.get("/posts/999999");
495
496         std::cout << "Status Code: " << response.status_code << "\n";
497
498         if (!response.is_success()) {
499             std::cout << "Request failed!\n";
500             std::cout << "Response body: " << response.body << "\n";
501         }
502
503     } catch (const std::exception& e) {
504         std::cerr << "Error: " << e.what() << "\n";
505     }
506 }
507
508 // =====
509 // SECTION 7: Best Practices Summary
510 // =====
511
512 void print_best_practices() {
513     std::cout << "\n" << std::string(70, '=') << "\n";
514     std::cout << "REST API BEST PRACTICES IN C++:\n";
515     std::cout << std::string(70, '=') << "\n\n";
516
517     std::cout << "1. Resource Management (RAII):\n";
518     std::cout << "    Use RAII wrappers for CURL handles\n";
519     std::cout << "    Ensure cleanup happens automatically\n";
520     std::cout << "    Exception-safe resource handling\n\n";
521
522     std::cout << "2. Error Handling:\n";
523     std::cout << "    Check CURLcode return values\n";
524     std::cout << "    Check HTTP status codes\n";
525     std::cout << "    Use exceptions for network errors\n";
526     std::cout << "    Parse JSON safely with try-catch\n\n";
527 }
```

```
528     std::cout << "3. Security:\n";
529     std::cout << "    Always use HTTPS for sensitive data\n";
530     std::cout << "    Validate SSL certificates (enabled by default)\n";
531     std::cout << "    Never hardcode API keys (use environment variables)\n";
532     std::cout << "    Use Bearer tokens for authentication\n\n";
533
534     std::cout << "4. Performance:\n";
535     std::cout << "    Reuse RestClient instances when possible\n";
536     std::cout << "    Set appropriate timeouts\n";
537     std::cout << "    Consider connection pooling for many requests\n";
538     std::cout << "    Use HTTP/2 when supported\n\n";
539
540     std::cout << "5. Modern C++ Features:\n";
541     std::cout << "    Use smart pointers and RAI\n";
542     std::cout << "    Leverage move semantics\n";
543     std::cout << "    Use structured bindings for map iteration\n";
544     std::cout << "    std::optional for nullable values\n\n";
545
546     std::cout << "6. Testing:\n";
547     std::cout << "    Mock HTTP responses for unit tests\n";
548     std::cout << "    Test error conditions\n";
549     std::cout << "    Use test APIs like JSONPlaceholder\n\n";
550 }
551
552 // =====
553 // MAIN FUNCTION
554 // =====
555
556 int main() {
557     std::cout << "\n";
558     std::cout << "                                \n";
559     std::cout << "          REST API CALLS IN C++ - Complete Examples
560           \n";
561     std::cout << "                                \n";
562     std::cout << "    Demonstrates HTTP methods: GET, POST, PUT, DELETE
563           \n";
564     std::cout << "    Using: libcurl + nlohmann::json
565           \n";
566     std::cout << "                                \n";
567
568     // Run all examples
569     example_json_placeholder_api();
570     example_create_post();
571     example_update_post();
572     example_delete_post();
573     example_with_query_parameters();
574     example_github_api();
575     example_error_handling();
576
577     // Print best practices
578     print_best_practices();
579
580     std::cout << "\n All examples completed successfully!\n";
```

```
578     std::cout << "\nNOTE: These examples use public test APIs:\n";
579     std::cout << "    - JSONPlaceholder (https://jsonplaceholder.typicode.com)\n"
580             "";
581     std::cout << "    - GitHub API (https://api.github.com)\n";
582     std::cout << "\nNo API key required. Responses are simulated/cached.\n\n";
583
584     return 0;
}
```

60 Source Code: RuleOf3_5_0.cpp

File: src/RuleOf3_5_0.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <memory>
4 #include <utility>
5 #include <vector>
6
7 // =====
8 // C++ SPECIAL MEMBER FUNCTIONS: RULE OF 3, 5, AND 0
9 // =====
10
11 // =====
12 // 1. RULE OF ZERO
13 // =====
14 // If you can avoid defining any special member functions (destructor,
15 // copy/move constructors, copy/move assignment), do so. Let the compiler
16 // generate them automatically. Use RAII wrappers like std::unique_ptr,
17 // std::shared_ptr, std::vector, std::string, etc.
18
19 class RuleOfZeroExample {
20 private:
21     std::string name;
22     std::vector<int> data;
23     std::unique_ptr<int> ptr;
24
25 public:
26     RuleOfZeroExample(const std::string& n, int value)
27         : name(n), data{1, 2, 3, 4, 5}, ptr(std::make_unique<int>(value)) {
28         std::cout << "RuleOfZero: Constructor for " << name << std::endl;
29     }
30
31     // No destructor needed - std::string, std::vector, std::unique_ptr
32     // handle cleanup automatically
33
34     // No copy constructor needed - compiler generates correct one
35     // (note: std::unique_ptr makes this non-copyable by default)
36
37     // No copy assignment needed
38
39     // No move constructor needed - compiler generates efficient one
40
41     // No move assignment needed
42
43     void display() const {
44         std::cout << " Name: " << name << ", Value: " << *ptr
45             << ", Data size: " << data.size() << std::endl;
46     }
47 };
48
49 void example_rule_of_zero() {
```

```
50    std::cout << "\n==== RULE OF ZERO ===" << std::endl;
51    std::cout << "Use RAII wrappers. No special member functions needed!\n" <<
52        std::endl;
53
54    RuleOfZeroExample obj1("Object1", 42);
55    obj1.display();
56
57    // Move semantics work automatically
58    RuleOfZeroExample obj2 = std::move(obj1);
59    obj2.display();
60
61    std::cout << "\n Compiler-generated special members handle everything
62        correctly" << std::endl;
63
64 // =====
65 // 2. RULE OF THREE (Pre-C++11)
66 // =====
67 // If you define any of the following, you should define all three:
68 // 1. Destructor
69 // 2. Copy constructor
70 // 3. Copy assignment operator
71
72 class RuleOfThreeExample {
73 private:
74     int* data;
75     size_t size;
76     std::string name;
77
78 public:
79     // Constructor
80     RuleOfThreeExample(const std::string& n, size_t s)
81         : data(new int[s]), size(s), name(n) {
82         for (size_t i = 0; i < size; ++i) {
83             data[i] = static_cast<int>(i);
84         }
85         std::cout << "RuleOfThree: Constructor for " << name
86             << " (size=" << size << ")" << std::endl;
87     }
88
89     // 1. Destructor
90     ~RuleOfThreeExample() {
91         std::cout << "RuleOfThree: Destructor for " << name << std::endl;
92         delete[] data;
93     }
94
95     // 2. Copy constructor
96     RuleOfThreeExample(const RuleOfThreeExample& other)
97         : data(new int[other.size]), size(other.size), name(other.name + "
98             _copy") {
99         for (size_t i = 0; i < size; ++i) {
100             data[i] = other.data[i];
101         }
102         std::cout << "RuleOfThree: Copy constructor for " << name << std::endl;
```

```
    ;
101 }
102
103 // 3. Copy assignment operator
104 RuleOfThreeExample& operator=(const RuleOfThreeExample& other) {
105     std::cout << "RuleOfThree: Copy assignment for " << name << std::endl;
106
107     if (this != &other) {
108         // Free existing resource
109         delete[] data;
110
111         // Allocate new resource and copy
112         size = other.size;
113         data = new int[size];
114         for (size_t i = 0; i < size; ++i) {
115             data[i] = other.data[i];
116         }
117         name = other.name + "_assigned";
118     }
119     return *this;
120 }
121
122 void display() const {
123     std::cout << " " << name << " data: [";
124     for (size_t i = 0; i < std::min(size, size_t(5)); ++i) {
125         std::cout << data[i] << (i < std::min(size, size_t(5)) - 1 ? ", " : "");
126     }
127     std::cout << (size > 5 ? "..." : "") << "]" << std::endl;
128 }
129 };
130
131 void example_rule_of_three() {
132     std::cout << "\n==== RULE OF THREE ===" << std::endl;
133     std::cout << "Define: Destructor, Copy Constructor, Copy Assignment\n" <<
134         std::endl;
135
136     RuleOfThreeExample obj1("Original", 10);
137     obj1.display();
138
139     // Copy constructor
140     RuleOfThreeExample obj2 = obj1;
141     obj2.display();
142
143     // Copy assignment
144     RuleOfThreeExample obj3("Another", 5);
145     obj3 = obj1;
146     obj3.display();
147
148     std::cout << "\n All three special members ensure proper resource
149         management" << std::endl;
150 }
```

```
151 // 3. RULE OF FIVE (C++11 and later)
152 // =====
153 // If you define any of the following, you should define all five:
154 // 1. Destructor
155 // 2. Copy constructor
156 // 3. Copy assignment operator
157 // 4. Move constructor
158 // 5. Move assignment operator
159
160 class RuleOfFiveExample {
161 private:
162     int* data;
163     size_t size;
164     std::string name;
165
166 public:
167     // Constructor
168     RuleOfFiveExample(const std::string& n, size_t s)
169         : data(new int[s]), size(s), name(n) {
170         for (size_t i = 0; i < size; ++i) {
171             data[i] = static_cast<int>(i * 10);
172         }
173         std::cout << "RuleOfFive: Constructor for " << name
174             << " (size=" << size << ")" << std::endl;
175     }
176
177     // 1. Destructor
178     ~RuleOfFiveExample() {
179         std::cout << "RuleOfFive: Destructor for " << name << std::endl;
180         delete[] data;
181     }
182
183     // 2. Copy constructor
184     RuleOfFiveExample(const RuleOfFiveExample& other)
185         : data(new int[other.size]), size(other.size), name(other.name + "_copy") {
186         for (size_t i = 0; i < size; ++i) {
187             data[i] = other.data[i];
188         }
189         std::cout << "RuleOfFive: Copy constructor for " << name << std::endl;
190     }
191
192     // 3. Copy assignment operator
193     RuleOfFiveExample& operator=(const RuleOfFiveExample& other) {
194         std::cout << "RuleOfFive: Copy assignment for " << name << std::endl;
195
196         if (this != &other) {
197             delete[] data;
198             size = other.size;
199             data = new int[size];
200             for (size_t i = 0; i < size; ++i) {
201                 data[i] = other.data[i];
202             }
203             name = other.name + "_copy_assigned";
204         }
205     }
206 }
```

```
204     }
205     return *this;
206 }
207
208 // 4. Move constructor
209 RuleOfFiveExample(RuleOfFiveExample&& other) noexcept
210     : data(other.data), size(other.size), name(std::move(other.name) + "  

211       _moved") {
212     other.data = nullptr;
213     other.size = 0;
214     std::cout << "RuleOfFive: Move constructor for " << name << std::endl;
215 }
216
217 // 5. Move assignment operator
218 RuleOfFiveExample& operator=(RuleOfFiveExample&& other) noexcept {
219     std::cout << "RuleOfFive: Move assignment for " << name << std::endl;
220
221     if (this != &other) {
222         delete[] data;
223
224         data = other.data;
225         size = other.size;
226         name = std::move(other.name) + "_move_assigned";
227
228         other.data = nullptr;
229         other.size = 0;
230     }
231     return *this;
232 }
233
234 void display() const {
235     if (data && size > 0) {
236         std::cout << " " << name << " data: [";
237         for (size_t i = 0; i < std::min(size, size_t(5)); ++i) {
238             std::cout << data[i] << (i < std::min(size, size_t(5)) - 1 ? "  

239               , " : "");
240         }
241         std::cout << (size > 5 ? "..." : "") << "]" << std::endl;
242     } else {
243         std::cout << " " << name << " (moved-from, empty)" << std::endl;
244     }
245 }
246
247 void example_rule_of_five() {
248     std::cout << "\n==== RULE OF FIVE ====" << std::endl;
249     std::cout << "Define: Destructor, Copy Constructor, Copy Assignment,  

250           << Move Constructor, Move Assignment\n" << std::endl;
251
252     RuleOfFiveExample obj1("Original", 8);
253     obj1.display();
254
255     // Copy constructor
256     RuleOfFiveExample obj2 = obj1;
```

```
256     obj2.display();  
257  
258     // Move constructor  
259     RuleOffFiveExample obj3 = std::move(obj1);  
260     obj3.display();  
261     std::cout << "After move:" << std::endl;  
262     obj1.display(); // obj1 is in valid but moved-from state  
263  
264     // Copy assignment  
265     RuleOffFiveExample obj4("Target1", 3);  
266     obj4 = obj2;  
267     obj4.display();  
268  
269     // Move assignment  
270     RuleOffFiveExample obj5("Target2", 3);  
271     obj5 = std::move(obj2);  
272     obj5.display();  
273     std::cout << "After move:" << std::endl;  
274     obj2.display(); // obj2 is in valid but moved-from state  
275  
276     std::cout << "\n All five special members handle both copy and move  
      semantics" << std::endl;  
277 }  
278  
279 // =====  
280 // 4. MODERN C++17/20 RELEVANCE  
281 // =====  
282  
283 #include <optional>  
284 #include <variant>  
285  
286 class ModernCpp17Example {  
287 private:  
288     std::string name;  
289     std::vector<int> data;  
290     std::optional<std::string> description; // C++17  
291     std::variant<int, double, std::string> value; // C++17  
292  
293 public:  
294     ModernCpp17Example(const std::string& n)  
295         : name(n), data{1, 2, 3}, description("A modern class"), value(42) {  
296         std::cout << "Modern C++17 class: " << name << std::endl;  
297     }  
298  
299     // NO special member functions needed!  
300     // Compiler generates everything correctly, including:  
301     // - Destructor (cleans up all RAII members)  
302     // - Copy constructor (deep copies std::string, std::vector, std::optional  
     , std::variant)  
303     // - Copy assignment (properly assigns all members)  
304     // - Move constructor (efficient moves for all members)  
305     // - Move assignment (efficient move assigns)  
306  
307     void display() const {
```

```
308     std::cout << "  Name: " << name;
309     if (description) {
310         std::cout << ", Desc: " << *description;
311     }
312     std::cout << ", Variant holds: ";
313     std::visit([](auto&& arg) { std::cout << arg; }, value);
314     std::cout << std::endl;
315 }
316 };
317
318 void example_modern_cpp_relevance() {
319     std::cout << "\n==== MODERN C++17/20 RELEVANCE ===" << std::endl;
320
321     std::cout << "\n RULE OF ZERO IS MORE RELEVANT THAN EVER!" << std::endl;
322     std::cout << "\nC++17/20 additions that strengthen Rule of Zero:" << std::endl;
323     std::cout << " • std::optional<T> - Optional values (no more raw pointers
324       !)" << std::endl;
325     std::cout << " • std::variant<Ts...> - Type-safe unions" << std::endl;
326     std::cout << " • std::any - Type-safe void*" << std::endl;
327     std::cout << " • std::string_view - Non-owning string references" << std::endl;
328     std::cout << " • std::span<T> (C++20) - Non-owning array views" << std::endl;
329     std::cout << " • std::make_shared array support (C++20)" << std::endl;
330
331     ModernCpp17Example obj1("Original");
332     obj1.display();
333
334     std::cout << "\nCopying (compiler-generated):" << std::endl;
335     ModernCpp17Example obj2 = obj1;
336     obj2.display();
337
338     std::cout << "\nMoving (compiler-generated):" << std::endl;
339     ModernCpp17Example obj3 = std::move(obj1);
340     obj3.display();
341
342     std::cout << "\n Zero manual resource management, all type-safe!" << std::endl;
343 }
344 // =====
345 // 5. COMPARISON: WHEN TO USE WHICH RULE
346 // =====
347
348 void example_comparison() {
349     std::cout << "\n==== WHEN TO USE WHICH RULE (2026 PERSPECTIVE) ===" << std::endl;
350
351     std::cout << "\n RULE OF ZERO (STRONGLY PREFERRED - 95%+ of cases):" << std::endl;
352     std::cout << "    Default choice for ALL new C++17/20 code" << std::endl;
353     std::cout << "    Use std::unique_ptr, std::shared_ptr, std::vector, std::
354       string" << std::endl;
```

```

354     std::cout << "      Use std::optional, std::variant, std::any (C++17)" <<
355         std::endl;
356     std::cout << "      Use std::span for views (C++20)" << std::endl;
357     std::cout << "      Let compiler generate ALL special members" << std::endl;
358     std::cout << "      Zero bugs from manual memory management" << std::endl;
359     std::cout << "      MOST RELEVANT IN MODERN C++!" << std::endl;
360
361     std::cout << "\n RULE OF THREE (LARGELY OBSOLETE):" << std::endl;
362     std::cout << "      Pre-C++11 guideline - avoid in new code" << std::endl;
363     std::cout << "      Maintain in legacy codebases only" << std::endl;
364     std::cout << "      Refactor to Rule of Zero when possible" << std::endl;
365     std::cout << "      Don't use for new C++17/20 code" << std::endl;
366
367     std::cout << "\n RULE OF FIVE (RARELY NEEDED - <5% of cases):" << std::
368         endl;
369     std::cout << "      Only when Rule of Zero is impossible" << std::endl;
370     std::cout << "      Custom allocators or exotic resources" << std::endl;
371     std::cout << "      Performance-critical kernel/driver code" << std::endl;
372     std::cout << "      Interop with C libraries or hardware" << std::endl;
373     std::cout << "      Consider if you really need it first" << std::endl;
374
375     std::cout << "\n MODERN C++17/20 BEST PRACTICES:" << std::endl;
376     std::cout << "  1. ALWAYS start with Rule of Zero" << std::endl;
377     std::cout << "  2. Use std::optional/variant instead of raw pointers" <<
378         std::endl;
379     std::cout << "  3. Use std::unique_ptr for ownership" << std::endl;
380     std::cout << "  4. Use std::span for non-owning views (C++20)" << std::
381         endl;
382     std::cout << "  5. Only implement special members if profiling proves
383         necessary" << std::endl;
384     std::cout << "  6. Use = default and = delete for explicit intent" << std
385         ::endl;
386     std::cout << "  7. Mark move operations noexcept (enables optimizations)"
387         << std::endl;
388
389     std::cout << "\n REALITY CHECK (2026):" << std::endl;
390     std::cout << " •  95%+ of classes should use Rule of Zero" << std::endl;
391     std::cout << " •  <5% need Rule of Five (custom resource managers)" << std
392         ::endl;
393     std::cout << " •  Rule of Three is legacy knowledge only" << std::endl;
394     std::cout << " •  Modern C++ makes manual memory management unnecessary"
395         << std::endl;
396 }
397
398 // =====
399 // 5. EXPLICIT CONTROL: DEFAULT AND DELETE
400 // =====
401
402 class DefaultAndDeleteExample {
403 private:
404     std::unique_ptr<int> ptr;
405
406 public:
407     DefaultAndDeleteExample() : ptr(std::make_unique<int>(42)) {}
408 }
```

```
399     // Explicitly defaulted destructor
400     ~DefaultAndDeleteExample() = default;
401
402     // Deleted copy operations (non-copyable)
403     DefaultAndDeleteExample(const DefaultAndDeleteExample&) = delete;
404     DefaultAndDeleteExample& operator=(const DefaultAndDeleteExample&) =
405         delete;
406
407     // Explicitly defaulted move operations
408     DefaultAndDeleteExample(DefaultAndDeleteExample&&) = default;
409     DefaultAndDeleteExample& operator=(DefaultAndDeleteExample&&) = default;
410
411     int getValue() const { return *ptr; }
412 };
413
414 void example_default_and_delete() {
415     std::cout << "\n==== DEFAULT AND DELETE ===" << std::endl;
416     std::cout << "Explicitly control which special members are available\n" <<
417         std::endl;
418
419     DefaultAndDeleteExample obj1;
420     std::cout << "Created obj1, value: " << obj1.getValue() << std::endl;
421
422     // DefaultAndDeleteExample obj2 = obj1; // ERROR: Copy deleted
423
424     DefaultAndDeleteExample obj3 = std::move(obj1); // OK: Move defaulted
425     std::cout << "Moved to obj3, value: " << obj3.getValue() << std::endl;
426
427     std::cout << "\n = delete prevents copying, = default enables moving" <<
428         std::endl;
429 }
430
431 // =====
432 // 6. EXPLICIT KEYWORD - PREVENTING IMPLICIT CONVERSIONS
433 // =====
434 // The explicit keyword prevents implicit type conversions that could
435 // lead to unexpected behavior or resource management issues
436
437 // BAD: Without explicit - allows implicit conversions
438 class ImplicitBuffer {
439 private:
440     std::unique_ptr<int[]> data;
441     size_t size;
442
443 public:
444     // Constructor without explicit - DANGEROUS!
445     ImplicitBuffer(size_t s) : data(std::make_unique<int[]>(s)), size(s) {
446         std::cout << "ImplicitBuffer: Allocated " << size << " ints" << std::
447             endl;
448     }
449
450     size_t getSize() const { return size; }
451 };
452
```

```
449
450 // GOOD: With explicit - prevents implicit conversions
451 class ExplicitBuffer {
452 private:
453     std::unique_ptr<int[]> data;
454     size_t size;
455
456 public:
457     // Constructor with explicit - SAFE!
458     explicit ExplicitBuffer(size_t s) : data(std::make_unique<int[]>(s)), size(s) {
459         std::cout << "ExplicitBuffer: Allocated " << size << " ints" << std::endl;
460     }
461
462     size_t getSize() const { return size; }
463 };
464
465 // Example with conversion operators
466 class SmartInt {
467 private:
468     int value;
469
470 public:
471     explicit SmartInt(int v) : value(v) {}
472
473     // C++11: explicit conversion operator
474     explicit operator int() const { return value; }
475
476     // Implicit conversion would be dangerous for bool
477     explicit operator bool() const { return value != 0; }
478 };
479
480 void processBuffer(const ExplicitBuffer& buf) {
481     std::cout << " Processing buffer of size: " << buf.getSize() << std::endl
482     ;
483 }
484
485 void processImplicitBuffer(const ImplicitBuffer& buf) {
486     std::cout << " Processing implicit buffer of size: " << buf.getSize() <<
487         std::endl;
488 }
489
490 void example_explicit_keyword() {
491     std::cout << "\n== EXPLICIT KEYWORD ==" << std::endl;
492     std::cout << "Prevents dangerous implicit conversions\n" << std::endl;
493
494     // Without explicit - COMPILES BUT DANGEROUS!
495     std::cout << "Without explicit keyword:" << std::endl;
496     ImplicitBuffer buf1(10); // OK: Direct initialization
497
498     // DANGEROUS: Implicit conversion from int to ImplicitBuffer!
499     processImplicitBuffer(100); // Creates temporary ImplicitBuffer(100) -
500         wasteful!
```

```
498 // Can even do this nonsense:  
499 ImplicitBuffer buf2 = 50; // Implicit conversion - looks like int  
500 // assignment!  
501 std::cout << " Created buffer with = 50 (confusing!)" << std::endl;  
502  
503 std::cout << "\nWith explicit keyword:" << std::endl;  
504 ExplicitBuffer buf3(10); // OK: Direct initialization  
505  
506 // processBuffer(100); // ERROR: Cannot implicitly convert int to  
// ExplicitBuffer  
507 // ExplicitBuffer buf4 = 50; // ERROR: Cannot use copy initialization  
508  
509 std::cout << " Must use direct initialization: ExplicitBuffer(100)" <<  
// std::endl;  
510 processBuffer(ExplicitBuffer(100)); // OK: Explicit construction  
511  
512 // Explicit conversion operators (C++11)  
513 std::cout << "\nExplicit conversion operators:" << std::endl;  
514 SmartInt smart(42);  
515  
516 // int x = smart; // ERROR: Cannot implicitly convert to int  
517 int x = static_cast<int>(smart); // OK: Explicit cast required  
518 std::cout << " Explicit cast to int: " << x << std::endl;  
519  
520 // if (smart) {} // OK: Contextual conversion to bool allowed  
521 std::cout << " Contextual bool conversion works in if/while statements"  
// << std::endl;  
522  
523 std::cout << "\n MODERN C++ BEST PRACTICES:" << std::endl;  
524 std::cout << " ALWAYS use explicit for single-parameter constructors"  
// << std::endl;  
525 std::cout << " Use explicit for conversion operators (except bool)" <<  
// std::endl;  
526 std::cout << " Prevents accidental temporary object creation" << std::  
// endl;  
527 std::cout << " Prevents resource allocation surprises" << std::endl;  
528 std::cout << " Makes code intent crystal clear" << std::endl;  
529  
530 std::cout << "\n WHEN IMPLICIT IS OK:" << std::endl;  
531 std::cout << " • String literals to std::string: std::string s = \"hello  
\\\";" << std::endl;  
532 std::cout << " • Initializer lists: std::vector<int> v = {1, 2, 3};" <<  
// std::endl;  
533 std::cout << " • Copy/move constructors (never explicit)" << std::endl;  
534 }  
535  
536 // =====  
537 // 7. POLICY-BASED DESIGN - PARAMETERIZED RESOURCE MANAGEMENT  
538 // =====  
539 // Modern C++ technique: Use template parameters to customize behavior  
540 // without runtime overhead or virtual functions  
541  
542 // Policy 1: Deletion Strategies
```

```
543 struct ArrayDelete {
544     template<typename T>
545     void operator()(T* ptr) const {
546         delete[] ptr;
547         std::cout << "    ArrayDelete: delete[] called" << std::endl;
548     }
549 };
550
551 struct SingleDelete {
552     template<typename T>
553     void operator()(T* ptr) const {
554         delete ptr;
555         std::cout << "    SingleDelete: delete called" << std::endl;
556     }
557 };
558
559 struct NoOpDelete {
560     template<typename T>
561     void operator()(T*) const {
562         std::cout << "    NoOpDelete: no deletion (externally managed)" << std
563             ::endl;
564     }
565 };
566
567 // Policy 2: Copy Strategies
568 struct DeepCopy {
569     template<typename T>
570     static T* copy(const T* src, size_t size) {
571         std::cout << "    DeepCopy: allocating and copying " << size << "
572             elements" << std::endl;
573         T* dest = new T[size];
574         std::copy(src, src + size, dest);
575         return dest;
576     }
577 };
578
579 struct ShallowCopy {
580     template<typename T>
581     static T* copy(const T* src, size_t) {
582         std::cout << "    ShallowCopy: returning same pointer (reference
583             counting)" << std::endl;
584         return const_cast<T*>(src); // Warning: For demo only!
585     }
586 };
587
588 // Policy 3: Thread Safety
589 struct NoThreadSafety {
590     void lock() const { /* no-op */ }
591     void unlock() const { /* no-op */ }
592 };
593
594 struct BasicThreadSafety {
595     void lock() const {
596         std::cout << "    BasicThreadSafety: acquiring lock" << std::endl;
```

```
594     }
595     void unlock() const {
596         std::cout << "    BasicThreadSafety: releasing lock" << std::endl;
597     }
598 };
599
600 // Policy-based Resource Manager
601 template<
602     typename T,
603     typename DeletePolicy = ArrayDelete,
604     typename CopyPolicy = DeepCopy,
605     typename ThreadPolicy = NoThreadSafety
606 >
607 class PolicyBasedBuffer {
608 private:
609     T* data_;
610     size_t size_;
611     DeletePolicy deleter_;
612     ThreadPolicy thread_policy_;
613
614 public:
615     // Constructor
616     PolicyBasedBuffer(size_t s) : data_(new T[s]), size_(s) {
617         std::cout << "    PolicyBasedBuffer: Constructor (size=" << size_ << ")"
618             << std::endl;
619     }
620
621     // Destructor
622     ~PolicyBasedBuffer() {
623         std::cout << "    PolicyBasedBuffer: Destructor" << std::endl;
624         thread_policy_.lock();
625         deleter_(data_);
626         thread_policy_.unlock();
627     }
628
629     // Copy constructor (uses CopyPolicy)
630     PolicyBasedBuffer(const PolicyBasedBuffer& other)
631         : data_(CopyPolicy::copy(other.data_, other.size_)),
632           size_(other.size_) {
633         std::cout << "    PolicyBasedBuffer: Copy constructor" << std::endl;
634     }
635
636     // Copy assignment
637     PolicyBasedBuffer& operator=(const PolicyBasedBuffer& other) {
638         if (this != &other) {
639             std::cout << "    PolicyBasedBuffer: Copy assignment" << std::endl;
640             thread_policy_.lock();
641             deleter_(data_);
642             data_ = CopyPolicy::copy(other.data_, other.size_);
643             size_ = other.size_;
644             thread_policy_.unlock();
645         }
646         return *this;
647     }
648 }
```

```
647 // Move constructor
648 PolicyBasedBuffer(PolicyBasedBuffer&& other) noexcept
649     : data_(other.data_), size_(other.size_) {
650     other.data_ = nullptr;
651     other.size_ = 0;
652     std::cout << " PolicyBasedBuffer: Move constructor" << std::endl;
653 }
654
655 // Move assignment
656 PolicyBasedBuffer& operator=(PolicyBasedBuffer&& other) noexcept {
657     if (this != &other) {
658         std::cout << " PolicyBasedBuffer: Move assignment" << std::endl;
659         thread_policy_.lock();
660         deleter_(data_);
661         data_ = other.data_;
662         size_ = other.size_;
663         other.data_ = nullptr;
664         other.size_ = 0;
665         thread_policy_.unlock();
666     }
667     return *this;
668 }
669
670
671     size_t size() const { return size_; }
672     T* data() { return data_; }
673 };
674
675 // Type aliases for common configurations
676 template<typename T>
677 using ArrayBuffer = PolicyBasedBuffer<T, ArrayDelete, DeepCopy, NoThreadSafety>;
678
679 template<typename T>
680 using ThreadSafeBuffer = PolicyBasedBuffer<T, ArrayDelete, DeepCopy,
681     BasicThreadSafety>;
682
683 template<typename T>
684 using SingleObjectBuffer = PolicyBasedBuffer<T, SingleDelete, DeepCopy,
685     NoThreadSafety>;
686
687 void example_policy_based_design() {
688     std::cout << "\n== POLICY-BASED DESIGN ==" << std::endl;
689     std::cout << "Parameterize behavior with template policies\n" << std::endl
690         ;
691
692     std::cout << "1. Standard array buffer (ArrayDelete + DeepCopy):" << std::endl;
693
694     {
695         ArrayBuffer<int> buf1(10);
696         std::cout << " Copying..." << std::endl;
697         ArrayBuffer<int> buf2 = buf1;
698         std::cout << " Moving..." << std::endl;
699         ArrayBuffer<int> buf3 = std::move(buf1);
```

```
696     std::cout << "    Cleanup:" << std::endl;
697 }
698
699 std::cout << "\n2. Thread-safe buffer (with BasicThreadSafety):" << std::
700     endl;
701 {
702     ThreadSafeBuffer<int> buf(5);
703     std::cout << "    Cleanup with thread safety:" << std::endl;
704 }
705
706 std::cout << "\n3. Custom policy combination (NoOpDelete for externally
707     managed):" << std::endl;
708 {
709     PolicyBasedBuffer<int, NoOpDelete, DeepCopy, NoThreadSafety> buf(3);
710     std::cout << "    Cleanup (no actual deletion):" << std::endl;
711 }
712
713 std::cout << "\n ADVANTAGES OF POLICY-BASED DESIGN:" << std::endl;
714 std::cout << "    Zero runtime overhead (compile-time selection)" << std::
715     endl;
716 std::cout << "    No virtual functions or vtables needed" << std::endl;
717 std::cout << "    Highly composable and reusable" << std::endl;
718 std::cout << "    Type-safe customization" << std::endl;
719 std::cout << "    Optimized for each configuration" << std::endl;
720
721 std::cout << "\n REAL-WORLD USES:" << std::endl;
722 std::cout << " • std::unique_ptr<T, Deleter> - Custom deleters" << std::
723     endl;
724 std::cout << " • STL containers with Allocator - Custom allocators" <<
725     std::endl;
726 std::cout << " • Thread-safety policies in concurrent code" << std::endl;
727 std::cout << " • Logging/tracing policies" << std::endl;
728 std::cout << " • Different storage strategies (stack vs heap)" << std::
729     endl;
730
731 std::cout << "\n MODERN C++ ALTERNATIVE:" << std::endl;
732 std::cout << "    Use std::unique_ptr<T, Deleter> for most cases:" << std::
733     endl;
734 std::cout << "    auto ptr = std::unique_ptr<int[], ArrayDelete>(new int
735     [10]);" << std::endl;
736 }
737
738 // =====
739 // 8. COPY-AND-SWAP IDIOM
740 // =====
741 // An elegant way to implement assignment operators
742
743 class CopyAndSwapExample {
744 private:
745     int* data;
746     size_t size;
747     std::string name;
748
749 public:
```

```
742     CopyAndSwapExample(const std::string& n, size_t s)
743         : data(new int[s]), size(s), name(n) {
744             for (size_t i = 0; i < size; ++i) {
745                 data[i] = static_cast<int>(i);
746             }
747         }
748
749     ~CopyAndSwapExample() {
750         delete[] data;
751     }
752
753     // Copy constructor
754     CopyAndSwapExample(const CopyAndSwapExample& other)
755         : data(new int[other.size]), size(other.size), name(other.name) {
756             for (size_t i = 0; i < size; ++i) {
757                 data[i] = other.data[i];
758             }
759         }
760
761     // Move constructor
762     CopyAndSwapExample(CopyAndSwapExample&& other) noexcept
763         : data(other.data), size(other.size), name(std::move(other.name)) {
764             other.data = nullptr;
765             other.size = 0;
766         }
767
768     // Swap function
769     friend void swap(CopyAndSwapExample& first, CopyAndSwapExample& second)
770         noexcept {
771         using std::swap;
772         swap(first.data, second.data);
773         swap(first.size, second.size);
774         swap(first.name, second.name);
775     }
776
777     // Unified assignment operator (handles both copy and move)
778     CopyAndSwapExample& operator=(CopyAndSwapExample other) {
779         swap(*this, other);
780         return *this;
781     }
782
783     void display() const {
784         if (data) {
785             std::cout << " " << name << " [size=" << size << "] " << std::endl
786             ;
787         } else {
788             std::cout << " " << name << " (empty)" << std::endl;
789         }
790     }
791 };
792
793 void example_copy_and_swap() {
794     std::cout << "\n==== COPY-AND-SWAP IDIOM ===" << std::endl;
795     std::cout << "Elegant and exception-safe assignment operator\n" << std::endl;
```

```
        endl;

794     CopyAndSwapExample obj1("Object1", 10);
795     CopyAndSwapExample obj2("Object2", 5);
796
797     obj1.display();
798     obj2.display();
799
800     std::cout << "\nAssigning obj1 = obj2 (copy):" << std::endl;
801     obj1 = obj2;
802     obj1.display();
803
804     std::cout << "\nAssigning obj1 = std::move(obj2) (move):" << std::endl;
805     obj1 = std::move(obj2);
806     obj1.display();
807     obj2.display();
808
809     std::cout << "\n Single assignment operator handles both copy and move!" 
810             << std::endl;
811 }

812 // =====
813 // MAIN FUNCTION
814 // =====
815
816
817 int main() {
818     std::cout << "\n"
819             =====" <<
820             std::endl;
821     std::cout << "  C++ SPECIAL MEMBER FUNCTIONS: RULE OF 3, 5, AND 0" << std
822             ::endl;
823     std::cout << "
824             =====" <<
825             std::endl;
826
827     example_rule_of_zero();
828     example_rule_of_three();
829     example_rule_of_five();
830     example_modern_cpp_relevance();
831     example_comparison();
832     example_default_and_delete();
833     example_explicit_keyword();
834     example_policy_based_design();
835     example_copy_and_swap();
836
837     std::cout << "\n"
838             =====" <<
839             std::endl;
840     std::cout << "  SUMMARY" << std::endl;
841     std::cout << " == RULE OF ZERO: Use in 95%+ of modern C++17/20 code!" <<
842             std::endl;
843     std::cout << "    - std::unique_ptr, std::optional, std::variant, std::
844             vector, etc." << std::endl;
845     std::cout << "    - Zero manual memory management = zero bugs" << std::endl;
```

```
837     ;
838     std::cout << "\n RULE OF THREE: Legacy guideline (pre-C++11)" << std::
839         endl;
840     std::cout << "    - Maintain in old codebases only" << std::endl;
841     std::cout << "    - Refactor to Rule of Zero when possible" << std::endl;
842
843     std::cout << "\n RULE OF FIVE: Rarely needed (<5% of cases)" << std::
844         endl;
845     std::cout << "    - Only for custom resource managers" << std::endl;
846     std::cout << "    - Performance-critical scenarios" << std::endl;
847
848     std::cout << "\n USE = DEFAULT AND = DELETE FOR EXPLICIT INTENT" << std::
849         endl;
850     std::cout << " Copy-and-swap idiom when you need Rule of Five" << std::
851         endl;
852
853     std::cout << "\n"
854     =====\n" <<
855         std::endl;
856
857     return 0;
858 }
```

61 Source Code: RuntimePolymorphism.cpp

File: src/RuntimePolymorphism.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <memory>
5 #include <chrono>
6
7 // =====
8 // VIRTUAL FUNCTIONS AND PURE VIRTUAL FUNCTIONS IN MODERN C++
9 // =====
10 // Demonstrates:
11 // 1. Virtual functions vs pure virtual functions
12 // 2. Abstract classes and interfaces
13 // 3. Runtime polymorphism
14 // 4. Virtual destructors (critical!)
15 // 5. override and final keywords (C++11)
16 // 6. When to use vs alternatives (CRTP, concepts)
17 // 7. Performance considerations
18 // 8. Modern C++ best practices
19 // =====
20
21 // =====
22 // 1. PURE VIRTUAL FUNCTIONS - ABSTRACT INTERFACE
23 // =====
24 // Pure virtual function: = 0
25 // Cannot instantiate class with pure virtual functions
26 // Derived classes MUST implement all pure virtual functions
27
28 class IShape {
29 public:
30     // Pure virtual function - no implementation
31     virtual double area() const = 0;
32     virtual double perimeter() const = 0;
33     virtual void draw() const = 0;
34     virtual std::string name() const = 0;
35
36     // Virtual destructor is CRITICAL for polymorphic classes
37     virtual ~IShape() = default;
38
39     // Can have non-virtual functions too
40     void info() const {
41         std::cout << name() << ": area=" << area()
42             << ", perimeter=" << perimeter() << std::endl;
43     }
44 };
45
46 class Circle : public IShape {
47 private:
48     double radius;
```

```
50 | public:
51 |     explicit Circle(double r) : radius(r) {}
52 |
53 |     // Must implement ALL pure virtual functions
54 |     double area() const override {
55 |         return 3.14159 * radius * radius;
56 |     }
57 |
58 |     double perimeter() const override {
59 |         return 2 * 3.14159 * radius;
60 |     }
61 |
62 |     void draw() const override {
63 |         std::cout << "Drawing Circle (radius=" << radius << ")" << std::endl;
64 |     }
65 |
66 |     std::string name() const override {
67 |         return "Circle";
68 |     }
69 | };
70 |
71 | class Rectangle : public IShape {
72 | private:
73 |     double width, height;
74 |
75 | public:
76 |     Rectangle(double w, double h) : width(w), height(h) {}
77 |
78 |     double area() const override {
79 |         return width * height;
80 |     }
81 |
82 |     double perimeter() const override {
83 |         return 2 * (width + height);
84 |     }
85 |
86 |     void draw() const override {
87 |         std::cout << "Drawing Rectangle (" << width << "x" << height << ")" <<
88 |             std::endl;
89 |     }
90 |
91 |     std::string name() const override {
92 |         return "Rectangle";
93 |     }
94 | };
95 |
96 | void example_pure_virtual() {
97 |     std::cout << "\n==== 1. PURE VIRTUAL FUNCTIONS (ABSTRACT INTERFACE) ===" <<
98 |             std::endl;
99 |
100 |     // IShape shape; // ERROR: Cannot instantiate abstract class
101 |     std::vector<std::unique_ptr<IShape>> shapes;
102 |     shapes.push_back(std::make_unique<Circle>(5.0));
```

```
102     shapes.push_back(std::make_unique<Rectangle>(4.0, 6.0));
103     shapes.push_back(std::make_unique<Circle>(3.0));
104
105     std::cout << "\nProcessing shapes polymorphically:" << std::endl;
106     for (const auto& shape : shapes) {
107         shape->draw();
108         shape->info();
109         std::cout << std::endl;
110     }
111
112     std::cout << "  PURE VIRTUAL (= 0):" << std::endl;
113     std::cout << "  • Forces derived classes to implement" << std::endl;
114     std::cout << "  • Creates abstract class (cannot instantiate)" << std::endl;
115     std::cout << "  • Defines interface contract" << std::endl;
116     std::cout << "  • Use for: Interfaces, abstract base classes" << std::endl;
117 }
118
119 // =====
120 // 2. VIRTUAL FUNCTIONS WITH DEFAULT IMPLEMENTATION
121 // =====
122 // Virtual function with implementation - can be overridden but not required
123
124 class Animal {
125 public:
126     virtual ~Animal() = default;
127
128     // Virtual with default implementation
129     virtual void makeSound() const {
130         std::cout << "Some generic animal sound" << std::endl;
131     }
132
133     // Virtual with default implementation
134     virtual void eat() const {
135         std::cout << "Animal is eating" << std::endl;
136     }
137
138     // Non-virtual - cannot override
139     void breathe() const {
140         std::cout << "Animal is breathing" << std::endl;
141     }
142 };
143
144 class Dog : public Animal {
145 public:
146     // Override with custom implementation
147     void makeSound() const override {
148         std::cout << "Woof! Woof!" << std::endl;
149     }
150
151     // Override eat
152     void eat() const override {
153         std::cout << "Dog is eating dog food" << std::endl;
```

```
154     }
155
156     // breathe() cannot be overridden (not virtual)
157 };
158
159 class Cat : public Animal {
160 public:
161     // Only override makeSound
162     void makeSound() const override {
163         std::cout << "Meow!" << std::endl;
164     }
165
166     // eat() uses default implementation from Animal
167 };
168
169 void example_virtual_with_default() {
170     std::cout << "\n==== 2. VIRTUAL FUNCTIONS WITH DEFAULT IMPLEMENTATION ==="
171             << std::endl;
172
173     std::vector<std::unique_ptr<Animal>> animals;
174     animals.push_back(std::make_unique<Dog>());
175     animals.push_back(std::make_unique<Cat>());
176
177     std::cout << "\nDog:" << std::endl;
178     animals[0]->makeSound(); // Custom implementation
179     animals[0]->eat(); // Custom implementation
180     animals[0]->breathe(); // Non-virtual (same for all)
181
182     std::cout << "\nCat:" << std::endl;
183     animals[1]->makeSound(); // Custom implementation
184     animals[1]->eat(); // Uses default from Animal
185     animals[1]->breathe(); // Non-virtual (same for all)
186
187     std::cout << "\n VIRTUAL WITH DEFAULT:" << std::endl;
188     std::cout << " • Provides base implementation" << std::endl;
189     std::cout << " • Derived classes can override if needed" << std::endl;
190     std::cout << " • Optional customization" << std::endl;
191     std::cout << " • Use for: Template Method pattern" << std::endl;
192 }
193 // =====
194 // 3. VIRTUAL DESTRUCTOR - CRITICAL FOR POLYMORPHISM!
195 // =====
196
197 class Base {
198 public:
199     Base() {
200         std::cout << "Base constructor" << std::endl;
201     }
202
203     // BAD: Non-virtual destructor in polymorphic class!
204     ~Base() {
205         std::cout << "Base destructor" << std::endl;
206     }
```

```
207 };
```

```
208 
```

```
209 class DerivedBad : public Base {
```

```
210     private:
```

```
211     int* data;
```

```
212 
```

```
213 public:
```

```
214     DerivedBad() {
pre>215         data = new int[100];
pre>216         std::cout << "DerivedBad constructor (allocated 100 ints)" << std::endl;
pre>217     }
```

```
218 
```

```
219     ~DerivedBad() {
pre>220         delete[] data;
pre>221         std::cout << "DerivedBad destructor (freed memory)" << std::endl;
pre>222     }
```

```
223 };
```

```
224 
```

```
225 class BaseGood {
pre>226 public:
pre>227     BaseGood() {
pre>228         std::cout << "BaseGood constructor" << std::endl;
pre>229     }
```

```
230 
```

```
231 // GOOD: Virtual destructor!
pre>232     virtual ~BaseGood() {
pre>233         std::cout << "BaseGood destructor" << std::endl;
pre>234     }
```

```
235 };
```

```
236 
```

```
237 class DerivedGood : public BaseGood {
pre>238 private:
pre>239     int* data;
```

```
240 
```

```
241 public:
pre>242     DerivedGood() {
pre>243         data = new int[100];
pre>244         std::cout << "DerivedGood constructor (allocated 100 ints)" << std::endl;
pre>245     }
```

```
246 
```

```
247     ~DerivedGood() override {
pre>248         delete[] data;
pre>249         std::cout << "DerivedGood destructor (freed memory)" << std::endl;
pre>250     }
```

```
251 };
```

```
252 
```

```
253 void example_virtual_destructor() {
pre>254     std::cout << "\n== 3. VIRTUAL DESTRUCTOR (CRITICAL!) ==" << std::endl;
pre>255 
pre>256     std::cout << "\n BAD: Non-virtual destructor:" << std::endl;
pre>257     {
pre>258         Base* ptr = new DerivedBad();
```

```
259     delete ptr; // MEMORY LEAK! Only Base destructor called
260 }
261
262 std::cout << "\n GOOD: Virtual destructor:" << std::endl;
263 {
264     BaseGood* ptr = new DerivedGood();
265     delete ptr; // Both destructors called correctly
266 }
267
268 std::cout << "\n RULE: Always make destructor virtual if class has
269     virtual functions!" << std::endl;
270 std::cout << " • Otherwise: Memory leaks, undefined behavior" << std::endl;
271 std::cout << " • Use: virtual ~ClassName() = default;" << std::endl;
272 }
273 // =====
274 // 4. OVERRIDE AND FINAL KEYWORDS (C++11)
275 // =====
276
277 class BaseKeywords {
278 public:
279     virtual void foo() const {
280         std::cout << "BaseKeywords::foo()" << std::endl;
281     }
282
283     virtual void bar() const {
284         std::cout << "BaseKeywords::bar()" << std::endl;
285     }
286
287     virtual ~BaseKeywords() = default;
288 };
289
290 class DerivedKeywords : public BaseKeywords {
291 public:
292     // override: Ensures we're actually overriding a base function
293     void foo() const override {
294         std::cout << "DerivedKeywords::foo()" << std::endl;
295     }
296
297     // This would cause compile error with override:
298     // void fooo() const override {} // Typo! No such function in base
299
300     // final: Cannot be overridden further
301     void bar() const final {
302         std::cout << "DerivedKeywords::bar() - cannot override further" << std::endl;
303     }
304 };
305
306 // final: Cannot be inherited from
307 class FinalClass final {
308 public:
309     void method() {
```

```
310         std::cout << "FinalClass::method()" << std::endl;
311     }
312 };
313
314 // This would cause compile error:
315 // class CannotDeriveFromFinal : public FinalClass { };
316
317 void example_override_final() {
318     std::cout << "\n==== 4. OVERRIDE AND FINAL KEYWORDS (C++11) ===" << std::endl;
319
320     std::unique_ptr<BaseKeywords> ptr = std::make_unique<DerivedKeywords>();
321     ptr->foo();
322     ptr->bar();
323
324     std::cout << "\n OVERRIDE KEYWORD:" << std::endl;
325     std::cout << " • Catches typos at compile time" << std::endl;
326     std::cout << " • Documents intent clearly" << std::endl;
327     std::cout << " • Prevents accidental shadowing" << std::endl;
328     std::cout << " • ALWAYS use it when overriding!" << std::endl;
329
330     std::cout << "\n FINAL KEYWORD:" << std::endl;
331     std::cout << " • Prevents further overriding (function)" << std::endl;
332     std::cout << " • Prevents inheritance (class)" << std::endl;
333     std::cout << " • Enables compiler optimizations" << std::endl;
334     std::cout << " • Use for: Performance, design intent" << std::endl;
335 }
336
337 // =====
338 // 5. WHEN TO USE VIRTUAL FUNCTIONS IN MODERN C++
339 // =====
340
341 void example_when_to_use() {
342     std::cout << "\n==== 5. WHEN TO USE VIRTUAL FUNCTIONS ===" << std::endl;
343
344     std::cout << "\n USE VIRTUAL FUNCTIONS WHEN:" << std::endl;
345     std::cout << " 1. Runtime polymorphism needed" << std::endl;
346     std::cout << "    - Heterogeneous containers (vector<Base*>)" << std::endl;
347     std::cout << "    - Plugin architectures" << std::endl;
348     std::cout << "    - Dynamic type selection" << std::endl;
349
350     std::cout << "\n 2. Interface definition" << std::endl;
351     std::cout << "    - Abstract base classes" << std::endl;
352     std::cout << "    - Pure virtual functions (= 0)" << std::endl;
353     std::cout << "    - Contract for derived classes" << std::endl;
354
355     std::cout << "\n 3. Framework design" << std::endl;
356     std::cout << "    - Template Method pattern" << std::endl;
357     std::cout << "    - Strategy pattern" << std::endl;
358     std::cout << "    - Factory pattern" << std::endl;
359
360     std::cout << "\n 4. Open/Closed principle" << std::endl;
361     std::cout << "    - Extend behavior without modifying base" << std::endl;
```

```
    ;
362     std::cout << "      - Add new types without changing existing code" << std
363         ::endl;
364 }
365 // =====
366 // 6. ALTERNATIVES TO VIRTUAL FUNCTIONS (MODERN C++)
367 // =====
368
369 // CRTP (Curiously Recurring Template Pattern) - Static Polymorphism
370 template<typename Derived>
371 class SensorBase {
372 public:
373     float read() {
374         // Static cast to derived - no runtime overhead!
375         return static_cast<Derived*>(this)->read_impl();
376     }
377 };
378
379 class TemperatureSensor : public SensorBase<TemperatureSensor> {
380 public:
381     float read_impl() {
382         return 25.5f; // Temperature reading
383     }
384 };
385
386 class PressureSensor : public SensorBase<PressureSensor> {
387 public:
388     float read_impl() {
389         return 1013.25f; // Pressure reading
390     }
391 };
392
393 template<typename Sensor>
394 void process_sensor(Sensor& sensor) {
395     // Compile-time polymorphism - fully inlineable!
396     std::cout << "Sensor reading: " << sensor.read() << std::endl;
397 }
398
399 void example_alternatives() {
400     std::cout << "\n==== 6. ALTERNATIVES TO VIRTUAL FUNCTIONS ===" << std::endl
401         ;
402
403     std::cout << "\n1. CRTP (STATIC POLYMORPHISM):" << std::endl;
404     TemperatureSensor temp;
405     PressureSensor pressure;
406
407     process_sensor(temp);
408     process_sensor(pressure);
409
410     std::cout << "\n      Advantages:" << std::endl;
411     std::cout << " •      Zero runtime overhead (no vtable)" << std::endl;
412     std::cout << " •      Fully inlineable" << std::endl;
413     std::cout << " •      Faster than virtual functions" << std::endl;
```

```

413     std::cout << " •      Good for embedded systems" << std::endl;
414
415     std::cout << "\n      Disadvantages:" << std::endl;
416     std::cout << " •      No heterogeneous containers" << std::endl;
417     std::cout << " •      Compile-time binding only" << std::endl;
418     std::cout << " •      More complex syntax" << std::endl;
419
420     std::cout << "\n2. CONCEPTS (C++20):" << std::endl;
421     std::cout << " •      Compile-time constraints" << std::endl;
422     std::cout << " •      Duck typing with type safety" << std::endl;
423     std::cout << " •      No inheritance needed" << std::endl;
424     std::cout << " •      Example: template<Drawable T> void draw(T& obj)" << std
        ::endl;
425
426     std::cout << "\n3. std::variant (C++17):" << std::endl;
427     std::cout << " •      Type-safe union" << std::endl;
428     std::cout << " •      std::visit for polymorphic behavior" << std::endl;
429     std::cout << " •      Value semantics (no pointers)" << std::endl;
430     std::cout << " •      Good for small, closed set of types" << std::endl;
431
432     std::cout << "\n4. std::function (C++11):" << std::endl;
433     std::cout << " •      Type-erased callable" << std::endl;
434     std::cout << " •      Works with lambdas, functors" << std::endl;
435     std::cout << " •      Runtime overhead (like virtual)" << std::endl;
436     std::cout << " •      Good for callbacks, strategies" << std::endl;
437 }
438
439 // =====
440 // 7. PERFORMANCE COMPARISON
441 // =====
442
443 class VirtualBase {
444 public:
445     virtual int compute(int x) { return x * 2; }
446     virtual ~VirtualBase() = default;
447 };
448
449 class VirtualDerived : public VirtualBase {
450 public:
451     int compute(int x) override { return x * 3; }
452 };
453
454 void example_performance() {
455     std::cout << "\n== 7. PERFORMANCE CONSIDERATIONS ==" << std::endl;
456
457     constexpr int iterations = 10'000'000;
458
459     // Virtual function call
460     VirtualBase* vptr = new VirtualDerived();
461     auto start_virtual = std::chrono::high_resolution_clock::now();
462     volatile int result_virtual = 0;
463     for (int i = 0; i < iterations; ++i) {
464         result_virtual += vptr->compute(i);
465     }
}

```

```
466 auto end_virtual = std::chrono::high_resolution_clock::now();
467 auto duration_virtual = std::chrono::duration_cast<std::chrono::
468     milliseconds>(
469         end_virtual - start_virtual).count();
470
471 // Direct function call (non-virtual)
472 VirtualDerived direct;
473 auto start_direct = std::chrono::high_resolution_clock::now();
474 volatile int result_direct = 0;
475 for (int i = 0; i < iterations; ++i) {
476     result_direct += direct.compute(i);
477 }
478 auto end_direct = std::chrono::high_resolution_clock::now();
479 auto duration_direct = std::chrono::duration_cast<std::chrono::
480     milliseconds>(
481         end_direct - start_direct).count();
482
483 delete vptr;
484
485 std::cout << "\nPerformance (10 million calls):" << std::endl;
486 std::cout << "    Virtual function: " << duration_virtual << " ms" << std
487     ::endl;
488 std::cout << "    Direct call:        " << duration_direct << " ms" << std::
489     endl;
490 std::cout << "    Overhead:           ~"
491     << (duration_virtual - duration_direct) << " ms" << std::endl;
492
493 std::cout << "\n OVERHEAD SOURCES:" << std::endl;
494 std::cout << "    1. Vtable lookup (8 bytes per object)" << std::endl;
495 std::cout << "    2. Indirect function call (cache miss)" << std::endl;
496 std::cout << "    3. Cannot be inlined by compiler" << std::endl;
497 std::cout << "    4. Branch prediction harder" << std::endl;
498
499 std::cout << "\n TRADE-OFF:" << std::endl;
500 std::cout << " • Virtual functions: Small overhead, big flexibility" <<
501     std::endl;
502 std::cout << " • Usually worth it for abstraction benefits" << std::endl
503     ;
504 std::cout << " • Only optimize if profiling shows bottleneck" << std::
505     endl;
506 }
507
508 // =====
509 // 8. MODERN C++ BEST PRACTICES
510 // =====
511
512 void example_best_practices() {
513     std::cout << "\n==== 8. MODERN C++ BEST PRACTICES ===" << std::endl;
514
515     std::cout << "\n DO:"
516     << std::endl;
517     std::cout << "    1. ALWAYS use 'override' keyword" << std::endl;
518     std::cout << "        void foo() override { }" << std::endl;
519     std::cout << "        void foo() { } // Easy to make mistakes" << std::
520     endl;
```

```
512
513     std::cout << "\n    2. ALWAYS make destructor virtual in polymorphic
514         classes" << std::endl;
515     std::cout << "            virtual ~Base() = default;" << std::endl;
516     std::cout << "            ~Base() { } // Memory leaks!" << std::endl;
517
518     std::cout << "\n    3. Use 'final' to prevent further overriding" << std::
519         endl;
520     std::cout << "            void foo() final { } // Design intent +
521         optimization" << std::endl;
522
523     std::cout << "\n    4. Use pure virtual (= 0) for interfaces" << std::endl;
524     std::cout << "            virtual void draw() const = 0; // Must implement"
525         << std::endl;
526
527     std::cout << "\n    5. Prefer smart pointers for polymorphic objects" <<
528         std::endl;
529     std::cout << "            std::unique_ptr<Base> ptr = std::make_unique<Derived
530         >();" << std::endl;
531     std::cout << "            Base* ptr = new Derived(); // Manual delete needed"
532         << std::endl;
533
534     std::cout << "\n    1. Don't use virtual for non-polymorphic classes" << std
535         ::endl;
536     std::cout << "            - Unnecessary overhead" << std::endl;
537
538     std::cout << "\n    2. Don't forget virtual destructor" << std::endl;
539     std::cout << "            - Causes memory leaks and undefined behavior" << std::
540         endl;
541
542     std::cout << "\n    3. Don't call virtual functions in constructor/
543         destructor" << std::endl;
544     std::cout << "            - Derived class not fully constructed yet" << std::
545         endl;
546     std::cout << "            - Will call base version, not derived!" << std::endl;
547
548     std::cout << "\n    4. Don't use virtual if CRTP/concepts work" << std::
549         endl;
550     std::cout << "            - Static polymorphism is faster" << std::endl;
551     std::cout << "            - Good for performance-critical code" << std::endl;
552 }

553 // =====
554 // 9. ARE VIRTUAL FUNCTIONS STILL RELEVANT?
555 // =====

556 void example_still_relevant() {
557     std::cout << "\n==== 9. ARE VIRTUAL FUNCTIONS STILL RELEVANT? ===" << std::
558         endl;
559
560     std::cout << "\n YES! Virtual functions are STILL HIGHLY RELEVANT:" <<
561         std::endl;
```

```
552     std::cout << "\n1. RUNTIME POLYMORPHISM:" << std::endl;
553     std::cout << " • Containers of heterogeneous objects" << std::endl;
554     std::cout << " • Plugin systems and dynamic loading" << std::endl;
555     std::cout << " • GUI frameworks (Qt, wxWidgets)" << std::endl;
556     std::cout << " • Game engines (entity systems)" << std::endl;
557
558     std::cout << "\n2. DESIGN PATTERNS:" << std::endl;
559     std::cout << " • Strategy, Observer, Command patterns" << std::endl;
560     std::cout << " • Factory method, Template method" << std::endl;
561     std::cout << " • Visitor pattern (double dispatch)" << std::endl;
562
563     std::cout << "\n3. API DESIGN:" << std::endl;
564     std::cout << " • Stable binary interfaces (ABIs)" << std::endl;
565     std::cout << " • Dynamic libraries (.dll, .so)" << std::endl;
566     std::cout << " • Cross-module boundaries" << std::endl;
567
568     std::cout << "\n4. SIMPLICITY:" << std::endl;
569     std::cout << " • Easier to understand than CRTP" << std::endl;
570     std::cout << " • More maintainable for most teams" << std::endl;
571     std::cout << " • Better error messages" << std::endl;
572
573     std::cout << "\n MODERN ALTERNATIVES (C++11-20):" << std::endl;
574     std::cout << " • CRTP - Compile-time polymorphism" << std::endl;
575     std::cout << " • Concepts (C++20) - Duck typing with constraints" << std
      ::endl;
576     std::cout << " • std::variant + std::visit (C++17)" << std::endl;
577     std::cout << " • std::function - Type-erased callables" << std::endl;
578
579     std::cout << "\n WHEN TO CHOOSE:" << std::endl;
580     std::cout << " • Virtual Functions:" << std::endl;
581     std::cout << " • Need runtime polymorphism" << std::endl;
582     std::cout << " • Heterogeneous containers" << std::endl;
583     std::cout << " • Plugin architectures" << std::endl;
584     std::cout << " • Simplicity and maintainability" << std::endl;
585
586     std::cout << "\n CRTP/Concepts:" << std::endl;
587     std::cout << " • Performance critical code" << std::endl;
588     std::cout << " • Compile-time polymorphism sufficient" << std::endl;
589     std::cout << " • Embedded systems (no vtable)" << std::endl;
590     std::cout << " • Header-only libraries" << std::endl;
591
592     std::cout << "\n BOTTOM LINE:" << std::endl;
593     std::cout << " • Virtual functions: Core C++ feature, still essential"
      << std::endl;
594     std::cout << " • Modern C++ adds alternatives, not replacements" << std
      ::endl;
595     std::cout << " • Choose based on requirements, not trends" << std::endl;
596     std::cout << " • Most codebases use BOTH virtual and static polymorphism
      " << std::endl;
597 }
598
599 // =====
600 // MAIN
601 // =====
```

```
602
603 int main() {
604     std::cout << "\n"
605     ===== " VIRTUAL FUNCTIONS AND PURE VIRTUAL FUNCTIONS IN MODERN C++ "
606     " << std::endl;
607     std::cout << "
608     ===== " SUMMARY: VIRTUAL FUNCTIONS IN MODERN C++ " << std::endl;
609     std::cout << "
610     ===== " KEY CONCEPTS:" << std::endl;
611     std::cout << " 1. Pure virtual (= 0) - Abstract interface, must
612         implement" << std::endl;
613     std::cout << " 2. Virtual - Can override, optional" << std::endl;
614     std::cout << " 3. Virtual destructor - ALWAYS for polymorphic classes"
615         << std::endl;
616     std::cout << " 4. override keyword - ALWAYS use when overriding" << std
617         ::endl;
618     std::cout << " 5. final keyword - Prevent further overriding" << std::
619         endl;
620
621     std::cout << "\n BEST PRACTICES:" << std::endl;
622     std::cout << " • Use 'override' on all virtual function overrides" <<
623         std::endl;
624     std::cout << " • Always virtual destructor for polymorphic classes" <<
625         std::endl;
626     std::cout << " • Prefer std::unique_ptr/shared_ptr over raw pointers" <<
627         std::endl;
628     std::cout << " • Consider CRTP/concepts for performance-critical code"
629         << std::endl;
630     std::cout << " • Don't call virtual functions in constructors/
631         destructors" << std::endl;
632
633     std::cout << "\n STILL RELEVANT IN MODERN C++:" << std::endl;
634     std::cout << " • YES! Essential for runtime polymorphism" << std::endl;
```

```
638     std::cout << " • Plugin systems, frameworks, design patterns" << std::endl;
639     std::cout << " • Modern C++ adds alternatives, not replacements" << std::endl;
640     std::cout << " • Choose based on requirements, not trends" << std::endl;
641
642     std::cout << "\n"
643             ======\n"
644     std::endl;
645
646     return 0;
647 }
```

62 Source Code: SOLIDPrinciples.cpp

File: src/SOLIDPrinciples.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // SOLID PRINCIPLES IN C++
3 // =====
4 // A comprehensive demonstration of the five SOLID design principles
5 // for object-oriented programming in Modern C++
6 //
7 // S - Single Responsibility Principle
8 // O - Open-Closed Principle
9 // L - Liskov Substitution Principle
10 // I - Interface Segregation Principle
11 // D - Dependency Inversion Principle
12 //
13 // Build: g++ -std=c++20 -Wall -Wextra -O2 -o SOLIDPrinciples SOLIDPrinciples.
14 // .cpp
15 // =====
16 #include <iostream>
17 #include <string>
18 #include <vector>
19 #include <memory>
20 #include <fstream>
21 #include <sstream>
22 #include <cmath>
23 #include <stdexcept>
24 //
25 // =====
26 // PRINCIPLE 1: SINGLE RESPONSIBILITY PRINCIPLE (SRP)
27 // =====
28 // A class should have only ONE reason to change
29 // Each class should do ONE thing and do it well
30
31 namespace single_responsibility {
32
33 // BAD: Class with multiple responsibilities
34 class BadEmployee {
35 private:
36     std::string name_;
37     double salary_;
38
39 public:
40     BadEmployee(const std::string& name, double salary)
41         : name_(name), salary_(salary) {}
42
43     // Responsibility 1: Employee data management
44     std::string getName() const { return name_; }
45     double getSalary() const { return salary_; }
46
47     // Responsibility 2: Salary calculation (WRONG!)
48     double calculateTax() const {
```

```
49     return salary_ * 0.25;
50 }
51
52 // Responsibility 3: Database operations (WRONG!)
53 void saveToDatabase() {
54     std::cout << "[BAD] Saving " << name_ << " to database...\n";
55     // Database logic here...
56 }
57
58 // Responsibility 4: Reporting (WRONG!)
59 void generatePayslip() {
60     std::cout << "[BAD] Generating payslip for " << name_ << "\n";
61     // Report generation logic...
62 }
63 };
64
65 // GOOD: Separate classes for separate responsibilities
66 class Employee {
67 private:
68     std::string name_;
69     double salary_;
70
71 public:
72     Employee(const std::string& name, double salary)
73         : name_(name), salary_(salary) {}
74
75     std::string getName() const { return name_; }
76     double getSalary() const { return salary_; }
77 };
78
79 // Responsibility 2: Tax calculation
80 class TaxCalculator {
81 public:
82     double calculateTax(const Employee& emp) const {
83         return emp.getSalary() * 0.25;
84     }
85 };
86
87 // Responsibility 3: Database operations
88 class EmployeeRepository {
89 public:
90     void save(const Employee& emp) {
91         std::cout << "[GOOD] Saving " << emp.getName() << " to database...\n";
92         // Database logic here...
93     }
94 };
95
96 // Responsibility 4: Reporting
97 class PayslipGenerator {
98 public:
99     void generate(const Employee& emp) {
100        std::cout << "[GOOD] Generating payslip for " << emp.getName() << "\n";
```

```
101     // Report generation logic...
102 }
103 };
104
105 void demonstrate() {
106     std::cout << "\n" << std::string(70, '=') << "\n";
107     std::cout << "PRINCIPLE 1: SINGLE RESPONSIBILITY PRINCIPLE (SRP)\n";
108     std::cout << std::string(70, '=') << "\n\n";
109
110    std::cout << " DEFINITION:\n";
111    std::cout << " A class should have only ONE reason to change.\n";
112    std::cout << " Each class should do ONE thing and do it well.\n\n";
113
114    std::cout << " BAD Example (Multiple Responsibilities):\n";
115    BadEmployee badEmp("John Doe", 50000);
116    badEmp.saveToDatabase();
117    badEmp.generatePayslip();
118    std::cout << " Problem: Employee class handles data, tax, DB, and
119      reports!\n\n";
120
121    std::cout << " GOOD Example (Single Responsibility):\n";
122    Employee goodEmp("Jane Smith", 60000);
123    TaxCalculator taxCalc;
124    EmployeeRepository repo;
125    PayslipGenerator payslip;
126
127    repo.save(goodEmp);
128    payslip.generate(goodEmp);
129    std::cout << " Tax: $" << taxCalc.calculateTax(goodEmp) << "\n\n";
130
131    std::cout << " BENEFITS:\n";
132    std::cout << " • Easier to understand and maintain\n";
133    std::cout << " • Changes to tax logic don't affect database code\n";
134    std::cout << " • Classes are more reusable and testable\n";
135    std::cout << " • Better separation of concerns\n";
136
137 } // namespace single_responsibility
138
139 // =====
140 // PRINCIPLE 2: OPEN-CLOSED PRINCIPLE (OCP)
141 // =====
142 // Open for extension, closed for modification
143 // You should be able to add new functionality without changing existing code
144
145 namespace open_closed {
146
147 // BAD: Need to modify existing code for each new shape
148 class BadShapeCalculator {
149 public:
150     double calculateArea(const std::string& shapeType, double dimension) {
151         if (shapeType == "circle") {
152             return 3.14159 * dimension * dimension;
153         } else if (shapeType == "square") {
```

```
154         return dimension * dimension;
155     }
156     // Need to modify this function for each new shape! (BAD)
157     return 0.0;
158 }
159 };
160
161 // GOOD: Use polymorphism - open for extension, closed for modification
162 class Shape {
163 public:
164     virtual ~Shape() = default;
165     virtual double area() const = 0;
166     virtual std::string name() const = 0;
167 };
168
169 class Circle : public Shape {
170 private:
171     double radius_;
172
173 public:
174     explicit Circle(double radius) : radius_(radius) {}
175
176     double area() const override {
177         return 3.14159 * radius_ * radius_;
178     }
179
180     std::string name() const override { return "Circle"; }
181 };
182
183 class Square : public Shape {
184 private:
185     double side_;
186
187 public:
188     explicit Square(double side) : side_(side) {}
189
190     double area() const override {
191         return side_ * side_;
192     }
193
194     std::string name() const override { return "Square"; }
195 };
196
197 class Triangle : public Shape {
198 private:
199     double base_;
200     double height_;
201
202 public:
203     Triangle(double base, double height) : base_(base), height_(height) {}
204
205     double area() const override {
206         return 0.5 * base_ * height_;
207     }
}
```

```

208     std::string name() const override { return "Triangle"; }
209 };
210
211 // This class is CLOSED for modification, but OPEN for extension
212 class AreaCalculator {
213 public:
214     double totalArea(const std::vector<std::unique_ptr<Shape>>& shapes) const
215     {
216         double total = 0.0;
217         for (const auto& shape : shapes) {
218             total += shape->area();
219         }
220         return total;
221     }
222
223     void printAreas(const std::vector<std::unique_ptr<Shape>>& shapes) const {
224         for (const auto& shape : shapes) {
225             std::cout << "    " << shape->name() << " area: "
226                         << shape->area() << "\n";
227         }
228     }
229 };
230
231 void demonstrate() {
232     std::cout << "\n" << std::string(70, '=') << "\n";
233     std::cout << "PRINCIPLE 2: OPEN-CLOSED PRINCIPLE (OCP)\n";
234     std::cout << std::string(70, '=') << "\n\n";
235
236     std::cout << "  DEFINITION:\n";
237     std::cout << "    Software entities should be OPEN for extension,\n";
238     std::cout << "    but CLOSED for modification.\n\n";
239
240     std::cout << "  BAD Example:\n";
241     BadShapeCalculator badCalc;
242     std::cout << "    Circle area: " << badCalc.calculateArea("circle", 5.0) <<
243                     "\n";
244     std::cout << "    Problem: Must modify calculateArea() for each new shape!\n
245                     \n";
246
247     std::cout << "  GOOD Example (Using Polymorphism):\n";
248     std::vector<std::unique_ptr<Shape>> shapes;
249     shapes.push_back(std::make_unique<Circle>(5.0));
250     shapes.push_back(std::make_unique<Square>(4.0));
251     shapes.push_back(std::make_unique<Triangle>(3.0, 6.0));
252
253     AreaCalculator calc;
254     calc.printAreas(shapes);
255     std::cout << "    Total area: " << calc.totalArea(shapes) << "\n\n";
256
257     std::cout << "  BENEFITS:\n";
258     std::cout << " • Add new shapes without modifying AreaCalculator\n";
259     std::cout << " • Existing code remains stable and tested\n";
260     std::cout << " • Reduces risk of breaking existing functionality\n";

```

```
259     std::cout << " • Promotes use of interfaces and polymorphism\n";
260 }
261
262 } // namespace open_closed
263
264 // =====
265 // PRINCIPLE 3: LISKOV SUBSTITUTION PRINCIPLE (LSP)
266 // =====
267 // Objects of a superclass should be replaceable with objects of a subclass
268 // without breaking the application
269
270 namespace liskov_substitution {
271
272 // BAD: Violates LSP - Square changes Rectangle's behavior
273 class BadRectangle {
274 protected:
275     int width_;
276     int height_;
277
278 public:
279     virtual ~BadRectangle() = default; // Virtual destructor for polymorphic
280     class
281     virtual void setWidth(int w) { width_ = w; }
282     virtual void setHeight(int h) { height_ = h; }
283
284     int getWidth() const { return width_; }
285     int getHeight() const { return height_; }
286
287     virtual int area() const { return width_ * height_; }
288 };
289
290 class BadSquare : public BadRectangle {
291 public:
292     // Violates LSP: Changes the behavior!
293     void setWidth(int w) override {
294         width_ = w;
295         height_ = w; // Square forces equal sides
296     }
297
298     void setHeight(int h) override {
299         width_ = h;
300         height_ = h; // Square forces equal sides
301     }
302
303 // GOOD: Use composition instead of inheritance for Square
304 class Shape {
305 public:
306     virtual ~Shape() = default;
307     virtual int area() const = 0;
308     virtual std::string type() const = 0;
309 };
310
311 class Rectangle : public Shape {
```

```
312 | private:
313 |     int width_;
314 |     int height_;
315 |
316 | public:
317 |     Rectangle(int w, int h) : width_(w), height_(h) {}
318 |
319 |     void setWidth(int w) { width_ = w; }
320 |     void setHeight(int h) { height_ = h; }
321 |
322 |     int getWidth() const { return width_; }
323 |     int getHeight() const { return height_; }
324 |
325 |     int area() const override { return width_ * height_; }
326 |     std::string type() const override { return "Rectangle"; }
327 };
328 |
329 class Square : public Shape {
330 private:
331     int side_;
332 |
333 public:
334     explicit Square(int side) : side_(side) {}
335 |
336     void setSide(int s) { side_ = s; }
337     int getSide() const { return side_; }
338 |
339     int area() const override { return side_ * side_; }
340     std::string type() const override { return "Square"; }
341 };
342 |
343 void demonstrate() {
344     std::cout << "\n" << std::string(70, '=') << "\n";
345     std::cout << "PRINCIPLE 3: LISKOV SUBSTITUTION PRINCIPLE (LSP)\n";
346     std::cout << std::string(70, '=') << "\n\n";
347 |
348     std::cout << " DEFINITION:\n";
349     std::cout << " Objects of a superclass should be replaceable with
350         objects\n";
351     std::cout << " of a subclass without breaking the application.\n\n";
352 |
353     std::cout << " BAD Example (LSP Violation):\n";
354     BadRectangle* rect = new BadSquare();
355     rect->setWidth(5);
356     rect->setHeight(4);
357     std::cout << "     Expected area: 20 (5x4)\n";
358     std::cout << "     Actual area: " << rect->area() << " (4x4)\n";
359     std::cout << "     Problem: Square changed Rectangle's behavior!\n";
360     delete rect;
361     std::cout << "\n";
362 |
363     std::cout << " GOOD Example (LSP Compliant):\n";
364     Rectangle goodRect(5, 4);
365     std::cout << "     Rectangle (5x4) area: " << goodRect.area() << "\n";
```

```
365     Square goodSquare(4);
366     std::cout << "    Square (4x4) area: " << goodSquare.area() << "\n\n";
367
368     std::cout << "    BENEFITS:\n";
369     std::cout << "    • Substitutability is preserved\n";
370     std::cout << "    • No unexpected behavior when using derived classes\n";
371     std::cout << "    • Polymorphism works correctly\n";
372     std::cout << "    • \"IS-A\" relationship is properly maintained\n";
373 }
374
375 } // namespace liskov_substitution
376
377 // =====
378 // PRINCIPLE 4: INTERFACE SEGREGATION PRINCIPLE (ISP)
379 // =====
380 // Clients should not be forced to depend on interfaces they don't use
381 // Many specific interfaces are better than one general-purpose interface
382
383 namespace interface_segregation {
384
385 // BAD: Fat interface forces implementations to provide unused methods
386 class BadWorker {
387 public:
388     virtual ~BadWorker() = default;
389     virtual void work() = 0;
390     virtual void eat() = 0;
391     virtual void sleep() = 0;
392 };
393
394
395 class BadHumanWorker : public BadWorker {
396 public:
397     void work() override {
398         std::cout << "[Human] Working...\n";
399     }
400
401     void eat() override {
402         std::cout << "[Human] Eating lunch...\n";
403     }
404
405     void sleep() override {
406         std::cout << "[Human] Sleeping...\n";
407     }
408 };
409
410 class BadRobotWorker : public BadWorker {
411 public:
412     void work() override {
413         std::cout << "[Robot] Working 24/7...\n";
414     }
415
416     // Robots don't eat or sleep! Forced to implement unused methods
417     void eat() override {
418         // Empty or throw exception (both are bad)
```

```
419     std::cout << "[Robot] ERROR: Robots don't eat!\n";
420 }
421
422 void sleep() override {
423     // Empty or throw exception (both are bad)
424     std::cout << "[Robot] ERROR: Robots don't sleep!\n";
425 }
426 };
427
428 // GOOD: Segregated interfaces - clients use only what they need
429 class Workable {
430 public:
431     virtual ~Workable() = default;
432     virtual void work() = 0;
433 };
434
435 class Eatable {
436 public:
437     virtual ~Eatable() = default;
438     virtual void eat() = 0;
439 };
440
441 class Sleepable {
442 public:
443     virtual ~Sleepable() = default;
444     virtual void sleep() = 0;
445 };
446
447 // Human implements all interfaces
448 class HumanWorker : public Workable, public Eatable, public Sleepable {
449 public:
450     void work() override {
451         std::cout << "[Human] Working...\n";
452     }
453
454     void eat() override {
455         std::cout << "[Human] Eating lunch...\n";
456     }
457
458     void sleep() override {
459         std::cout << "[Human] Sleeping...\n";
460     }
461 };
462
463 // Robot only implements what it needs
464 class RobotWorker : public Workable {
465 public:
466     void work() override {
467         std::cout << "[Robot] Working 24/7...\n";
468     }
469     // No eat() or sleep() - not forced to implement them!
470 };
471
472 void demonstrate() {
```

```
473     std::cout << "\n" << std::string(70, '=') << "\n";
474     std::cout << "PRINCIPLE 4: INTERFACE SEGREGATION PRINCIPLE (ISP)\n";
475     std::cout << std::string(70, '=') << "\n\n";
476
477     std::cout << "  DEFINITION:\n";
478     std::cout << "    Clients should not be forced to depend on interfaces\n";
479     std::cout << "    they don't use. Prefer many specific interfaces over\n";
480     std::cout << "    one general-purpose interface.\n\n";
481
482     std::cout << "  BAD Example (Fat Interface):\n";
483     BadRobotWorker badRobot;
484     badRobot.work();
485     badRobot.eat(); // Forced to implement, but doesn't make sense!
486     badRobot.sleep(); // Forced to implement, but doesn't make sense!
487     std::cout << "\n";
488
489     std::cout << "  GOOD Example (Segregated Interfaces):\n";
490     HumanWorker human;
491     human.work();
492     human.eat();
493     human.sleep();
494     std::cout << "\n";
495
496     RobotWorker robot;
497     robot.work();
498     std::cout << "    [Robot] No eat() or sleep() methods - clean interface!\n"
499         " ";
500
501     std::cout << "  BENEFITS:\n";
502     std::cout << "  • Classes implement only what they need\n";
503     std::cout << "  • No dummy implementations or exceptions\n";
504     std::cout << "  • Better decoupling and flexibility\n";
505     std::cout << "  • Easier to understand and maintain\n";
506 }
507 } // namespace interface_segregation
508
509 // =====
510 // PRINCIPLE 5: DEPENDENCY INVERSION PRINCIPLE (DIP)
511 // =====
512 // High-level modules should not depend on low-level modules
513 // Both should depend on abstractions (interfaces)
514 // Abstractions should not depend on details, details should depend on
515 // abstractions
516
517 namespace dependency_inversion {
518
519 // BAD: High-level class depends on low-level concrete classes
520 class BadMySQLDatabase {
521 public:
522     void connect() {
523         std::cout << "    [BAD] Connecting to MySQL...\n";
524     }
525 }
```

```
525     void saveData(const std::string& data) {
526         std::cout << "    [BAD] Saving to MySQL: " << data << "\n";
527     }
528 };
529
530 class BadUserService {
531 private:
532     BadMySQLDatabase database_; // Tightly coupled to MySQL!
533
534 public:
535     void saveUser(const std::string& user) {
536         database_.connect();
537         database_.saveData(user);
538         // If we want to switch to PostgreSQL, we must modify this class!
539     }
540 };
541
542 // GOOD: Depend on abstraction, not concrete implementation
543 class IDatabase {
544 public:
545     virtual ~IDatabase() = default;
546     virtual void connect() = 0;
547     virtual void saveData(const std::string& data) = 0;
548 };
549
550 // Low-level modules implement the interface
551 class MySQLDatabase : public IDatabase {
552 public:
553     void connect() override {
554         std::cout << "    [GOOD] Connecting to MySQL...\n";
555     }
556
557     void saveData(const std::string& data) override {
558         std::cout << "    [GOOD] Saving to MySQL: " << data << "\n";
559     }
560 };
561
562 class PostgreSQLDatabase : public IDatabase {
563 public:
564     void connect() override {
565         std::cout << "    [GOOD] Connecting to PostgreSQL...\n";
566     }
567
568     void saveData(const std::string& data) override {
569         std::cout << "    [GOOD] Saving to PostgreSQL: " << data << "\n";
570     }
571 };
572
573 class MongoDBDatabase : public IDatabase {
574 public:
575     void connect() override {
576         std::cout << "    [GOOD] Connecting to MongoDB...\n";
577     }
578 }
```

```
579     void saveData(const std::string& data) override {
580         std::cout << "[GOOD] Saving to MongoDB: " << data << "\n";
581     }
582 };
583
584 // High-level module depends on abstraction (IDatabase), not concrete class
585 class UserService {
586 private:
587     IDatabase& database_; // Depends on interface, not implementation!
588
589 public:
590     explicit UserService(IDatabase& db) : database_(db) {}
591
592     void saveUser(const std::string& user) {
593         database_.connect();
594         database_.saveData(user);
595         // Can switch database without modifying this class!
596     }
597 };
598
599 void demonstrate() {
600     std::cout << "\n" << std::string(70, '=') << "\n";
601     std::cout << "PRINCIPLE 5: DEPENDENCY INVERSION PRINCIPLE (DIP)\n";
602     std::cout << std::string(70, '=') << "\n\n";
603
604     std::cout << " DEFINITION:\n";
605     std::cout << " 1. High-level modules should not depend on low-level
606         modules.\n";
607     std::cout << "      Both should depend on abstractions.\n";
608     std::cout << " 2. Abstractions should not depend on details.\n";
609     std::cout << "      Details should depend on abstractions.\n\n";
610
611     std::cout << " BAD Example (Tight Coupling):\n";
612     BadUserService badService;
613     badService.saveUser("John Doe");
614     std::cout << " Problem: UserService is tightly coupled to MySQL!\n\n";
615
616     std::cout << " GOOD Example (Dependency Injection):\n";
617
618     MySQLDatabase mysql;
619     UserService service1(mysql);
620     service1.saveUser("Jane Smith");
621     std::cout << "\n";
622
623     PostgreSQLDatabase postgres;
624     UserService service2(postgres);
625     service2.saveUser("Bob Johnson");
626     std::cout << "\n";
627
628     MongoDBDatabase mongo;
629     UserService service3(mongo);
630     service3.saveUser("Alice Williams");
631     std::cout << "\n";
```

```
632     std::cout << " BENEFITS:\n";
633     std::cout << " • Loose coupling between modules\n";
634     std::cout << " • Easy to switch implementations\n";
635     std::cout << " • Better testability (can inject mocks)\n";
636     std::cout << " • Follows \"Program to an interface, not an
637         implementation\"\n";
638 }
639 } // namespace dependency_inversion
640
641 // =====
642 // MAIN - Demonstrate All SOLID Principles
643 // =====
644
645 int main() {
646     std::cout << "\n";
647     std::cout << "                                     \n";
648     std::cout << "                                     SOLID PRINCIPLES IN C++\n";
649     std::cout << "                                     Object-Oriented Design Best Practices\n";
650     std::cout << "                                     \n";
651
652     try {
653         // S - Single Responsibility Principle
654         single_responsibility::demonstrate();
655
656         // O - Open-Closed Principle
657         open_closed::demonstrate();
658
659         // L - Liskov Substitution Principle
660         liskov_substitution::demonstrate();
661
662         // I - Interface Segregation Principle
663         interface_segregation::demonstrate();
664
665         // D - Dependency Inversion Principle
666         dependency_inversion::demonstrate();
667
668         // Summary
669         std::cout << "\n" << std::string(70, '=') << "\n";
670         std::cout << "SUMMARY: SOLID PRINCIPLES\n";
671         std::cout << std::string(70, '=') << "\n\n";
672
673         std::cout << "S - Single Responsibility Principle:\n";
674         std::cout << "     One class, one job, one reason to change\n\n";
675
676         std::cout << "O - Open-Closed Principle:\n";
677         std::cout << "     Open for extension, closed for modification\n\n";
678
679         std::cout << "L - Liskov Substitution Principle:\n";
680         std::cout << "     Derived classes must be substitutable for base
681             classes\n\n";
```

```
682     std::cout << "I - Interface Segregation Principle:\n";
683     std::cout << "    Many specific interfaces > one general interface\n\n"
684             "";
685
686     std::cout << "D - Dependency Inversion Principle:\n";
687     std::cout << "    Depend on abstractions, not concrete implementations\n\n";
688
689     std::cout << " APPLYING SOLID:\n";
690     std::cout << " • Leads to more maintainable code\n";
691     std::cout << " • Reduces coupling between components\n";
692     std::cout << " • Makes code more testable\n";
693     std::cout << " • Improves code reusability\n";
694     std::cout << " • Easier to understand and modify\n\n";
695
696     std::cout << "                                     \n";
697     std::cout << "                         ALL SOLID PRINCIPLES DEMONSTRATED!\n";
698             "\n";
699     std::cout << "                                     \n\n";
700
701 } catch (const std::exception& e) {
702     std::cerr << " Error: " << e.what() << "\n";
703     return 1;
704 }
705
706 return 0;
}
```

63 Source Code: STLContainersNoHeap.cpp

File: src/STLContainersNoHeap.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <vector>
4 #include <memory>
5 #include <cstdint>
6 #include <cstring>
7 #include <algorithm>
8 #include <span>
9
10 // =====
11 // CAN STL CONTAINERS WORK ON SYSTEMS WITHOUT HEAP?
12 // =====
13 // Comprehensive answer:
14 // 1. Most STL containers (vector, map, list) require heap by default
15 // 2. std::array works WITHOUT heap (C++11)
16 // 3. std::span works WITHOUT heap (C++20)
17 // 4. Custom allocators can use stack/static memory
18 // 5. C++17 PMR (Polymorphic Memory Resources) for flexible allocation
19 //
20 // This example demonstrates ALL approaches for heap-less STL usage
21 // =====
22
23 // =====
24 // 1. STACK-BASED CONTAINERS - std::array (NO HEAP!)
25 // =====
26
27 void example_std_array() {
28     std::cout << "\n== 1. std::array - STACK-BASED, NO HEAP ==" << std::endl
29         ;
30
31     // std::array: Fixed size, stack allocated, zero heap usage
32     std::array<int, 10> sensor_data = {10, 20, 30, 40, 50, 60, 70, 80, 90,
33                                         100};
34
35     std::cout << "\nSensor readings:" << std::endl;
36     for (size_t i = 0; i < sensor_data.size(); ++i) {
37         std::cout << " Sensor " << i << ":" << sensor_data[i] << std::endl;
38     }
39
40     // Full STL algorithm support
41     std::cout << "\nSorted readings:" << std::endl;
42     std::sort(sensor_data.begin(), sensor_data.end());
43     for (const auto& reading : sensor_data) {
44         std::cout << " " << reading;
45     }
46     std::cout << std::endl;
47
48     // constexpr support (C++17)
49     constexpr std::array<int, 5> compile_time = {1, 2, 3, 4, 5};
```

```

48 [[maybe_unused]] constexpr int sum = compile_time[0] + compile_time[1];
    // Compile-time computation
49
50 std::cout << "\n BENEFITS:" << std::endl;
51 std::cout << " • Zero heap allocation" << std::endl;
52 std::cout << " • Stack-based (fast access)" << std::endl;
53 std::cout << " • Fixed size known at compile time" << std::endl;
54 std::cout << " • Same interface as std::vector" << std::endl;
55 std::cout << " • constexpr support (C++17)" << std::endl;
56 std::cout << " • Perfect for embedded systems" << std::endl;
57
58 std::cout << "\n LIMITATIONS:" << std::endl;
59 std::cout << " • Fixed size (cannot grow/shrink)" << std::endl;
60 std::cout << " • Size must be known at compile time" << std::endl;
61 }
62
63 // =====
64 // 2. NON-OWNING VIEWS - std::span (C++20, NO HEAP!)
65 // =====
66
67 void process_data(std::span<int> data) {
68     std::cout << " Processing " << data.size() << " elements: ";
69     for (auto val : data) {
70         std::cout << val << " ";
71     }
72     std::cout << std::endl;
73 }
74
75 void example_std_span() {
76     std::cout << "\n==== 2. std::span - NON-OWNING VIEW, NO HEAP ===" << std::endl;
77
78     // Stack-based data
79     std::array<int, 5> arr = {1, 2, 3, 4, 5};
80     int c_array[] = {10, 20, 30, 40};
81
82     // std::span: Non-owning view, zero allocation
83     std::span<int> span1(arr);
84     std::span<int> span2(c_array, 4);
85
86     std::cout << "\nProcessing array:" << std::endl;
87     process_data(span1);
88
89     std::cout << "\nProcessing C array:" << std::endl;
90     process_data(span2);
91
92     // Sub-spans (slicing)
93     auto first_three = span1.first(3);
94     std::cout << "\nFirst 3 elements:" << std::endl;
95     process_data(first_three);
96
97     std::cout << "\n BENEFITS:" << std::endl;
98     std::cout << " • Zero allocation (view only)" << std::endl;
99     std::cout << " • Works with std::array, C arrays, std::vector" << std::endl;

```

```
        endl;
100    std::cout << " • Safe bounds checking (can enable)" << std::endl;
101    std::cout << " • Sub-span support (slicing)" << std::endl;
102    std::cout << " • Modern replacement for (T*, size_t)" << std::endl;
103
104    std::cout << "\n CAUTION:" << std::endl;
105    std::cout << " • Non-owning (must ensure lifetime)" << std::endl;
106    std::cout << " • Can dangle if underlying data destroyed" << std::endl;
107 }
108
109 // =====
110 // 3. CUSTOM STACK ALLOCATOR FOR std::vector
111 // =====
112
113 template<typename T, size_t N>
114 class StackAllocator {
115 private:
116     alignas(T) uint8_t storage[N * sizeof(T)];
117     size_t used = 0;
118
119 public:
120     using value_type = T;
121     using size_type = std::size_t;
122     using difference_type = std::ptrdiff_t;
123
124     StackAllocator() = default;
125
126     template<typename U>
127     StackAllocator(const StackAllocator<U, N>&) noexcept {}
128
129     template<typename U>
130     struct rebind {
131         using other = StackAllocator<U, N>;
132     };
133
134     T* allocate(size_t n) {
135         if (used + n > N) {
136             throw std::bad_alloc(); // Or return nullptr in embedded
137         }
138
139         T* result = reinterpret_cast<T*>(storage + used * sizeof(T));
140         used += n;
141         return result;
142     }
143
144     void deallocate(T* p, size_t n) noexcept {
145         // Simple stack allocator: only deallocate if it's the last allocation
146         T* last = reinterpret_cast<T*>(storage + (used - n) * sizeof(T));
147         if (p == last) {
148             used -= n;
149         }
150         // Otherwise, memory is "leaked" until allocator is destroyed
151         // For better deallocation, use a more sophisticated allocator
152     }
}
```

```
153     size_t capacity() const { return N; }
154     size_t available() const { return N - used; }
155 };
156
157
158 template<typename T, size_t N, typename U, size_t M>
159 bool operator==(const StackAllocator<T, N>&, const StackAllocator<U, M>&)
160     noexcept {
161     return false; // Different allocators are never equal
162 }
163
164 template<typename T, size_t N, typename U, size_t M>
165 bool operator!=(const StackAllocator<T, N>&, const StackAllocator<U, M>&)
166     noexcept {
167     return true;
168 }
169
170
171 void example_custom_stack_allocator() {
172     std::cout << "\n==== 3. CUSTOM STACK ALLOCATOR FOR std::vector ===" << std
173         ::endl;
174
175     // std::vector with stack allocator - NO HEAP!
176     using StackVec = std::vector<int, StackAllocator<int, 20>;
177     StackVec vec;
178
179     std::cout << "\nAdding elements (stack allocation):" << std::endl;
180     vec.reserve(10); // Pre-reserve to avoid reallocation
181     for (int i = 0; i < 10; ++i) {
182         vec.push_back(i * 10);
183         std::cout << " Added " << i * 10
184             << ", size=" << vec.size() << std::endl;
185     }
186
187     std::cout << std::endl;
188
189     std::cout << "\n BENEFITS:" << std::endl;
190     std::cout << " • Uses std::vector interface" << std::endl;
191     std::cout << " • Stack-based (no heap)" << std::endl;
192     std::cout << " • Can still push_back(), resize(), etc." << std::endl;
193     std::cout << " • Custom allocator handles memory" << std::endl;
194
195     std::cout << "\n LIMITATIONS:" << std::endl;
196     std::cout << " • Fixed maximum capacity (20 in this case)" << std::endl;
197     std::cout << " • Simple deallocation strategy" << std::endl;
198     std::cout << " • Throws exception when out of memory" << std::endl;
199 }
200
201 // =====
202 // 4. STATIC MEMORY POOL ALLOCATOR
203 // =====
```

```
204
205 template<typename T, size_t PoolSize>
206 class PoolAllocator {
207 private:
208     struct Block {
209         alignas(T) uint8_t data[sizeof(T)];
210     };
211
212     // Static storage - shared across all instances
213     inline static Block storage[PoolSize];
214     inline static bool used[PoolSize] = {};
215     inline static size_t allocated_count = 0;
216
217 public:
218     using value_type = T;
219     using size_type = std::size_t;
220     using difference_type = std::ptrdiff_t;
221
222     PoolAllocator() noexcept = default;
223
224     template<typename U>
225     PoolAllocator(const PoolAllocator<U, PoolSize>&) noexcept {}
226
227     template<typename U>
228     struct rebinding {
229         using other = PoolAllocator<U, PoolSize>;
230     };
231
232     T* allocate(size_t n) {
233         if (n > PoolSize || allocated_count + n > PoolSize) {
234             throw std::bad_alloc();
235         }
236
237         // Find contiguous free blocks
238         for (size_t i = 0; i <= PoolSize - n; ++i) {
239             bool found = true;
240             for (size_t j = 0; j < n; ++j) {
241                 if (used[i + j]) {
242                     found = false;
243                     break;
244                 }
245             }
246
247             if (found) {
248                 for (size_t j = 0; j < n; ++j) {
249                     used[i + j] = true;
250                 }
251                 allocated_count += n;
252                 return reinterpret_cast<T*>(&storage[i]);
253             }
254         }
255
256         throw std::bad_alloc();
257     }
```

```
258     void deallocate(T* p, size_t n) noexcept {
259         if (!p) return;
260
261         auto base = reinterpret_cast<Block*>(storage);
262         auto block = reinterpret_cast<Block*>(p);
263         size_t index = block - base;
264
265         if (index < PoolSize) {
266             for (size_t i = 0; i < n && (index + i) < PoolSize; ++i) {
267                 used[index + i] = false;
268             }
269             allocated_count -= n;
270         }
271     }
272
273     static size_t pool_size() { return PoolSize; }
274 };
275
276
277 template<typename T, size_t N, typename U, size_t M>
278 bool operator==(const PoolAllocator<T, N>&, const PoolAllocator<U, M>&)
279     noexcept {
280     return N == M;
281 }
282
283 template<typename T, size_t N, typename U, size_t M>
284 bool operator!=(const PoolAllocator<T, N>&, const PoolAllocator<U, M>&)
285     noexcept {
286     return N != M;
287 }
288
289 void example_pool_allocator() {
290     std::cout << "\n==== 4. STATIC MEMORY POOL ALLOCATOR ===" << std::endl;
291
292     struct Sensor {
293         int id;
294         float value;
295         Sensor(int i, float v) : id(i), value(v) {
296             std::cout << "    Sensor(" << id << ", " << value << ")" << std::endl;
297         }
298         ~Sensor() {
299             std::cout << "    ~Sensor(" << id << ")" << std::endl;
300         }
301     };
302
303     using SensorVec = std::vector<Sensor, PoolAllocator<Sensor, 10>>;
304
305     std::cout << "\nAllocating sensors from static pool:" << std::endl;
306     {
307         SensorVec sensors;
308         sensors.push_back(Sensor(1, 25.5f));
309         sensors.push_back(Sensor(2, 30.2f));
310         sensors.push_back(Sensor(3, 28.7f));
```

```
309     std::cout << "\nSensors in vector: " << sensors.size() << std::endl;
310 }
312 std::cout << "\nVector destroyed, memory returned to pool" << std::endl;
313
314 std::cout << "\n BENEFITS:" << std::endl;
315 std::cout << " • Static memory (no heap)" << std::endl;
316 std::cout << " • Fast O(1) allocation/deallocation" << std::endl;
317 std::cout << " • No fragmentation" << std::endl;
318 std::cout << " • Works with std::vector, std::list, etc." << std::endl;
319 std::cout << " • Memory reused across instances" << std::endl;
320
321 std::cout << "\n LIMITATIONS:" << std::endl;
322 std::cout << " • Fixed pool size" << std::endl;
323 std::cout << " • Static storage (lifetime of program)" << std::endl;
324 std::cout << " • Simple implementation (one object per allocation)" <<
325     std::endl;
326 }
327 // =====
328 // 5. FIXED CAPACITY VECTOR (NO ALLOCATOR NEEDED)
329 // =====
330
331 template<typename T, size_t Capacity>
332 class FixedVector {
333 private:
334     alignas(T) uint8_t storage[Capacity * sizeof(T)];
335     size_t count = 0;
336
337 public:
338     using value_type = T;
339     using iterator = T*;
340     using const_iterator = const T*;
341
342     FixedVector() = default;
343
344     ~FixedVector() {
345         clear();
346     }
347
348     // Copy constructor
349     FixedVector(const FixedVector& other) : count(0) {
350         for (size_t i = 0; i < other.count; ++i) {
351             push_back(other[i]);
352         }
353     }
354
355     // Move constructor
356     FixedVector(FixedVector&& other) noexcept : count(0) {
357         for (size_t i = 0; i < other.count; ++i) {
358             push_back(std::move(other[i]));
359         }
360         other.clear();
361     }
```

```
362     void push_back(const T& value) {
363         if (count >= Capacity) {
364             // In embedded: return error code or assert
365             throw std::length_error("FixedVector capacity exceeded");
366         }
367         new (storage + count * sizeof(T)) T(value);
368         ++count;
369     }
370
371     void push_back(T&& value) {
372         if (count >= Capacity) {
373             throw std::length_error("FixedVector capacity exceeded");
374         }
375         new (storage + count * sizeof(T)) T(std::move(value));
376         ++count;
377     }
378
379     template<typename... Args>
380     void emplace_back(Args&&... args) {
381         if (count >= Capacity) {
382             throw std::length_error("FixedVector capacity exceeded");
383         }
384         new (storage + count * sizeof(T)) T(std::forward<Args>(args)...);
385         ++count;
386     }
387
388     void pop_back() {
389         if (count > 0) {
390             --count;
391             reinterpret_cast<T*>(storage + count * sizeof(T))->~T();
392         }
393     }
394
395     void clear() {
396         while (count > 0) {
397             pop_back();
398         }
399     }
400
401     T& operator[](size_t index) {
402         return *reinterpret_cast<T*>(storage + index * sizeof(T));
403     }
404
405     const T& operator[](size_t index) const {
406         return *reinterpret_cast<const T*>(storage + index * sizeof(T));
407     }
408
409     T& front() { return (*this)[0]; }
410     const T& front() const { return (*this)[0]; }
411     T& back() { return (*this)[count - 1]; }
412     const T& back() const { return (*this)[count - 1]; }
413
414     size_t size() const { return count; }
```

```

416     size_t capacity() const { return Capacity; }
417     bool empty() const { return count == 0; }
418     bool full() const { return count == Capacity; }
419
420     iterator begin() { return reinterpret_cast<T*>(storage); }
421     iterator end() { return reinterpret_cast<T*>(storage + count * sizeof(T)); }
422     const_iterator begin() const { return reinterpret_cast<const T*>(storage); }
423     const_iterator end() const { return reinterpret_cast<const T*>(storage +
424                               count * sizeof(T)); }
424 };
425
426 void example_fixed_vector() {
427     std::cout << "\n==== 5. FIXED CAPACITY VECTOR (NO ALLOCATOR) ===" << std::endl;
428
429     FixedVector<int, 10> vec;
430
431     std::cout << "\nAdding elements:" << std::endl;
432     for (int i = 0; i < 8; ++i) {
433         vec.push_back(i * 5);
434         std::cout << " Pushed " << i * 5
435                     << ", size=" << vec.size()
436                     << "/" << vec.capacity() << std::endl;
437     }
438
439     std::cout << "\nVector contents:" << std::endl;
440     for (const auto& val : vec) {
441         std::cout << " " << val;
442     }
443     std::cout << std::endl;
444
445     std::cout << "\n BENEFITS:" << std::endl;
446     std::cout << " • Complete control over memory" << std::endl;
447     std::cout << " • No allocator overhead" << std::endl;
448     std::cout << " • Vector-like interface" << std::endl;
449     std::cout << " • Stack or static storage" << std::endl;
450     std::cout << " • Perfect for embedded systems" << std::endl;
451     std::cout << " • Compile-time capacity checking" << std::endl;
452 }
453
454 // =====
455 // 6. SUMMARY TABLE
456 // =====
457
458 void example_summary() {
459     std::cout << "\n==== 6. SUMMARY: STL ON HEAP-LESS SYSTEMS ===" << std::endl
460     ;
461
462     std::cout << " \n" << std::endl;
463     std::cout << " APPROACH" << " HEAP? GROWS? COMPLEXITY USE"
464             << std::endl;
465     std::cout << " CASE" << std::endl;
466     std::cout << " " << std::endl;

```

```

464     std::cout << "  std::array"           NO      NO      SIMPLE   Fixed
465         "  << std::endl;
466     std::cout << "  std::span (C++20)" NO      NO      SIMPLE   View
467         "  << std::endl;
468     std::cout << "  Stack Allocator"    NO      YES     MEDIUM
469         "  Temporary" << std::endl;
470     std::cout << "  Pool Allocator"    NO      YES     MEDIUM
471         "  Reusable" << std::endl;
472     std::cout << "  FixedVector"       NO      YES     LOW
473         "  Embedded" << std::endl;
474     std::cout << "  std::vector (default)" YES     YES     SIMPLE
475         "  General" << std::endl;
476     std::cout << "                                " << std::endl;
477
478     std::cout << "\n ANSWER: Can STL containers work without heap?" << std::endl;
479
480     std::cout << "\n YES! Multiple approaches:" << std::endl;
481     std::cout << "    1. Use std::array - Fixed size, stack-based" << std::endl;
482         ;
483     std::cout << "    2. Use std::span - Non-owning view (C++20)" << std::endl;
484     std::cout << "    3. Custom stack allocator - std::vector on stack" << std::endl;
485         ;
486     std::cout << "    4. Static pool allocator - Pre-allocated memory" << std::endl;
487         ;
488     std::cout << "    5. Custom fixed vector - Complete control" << std::endl;
489
490
491     std::cout << "\n NO (by default):" << std::endl;
492     std::cout << "  •  std::vector - Uses heap by default" << std::endl;
493     std::cout << "  •  std::map - Uses heap by default" << std::endl;
494     std::cout << "  •  std::list - Uses heap by default" << std::endl;
495     std::cout << "  •  std::string - Uses heap (except SSO)" << std::endl;
496     std::cout << "  •  All use std::allocator which calls new/delete" << std::endl;
497
498
499     std::cout << "\n BEST PRACTICES FOR EMBEDDED SYSTEMS:" << std::endl;
500
501     std::cout << "  1. PREFER std::array:" << std::endl;
502         "    Simple, safe, zero overhead" << std::endl;
503         "    Compile-time size checking" << std::endl;
504         "    Full STL algorithm support" << std::endl;
505
506
507     std::cout << "\n  2. USE std::span for function parameters:" << std::endl;
508     std::cout << "    Works with array, vector, C arrays" << std::endl;
509     std::cout << "    Zero allocation" << std::endl;
510     std::cout << "    Modern replacement for (T*, size_t)" << std::endl;
511
512
513     std::cout << "\n  3. CUSTOM ALLOCATORS when needed:" << std::endl;
514     std::cout << "    std::vector with stack/pool allocator" << std::endl;
515     std::cout << "    Keep std::vector interface" << std::endl;
516     std::cout << "    More complex, test thoroughly" << std::endl;
517
518
519     std::cout << "\n  4. CUSTOM CONTAINERS for critical paths:" << std::endl;
520     std::cout << "    FixedVector, CircularBuffer, etc." << std::endl;
521     std::cout << "    Complete control over behavior" << std::endl;
522     std::cout << "    Optimized for specific use case" << std::endl;

```

```
507 }
508
509 // =====
510 // 7. REAL-WORLD EXAMPLE: SENSOR DATA COLLECTION
511 // =====
512
513 void example_real_world() {
514     std::cout << "\n==== 7. REAL-WORLD: SENSOR DATA COLLECTION ===" << std::
515         endl;
516
517     std::cout << "\n SCENARIO:" << std::endl;
518     std::cout << " • ARM Cortex-M4 @ 80MHz" << std::endl;
519     std::cout << " • 64KB RAM (no heap)" << std::endl;
520     std::cout << " • Collect 100 sensor readings" << std::endl;
521     std::cout << " • Process with STL algorithms" << std::endl;
522
523     // Solution 1: std::array (simplest)
524     std::cout << "\n SOLUTION 1: std::array" << std::endl;
525     std::array<float, 100> readings1 = {};
526     for (size_t i = 0; i < 100; ++i) {
527         readings1[i] = 20.0f + (i % 10) * 0.5f; // Simulated readings
528     }
529
530     auto min_max1 = std::minmax_element(readings1.begin(), readings1.end());
531     std::cout << "    Min: " << *min_max1.first
532                     << ", Max: " << *min_max1.second << std::endl;
533
534     // Solution 2: FixedVector (dynamic-like)
535     std::cout << "\n SOLUTION 2: FixedVector" << std::endl;
536     FixedVector<float, 100> readings2;
537     for (int i = 0; i < 100; ++i) {
538         readings2.push_back(20.0f + (i % 10) * 0.5f);
539     }
540
541     auto min_max2 = std::minmax_element(readings2.begin(), readings2.end());
542     std::cout << "    Min: " << *min_max2.first
543                     << ", Max: " << *min_max2.second << std::endl;
544
545     std::cout << "\n BOTH WORK WITHOUT HEAP!" << std::endl;
546     std::cout << " • Zero dynamic allocation" << std::endl;
547     std::cout << " • Full STL algorithm support" << std::endl;
548     std::cout << " • Predictable memory usage" << std::endl;
549     std::cout << " • Real-time safe" << std::endl;
550
551 // =====
552 // MAIN
553 // =====
554
555 int main() {
556     std::cout << "\n
557         =====" <<
558         std::endl;
559     std::cout << " CAN STL CONTAINERS WORK ON SYSTEMS WITHOUT HEAP?" << std::endl;
```

```
558     endl;
559     std::cout << "
560         ====="
561     std::endl;
562
563     example_std_array();
564     example_std_span();
565     example_custom_stack_allocator();
566     example_pool_allocator();
567     example_fixed_vector();
568     example_summary();
569     example_real_world();
570
571     std::cout << "\n"
572         ====="
573     std::endl;
574     std::cout << "    FINAL ANSWER" << std::endl;
575     std::cout << "
576         ====="
577     std::endl;
578
579     std::cout << "\nYES! STL containers CAN work without heap:" << std::endl
580         ;
581
582     std::cout << "\n1. BUILT-IN HEAP-LESS CONTAINERS:" << std::endl;
583     std::cout << "    • std::array (C++11) - Fixed size, stack-based" << std::
584         endl;
585     std::cout << "    • std::span (C++20) - Non-owning view" << std::endl;
586     std::cout << "    • std::string_view (C++17) - String view" << std::endl;
587
588     std::cout << "\n2. CUSTOM ALLOCATORS:" << std::endl;
589     std::cout << "    • Stack allocator - Use stack memory" << std::endl;
590     std::cout << "    • Pool allocator - Pre-allocated pools" << std::endl;
591     std::cout << "    • PMR allocators - C++17 polymorphic" << std::endl;
592     std::cout << "    • Works with: vector, map, list, etc." << std::endl;
593
594     std::cout << "\n3. CUSTOM CONTAINERS:" << std::endl;
595     std::cout << "    • FixedVector - Vector with capacity limit" << std::endl;
596     std::cout << "    • CircularBuffer - Ring buffer" << std::endl;
597     std::cout << "    • StaticString - Fixed-size string" << std::endl;
598     std::cout << "    • Full control over allocation" << std::endl;
599
600
601     std::cout << "\n DEFAULT STL CONTAINERS USE HEAP:" << std::endl;
602     std::cout << "    • std::vector - std::allocator uses new/delete" << std::
603         endl;
604     std::cout << "    • std::map - std::allocator uses new/delete" << std::endl
605         ;
606     std::cout << "    • std::string - std::allocator (except SSO)" << std::endl
607         ;
608     std::cout << "    • Must use custom allocator or alternatives" << std::endl
609         ;
610
611
612     std::cout << "\n RECOMMENDATION FOR EMBEDDED/REAL-TIME:" << std::endl;
613     std::cout << "    1st choice: std::array (simple, safe)" << std::endl;
```

```
599     std::cout << "    2nd choice: std::span for parameters" << std::endl;
600     std::cout << "    3rd choice: Custom allocators for std::vector" << std::
601         endl;
601     std::cout << "    4th choice: Custom containers (FixedVector)" << std::endl
602         ;
602     std::cout << "    Avoid: Default std::vector, std::map, std::string" <<
603         std::endl;
603
604     std::cout << "\n"
604     =====\n" <<
605         std::endl;
605
606     return 0;
607 }
```

64 Source Code: SafetyCriticalSTLContainers.cpp

File: src/SafetyCriticalSTLContainers.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // STL CONTAINERS FOR SAFETY-CRITICAL SYSTEMS
3 // =====
4 // Comprehensive guide for using STL containers in:
5 // - ISO 26262 (Automotive functional safety)
6 // - DO-178C (Avionics software)
7 // - IEC 61508 (Industrial safety)
8 // - Medical device software (IEC 62304)
9 //
10 // Based on:
11 // - MISRA C++:2008 and MISRA C++:2023
12 // - AUTOSAR C++14 Coding Guidelines
13 // - High Integrity C++ (HICPP)
14 // - JSF AV C++ Coding Standards
15 //
16 // Key concerns in safety-critical systems:
17 // 1. Deterministic behavior (no unpredictable timing)
18 // 2. Bounded memory usage (no dynamic allocation at runtime)
19 // 3. No hidden control flow (exceptions, virtual functions)
20 // 4. Verifiable and testable code
21 // 5. No undefined behavior
22 //
23 // Build: g++ -std=c++20 -Wall -Wextra -Wpedantic -O2 -o
24 // SafetyCriticalSTLContainers SafetyCriticalSTLContainers.cpp
25 // =====
26 #include <iostream>
27 #include <array>
28 #include <vector>
29 #include <list>
30 #include <forward_list>
31 #include <set>
32 #include <map>
33 #include <unordered_set>
34 #include <unordered_map>
35 #include <memory>
36 #include <cstdint>
37 #include <string>
38 #include <algorithm>
39 //
40 // =====
41 // SECTION 1: CONTAINER CLASSIFICATION FOR SAFETY-CRITICAL SYSTEMS
42 // =====
43
44 namespace container_classification {
45
46 void demonstrate() {
47     std::cout << "\n" << std::string(80, '=') << "\n";
48     std::cout << "SECTION 1: STL CONTAINERS - SAFETY-CRITICAL CLASSIFICATION\n";
```

```

        ";
49  std::cout << std::string(80, '=' ) << "\n\n";
50
51  std::cout << "                                     \n";
52  std::cout << "  CONTAINER          HEAP?  NODE-BASED?  SAFE?  NOTES
53  std::cout << "           \n";
54  std::cout << "  std::array          NO      NO          BEST for
55  std::cout << "    safety       \n";
56  std::cout << "  std::vector         YES     NO          OK with
57  std::cout << "    allocator     \n";
58  std::cout << "  std::list          YES     YES         AVOID per-
59  std::cout << "    node        \n";
60  std::cout << "  std::forward_list  YES     YES         AVOID per-
61  std::cout << "    node        \n";
62  std::cout << "  std::deque          YES     NO          AVOID
63  std::cout << "    complex      \n";
64  std::cout << "  std::set            YES     YES         AVOID per-
65  std::cout << "    node        \n";
66  std::cout << "  std::map            YES     YES         AVOID per-
67  std::cout << "    node        \n";
68  std::cout << "  std::multiset        YES     YES         AVOID per-
69  std::cout << "    node        \n";
70  std::cout << "  std::multimap        YES     YES         AVOID per-
71  std::cout << "    node        \n";
72  std::cout << "  std::unordered_set   YES     YES         AVOID per-
73  std::cout << "    bucket      \n";
74  std::cout << "  std::unordered_map   YES     YES         AVOID per-
75  std::cout << "    bucket      \n";
76  std::cout << "  std::unordered_*      YES     YES         AVOID per-
77  std::cout << "    bucket      \n";
78  std::cout << "                                     \n\n";
79  std::cout << "KEY ISSUES WITH HEAP ALLOCATION IN SAFETY-CRITICAL SYSTEMS:\n
80
81  std::cout << "1. NON-DETERMINISTIC TIMING:\n";
82  std::cout << "  •  malloc/new can take variable time depending on:\n";
83  std::cout << "    - Current heap fragmentation\n";
84  std::cout << "    - Size of allocation request\n";
85  std::cout << "    - Operating system state\n";
86  std::cout << "  •  Worst-case execution time (WCET) becomes unpredictable\n";
87  std::cout << "  •  Unacceptable for hard real-time systems\n\n";
88
89  std::cout << "2. MEMORY FRAGMENTATION:\n";
90  std::cout << "  •  Repeated allocations/deallocations cause fragmentation\n";
91  std::cout << "  •  Can lead to allocation failures even with available
92  std::cout << "    memory\n";
93  std::cout << "  •  Node-based containers (list, map, set) are worst
94  std::cout << "    offenders\n";
95  std::cout << "  •  Each element requires separate heap allocation\n\n";

```

```

84     std::cout << "3. ALLOCATION FAILURES:\n";
85     std::cout << " • new can throw std::bad_alloc (exception handling
86         required)\n";
86     std::cout << " • malloc can return nullptr (error handling required)\n";
87     std::cout << " • Difficult to recover gracefully in critical systems\n";
88     std::cout << " • May violate MISRA/AUTOSAR guidelines on exceptions\n\n"
89         ;
90
90     std::cout << "4. NODE-BASED CONTAINERS (list, map, set, unordered_*):\n";
91     std::cout << " • EACH ELEMENT requires separate heap allocation\n";
92     std::cout << " • 1000 elements = 1000 malloc/free calls\n";
93     std::cout << " • Massive fragmentation over time\n";
94     std::cout << " • Iterator/pointer invalidation issues\n";
95     std::cout << " • Hidden per-node overhead (8-24 bytes per element)\n\n";
96
97     std::cout << "5. STANDARDS GUIDANCE:\n";
98     std::cout << " • MISRA C++ Rule 18-4-1: Dynamic heap allocation shall
99         not be used\n";
99     std::cout << " • AUTOSAR A18-5-1: Functions malloc, calloc, realloc,
100        free not used\n";
100    std::cout << " • ISO 26262: Recommends static memory allocation for ASIL
101        -D\n";
101    std::cout << " • DO-178C: Dynamic allocation discouraged for Level A
102        software\n";
102}
103
104} // namespace container_classification
105
106// =====
107// SECTION 2: CONTAINERS TO AVOID IN SAFETY-CRITICAL SYSTEMS
108// =====
109
110namespace containers_to_avoid {
111
112void demonstrate_list_issues() {
113    std::cout << "\n" << std::string(80, '-') << "\n";
114    std::cout << "WHY AVOID std::list, std::forward_list?\n";
115    std::cout << std::string(80, '-') << "\n\n";
116
117    std::cout << "PROBLEM: Each element requires separate heap allocation\n\n"
118        ;
119
120    // Demonstrate list overhead
121    std::list<int32_t> my_list;
122
123    std::cout << "Adding 5 elements to std::list:\n";
124    for (int32_t i = 0; i < 5; ++i) {
125        my_list.push_back(i * 10);
126        std::cout << " push_back(" << i * 10 << ") - HEAP ALLOCATION #" << (i
127            + 1) << "\n";
128    }
129
130    std::cout << "\n ISSUES:\n";
131    std::cout << " • 5 separate malloc() calls - non-deterministic timing\n";

```

```

    ;
130 std::cout << " • Each node has pointer overhead (16-24 bytes per element
      )\n";
131 std::cout << " • Fragmentation increases with each allocation\n";
132 std::cout << " • Cannot use custom allocator to pre-allocate (node-by-
      node)\n";
133 std::cout << " • Cache-unfriendly (nodes scattered in memory)\n\n";
134
135 std::cout << " ALTERNATIVE: std::array or std::vector with reserve()\n";
136 }
137
138 void demonstrate_map_set_issues() {
139 std::cout << "\n" << std::string(80, '-') << "\n";
140 std::cout << "WHY AVOID std::map, std::set, std::multimap, std::multiset?\n
      ";
141 std::cout << std::string(80, '-') << "\n\n";
142
143 std::cout << "PROBLEM: Red-black tree with per-node heap allocation\n\n";
144
145 std::map<int32_t, std::string> my_map;
146
147 std::cout << "Adding 3 entries to std::map:\n";
148 my_map[1] = "Critical";
149 std::cout << " map[1] = \"Critical\" - HEAP ALLOCATION for node\n";
150 my_map[2] = "Warning";
151 std::cout << " map[2] = \"Warning\" - HEAP ALLOCATION for node\n";
152 my_map[3] = "Info";
153 std::cout << " map[3] = \"Info\" - HEAP ALLOCATION for node\n";
154
155 std::cout << "\n ISSUES:\n";
156 std::cout << " • Each insertion allocates a tree node (40-64 bytes
      overhead!)\n";
157 std::cout << " • Rebalancing operations (rotations) at runtime\n";
158 std::cout << " • Non-constant insertion time: O(log n) with allocation\n
      ";
159 std::cout << " • Cannot pre-allocate all nodes\n";
160 std::cout << " • Iterators invalidated on modification\n\n";
161
162 std::cout << " ALTERNATIVES:\n";
163 std::cout << " • std::array of key-value pairs + binary search\n";
164 std::cout << " • std::vector of pairs + sort + binary search\n";
165 std::cout << " • Fixed-size hash table (compile-time allocation)\n";
166 }
167
168 void demonstrate_unordered_issues() {
169 std::cout << "\n" << std::string(80, '-') << "\n";
170 std::cout << "WHY AVOID std::unordered_map, std::unordered_set, std::
      ::unordered_multimap?\n";
171 std::cout << std::string(80, '-') << "\n\n";
172
173 std::cout << "PROBLEM: Hash table with bucket allocation + chaining\n\n";
174
175 std::unordered_map<int32_t, std::string> my_unordered_map;
176

```

```
177 std::cout << "Adding 3 entries to std::unordered_map:\n";
178 my_unordered_map[100] = "Sensor1";
179 std::cout << " map[100] = \"Sensor1\" - HEAP: buckets + node\n";
180 my_unordered_map[200] = "Sensor2";
181 std::cout << " map[200] = \"Sensor2\" - HEAP: buckets + node\n";
182 my_unordered_map[300] = "Sensor3";
183 std::cout << " map[300] = \"Sensor3\" - HEAP: buckets + node\n";
184
185 std::cout << "\n ISSUES:\n";
186 std::cout << " • Initial bucket array allocation\n";
187 std::cout << " • Each element allocated separately (chaining)\n";
188 std::cout << " • REHASHING at runtime (load factor > threshold)\n";
189 std::cout << " - Allocates NEW larger bucket array\n";
190 std::cout << " - Rehashes ALL elements (moves to new buckets)\n";
191 std::cout << " - Deallocates old bucket array\n";
192 std::cout << " - MASSIVE non-determinism!\n";
193 std::cout << " • Cannot predict WCET (worst-case execution time)\n";
194 std::cout << " • Hash collisions cause unpredictable performance\n\n";
195
196 std::cout << " ALTERNATIVES:\n";
197 std::cout << " • Fixed-size hash table (no rehashing)\n";
198 std::cout << " • Perfect hashing (compile-time)\n";
199 std::cout << " • Sorted std::array + binary search\n";
200 }
201
202 void demonstrate_deque_issues() {
203     std::cout << "\n" << std::string(80, '-') << "\n";
204     std::cout << "WHY AVOID std::deque?\n";
205     std::cout << std::string(80, '-') << "\n\n";
206
207     std::cout << "PROBLEM: Complex internal structure with multiple
208                 allocations\n\n";
209
210     std::cout << "std::deque internal structure:\n";
211     std::cout << " • Array of pointers to fixed-size chunks\n";
212     std::cout << " • Each chunk allocated separately\n";
213     std::cout << " • Grows by allocating new chunks + updating pointer array\
214                 \n";
215     std::cout << " • Pointer array itself may need reallocation\n\n";
216
217     std::cout << " ISSUES:\n";
218     std::cout << " • Multiple heap allocations (chunks + pointer array)\n";
219     std::cout << " • Complex iterator invalidation rules\n";
220     std::cout << " • Non-contiguous memory (cache-unfriendly)\n";
221     std::cout << " • Unpredictable memory usage pattern\n";
222     std::cout << " • Difficult to analyze for WCET\n\n";
223
224     std::cout << " ALTERNATIVES:\n";
225     std::cout << " • std::array (fixed size)\n";
226     std::cout << " • std::vector with reserve() (growable)\n";
227     std::cout << " • Circular buffer (custom implementation)\n";
228 }
```

```
229     std::cout << "\n" << std::string(80, '=' ) << "\n";
230     std::cout << "SECTION 2: CONTAINERS TO AVOID IN SAFETY-CRITICAL SYSTEMS\n"
231     ;
232     std::cout << std::string(80, '=' ) << "\n";
233 
234     demonstrate_list_issues();
235     demonstrate_map_set_issues();
236     demonstrate_unordered_issues();
237     demonstrate_deque_issues();
238 }
239 } // namespace containers_to_avoid
240
241 // =====
242 // SECTION 3: SAFE ALTERNATIVES - USING CUSTOM ALLOCATORS
243 // =====
244
245 namespace safe_alternatives {
246
247 // Pre-allocated memory pool allocator for safety-critical systems
248 template<typename T, size_t PoolSize>
249 class SafetyPoolAllocator {
250 private:
251     struct alignas(T) Block {
252         uint8_t data[sizeof(T)];
253     };
254
255     // Static storage - allocated at compile time
256     inline static Block storage[PoolSize];
257     inline static bool used[PoolSize] = {};
258     inline static size_t allocated_count = 0;
259
260 public:
261     using value_type = T;
262     using size_type = std::size_t;
263
264     SafetyPoolAllocator() noexcept = default;
265
266     template<typename U>
267     SafetyPoolAllocator(const SafetyPoolAllocator<U, PoolSize>&) noexcept {}
268
269     template<typename U>
270     struct rebind {
271         using other = SafetyPoolAllocator<U, PoolSize>;
272     };
273
274     // Allocate from pool - bounded, deterministic
275     [[nodiscard]] T* allocate(size_t n) {
276         if (n > PoolSize || allocated_count + n > PoolSize) {
277             // In safety-critical systems, handle gracefully without exception
278             return nullptr; // Or use error code
279         }
280
281         // Find contiguous free blocks
```

```
282     for (size_t i = 0; i <= PoolSize - n; ++i) {
283         bool found = true;
284         for (size_t j = 0; j < n; ++j) {
285             if (used[i + j]) {
286                 found = false;
287                 break;
288             }
289         }
290         if (found) {
291             for (size_t j = 0; j < n; ++j) {
292                 used[i + j] = true;
293             }
294             allocated_count += n;
295             return reinterpret_cast<T*>(&storage[i]);
296         }
297     }
298 }
299
300 return nullptr; // Pool exhausted
301 }
302
303 void deallocate(T* p, size_t n) noexcept {
304     if (!p) return;
305
306     // Find and mark blocks as free
307     for (size_t i = 0; i < PoolSize; ++i) {
308         if (reinterpret_cast<T*>(&storage[i]) == p) {
309             for (size_t j = 0; j < n && (i + j) < PoolSize; ++j) {
310                 used[i + j] = false;
311             }
312             allocated_count -= n;
313             return;
314         }
315     }
316 }
317
318 static size_t capacity() { return PoolSize; }
319 static size_t available() { return PoolSize - allocated_count; }
320 };
321
322 template<typename T, size_t N, typename U, size_t M>
323 bool operator==(const SafetyPoolAllocator<T, N>&, const SafetyPoolAllocator<U, M>&) noexcept {
324     return N == M;
325 }
326
327 template<typename T, size_t N, typename U, size_t M>
328 bool operator!=(const SafetyPoolAllocator<T, N>&, const SafetyPoolAllocator<U, M>&) noexcept {
329     return N != M;
330 }
331
332 void demonstrate_vector_with_allocator() {
333     std::cout << "\n" << std::string(80, '-') << "\n";
```

```

334     std::cout << "SAFE: std::vector WITH CUSTOM ALLOCATOR\n";
335     std::cout << std::string(80, '-') << "\n\n";
336
337     std::cout << " Solution: Pre-allocated pool at initialization\n\n";
338
339     using SafeVector = std::vector<int32_t, SafetyPoolAllocator<int32_t,
340         100>>;
341
342     std::cout << "Creating std::vector with SafetyPoolAllocator<int32_t,
343         100>:\n";
344     std::cout << " • Pool allocated at compile-time (static storage)\n";
345     std::cout << " • Max 100 elements (bounded memory)\n";
346     std::cout << " • No heap allocation during runtime\n";
347     std::cout << " • Deterministic allocation from pool\n\n";
348
349     SafeVector safe_vec;
350     safe_vec.reserve(10); // Reserve from pool
351
352     std::cout << "Adding 10 elements:\n";
353     for (int32_t i = 0; i < 10; ++i) {
354         safe_vec.push_back(i * 10);
355         std::cout << " push_back(" << i * 10 << ") - from POOL, not heap\n";
356     }
357
358     std::cout << "\n BENEFITS:\n";
359     std::cout << " • NO heap allocation (malloc/new)\n";
360     std::cout << " • Deterministic timing (pool allocation is O(n) bounded)\n";
361     std::cout << " • No fragmentation\n";
362     std::cout << " • Bounded memory usage (max 100 elements)\n";
363     std::cout << " • Keeps std::vector interface\n";
364     std::cout << " • Compatible with algorithms (sort, find, etc.)\n\n";
365
366     std::cout << " LIMITATIONS:\n";
367     std::cout << " • Fixed maximum capacity (100 in this example)\n";
368     std::cout << " • Must handle allocation failures gracefully\n";
369     std::cout << " • Pool exhaustion returns nullptr (not exception)\n";
370     std::cout << " • Requires careful sizing during design phase\n";
371
372     void demonstrate_array_alternative() {
373         std::cout << "\n" << std::string(80, '-') << "\n";
374         std::cout << "SAFEST: std::array - NO ALLOCATOR NEEDED\n";
375         std::cout << std::string(80, '-') << "\n\n";
376
377         std::cout << " BEST SOLUTION for fixed-size data: std::array\n\n";
378
379         std::array<int32_t, 10> safe_array = {0, 10, 20, 30, 40, 50, 60, 70, 80,
380             90};
381
382         std::cout << "std::array<int32_t, 10> properties:\n";
383         std::cout << " • Zero heap allocation (stack or static storage)\n";
384         std::cout << " • Size known at compile time\n";
385         std::cout << " • Bounds checking with .at()\n";

```

```

384     std::cout << " • Compatible with STL algorithms\n";
385     std::cout << " • constexpr support (C++17)\n";
386     std::cout << " • No overhead vs C array\n\n";
387
388     std::cout << "Array contents:\n ";
389     for (const auto& val : safe_array) {
390         std::cout << val << " ";
391     }
392     std::cout << "\n\n";
393
394     std::cout << " • PERFECT FOR SAFETY-CRITICAL:\n";
395     std::cout << " • ISO 26262 ASIL-D compliant\n";
396     std::cout << " • MISRA C++ compliant (prefer over C arrays)\n";
397     std::cout << " • AUTOSAR C++14 recommended\n";
398     std::cout << " • DO-178C Level A acceptable\n";
399     std::cout << " • Deterministic behavior (O(1) access)\n";
400     std::cout << " • Predictable memory footprint\n";
401     std::cout << " • No hidden control flow\n";
402     std::cout << " • Verifiable and testable\n";
403 }
404
405 void demonstrate_initialization_phase_pattern() {
406     std::cout << "\n" << std::string(80, '-') << "\n";
407     std::cout << "PATTERN: Initialization Phase vs Runtime Phase\n";
408     std::cout << std::string(80, '-') << "\n\n";
409
410     std::cout << "GOLDEN RULE for safety-critical systems:\n";
411     std::cout << " 'Allocate during INITIALIZATION, operate during RUNTIME'\n"
412             "\n";
413     std::cout << "                                     \n";
414     std::cout << " PHASE           ALLOWED          FORBIDDEN
415             \n";
416     std::cout << "             \n";
417     std::cout << " INITIALIZATION • Dynamic allocation • Nothing
418             \n";
419     std::cout << " (startup)   •             reserve()
420             \n";
421     std::cout << "             •             Pool setup
422             \n";
423     std::cout << "             •             Resource acquisition
424             \n";
425     std::cout << "             \n";
426     std::cout << " RUNTIME   •             Read/write data • new/malloc
427             \n";
428     std::cout << "             •             Fixed operations • delete/free
429             \n";
430     std::cout << " (operational) •             Pool allocation • realloc
431             \n";
432     std::cout << "             •             Bounded algorithms • resize/grow
433             \n";
434     std::cout << "             •             Exceptions
435             \n";
436     std::cout << "                                     \n\n";

```

```
427     std::cout << "EXAMPLE: Two-phase lifecycle\n\n";
428
429     std::cout << "// ===== INITIALIZATION PHASE (startup, non-critical) =====\n";
430     std::cout << "void initialize() {\n";
431     std::cout << "    static std::vector<SensorData> sensor_buffer;\n";
432     std::cout << "    sensor_buffer.reserve(1000); // ONE-TIME allocation\n";
433     std::cout << "    // Pre-allocate ALL buffers, pools, resources\n";
434     std::cout << "}\n\n";
435
436
437     std::cout << "// ===== RUNTIME PHASE (operational, time-critical) =====\n";
438     std::cout << "void process_sensor_data(SensorData data) {\n";
439     std::cout << "    // NO allocation here! Only use pre-allocated memory\n";
440     std::cout << "    sensor_buffer.push_back(data); // No realloc (reserved)\n";
441     std::cout << "    if (sensor_buffer.size() > 1000) {\n";
442     std::cout << "        sensor_buffer.erase(sensor_buffer.begin()); //\n";
443     std::cout << "        Shift\n";
444     std::cout << "    }\n";
445     std::cout << "}\n\n";
446
447     std::cout << "KEY PRINCIPLES:\n";
448     std::cout << "1. Allocate ONCE during initialization\n";
449     std::cout << "2. Use reserve() to prevent reallocation\n";
450     std::cout << "3. Never exceed reserved capacity at runtime\n";
451     std::cout << "4. Use static or global storage for long-lived data\n";
452     std::cout << "5. Monitor memory usage during testing\n";
453     std::cout << "6. Assert/verify no runtime allocation in production\n";
454 }
455
456 void demonstrate() {
457     std::cout << "\n" << std::string(80, '=') << "\n";
458     std::cout << "SECTION 3: SAFE ALTERNATIVES WITH CUSTOM ALLOCATORS\n";
459     std::cout << std::string(80, '=') << "\n";
460
461     demonstrate_vector_with_allocator();
462     demonstrate_array_alternative();
463     demonstrate_initialization_phase_pattern();
464 }
465 } // namespace safe_alternatives
466
467 // =====
468 // SECTION 4: STANDARDS AND GUIDELINES SUMMARY
469 // =====
470
471 namespace standards_summary {
472
473 void demonstrate() {
474     std::cout << "\n" << std::string(80, '=') << "\n";
475     std::cout << "SECTION 4: STANDARDS AND GUIDELINES SUMMARY\n";
476     std::cout << std::string(80, '=') << "\n\n";
```



```

509     std::cout << "CONTAINER RECOMMENDATIONS BY STANDARD:\n\n";
510
511     std::cout << "  UNIVERSALLY ACCEPTED (all standards):\n";
512     std::cout << "    •    std::array - Fixed size, no allocation\n";
513     std::cout << "    •    std::span (C++20) - Non-owning view\n";
514     std::cout << "    •    C arrays with size (if bounds-checked)\n\n";
515
516     std::cout << "  CONDITIONALLY ACCEPTED (with restrictions):\n";
517     std::cout << "    •    std::vector - ONLY with:\n";
518     std::cout << "        - reserve() called during initialization\n";
519     std::cout << "        - Custom allocator (pool-based)\n";
520     std::cout << "        - Never exceeds reserved capacity at runtime\n";
521     std::cout << "        - Documented maximum size\n\n";
522
523     std::cout << "  UNIVERSALLY FORBIDDEN (all standards):\n";
524     std::cout << "    •    std::list - Per-node heap allocation\n";
525     std::cout << "    •    std::forward_list - Per-node heap allocation\n";
526     std::cout << "    •    std::map / std::set - Per-node heap allocation\n";
527     std::cout << "    •    std::multimap / std::multiset - Per-node heap
528         allocation\n";
529     std::cout << "    •    std::unordered_map / std::unordered_set - Rehashing\n";
530     std::cout << "    •    std::unordered_multimap / std::unordered_multiset -
531         Rehashing\n";
532     std::cout << "    •    std::deque - Complex internal structure\n";
533     std::cout << "    •    std::string - Dynamic (unless with custom allocator)\n\n";
534
535     std::cout << "RATIONALE FOR PROHIBITIONS:\n\n";
536
537     std::cout << "1. NODE-BASED CONTAINERS (list, map, set):\n";
538     std::cout << "    Problem: Each element → separate allocation\n";
539     std::cout << "    Impact: 1000 elements = 1000 heap operations\n";
540     std::cout << "    Result: Massive fragmentation + non-deterministic timing\n\n";
541
542     std::cout << "2. HASH CONTAINERS (unordered_map, unordered_set):\n";
543     std::cout << "    Problem: Rehashing at unpredictable times\n";
544     std::cout << "    Impact: Can reallocate entire bucket array at runtime\n";
545     std::cout << "    Result: Unpredictable latency spikes (WCET violation)\n\n";
546
547     std::cout << "3. DEQUE:\n";
548     std::cout << "    Problem: Complex multi-level allocation\n";
549     std::cout << "    Impact: Chunks + pointer array allocations\n";
550     std::cout << "    Result: Difficult to analyze and verify\n\n";
551 }
552 } // namespace standards_summary
553
554 // =====
555 // SECTION 5: PRACTICAL DECISION GUIDE
556 // =====
557

```

```
558 namespace decision_guide {  
559  
560 void demonstrate() {  
561     std::cout << "\n" << std::string(80, '=') << "\n";  
562     std::cout << "SECTION 5: PRACTICAL DECISION GUIDE\n";  
563     std::cout << std::string(80, '=') << "\n\n";  
564  
565     std::cout << "DECISION TREE: Which Container Should I Use?\n\n";  
566  
567     std::cout << "    Q: Is the size KNOWN at compile time?\n";  
568     std::cout << "\n";  
569     std::cout << "    YES → Use std::array<T, N>\n";  
570     std::cout << "                BEST choice for safety-critical\n";  
571     std::cout << "    • Zero overhead\n";  
572     std::cout << "    • No allocation\n";  
573     std::cout << "    • Compile-time size checking\n";  
574     std::cout << "\n";  
575     std::cout << "    NO → Continue to Q2\n\n";  
576  
577     std::cout << "    Q: Can I determine MAXIMUM size at design time?\n";  
578     std::cout << "\n";  
579     std::cout << "    YES → Use std::vector with reserve(MAX_SIZE)\n";  
580     std::cout << "                ACCEPTABLE with these conditions:\n";  
581     std::cout << "    1. Call reserve() during initialization\n";  
582     std::cout << "    2. Never exceed reserved capacity at runtime\n";  
583     std::cout << "    3. Monitor usage during testing\n";  
584     std::cout << "    4. Document maximum size\n";  
585     std::cout << "    5. Consider custom allocator for extra safety\n";  
586     std::cout << "\n";  
587     std::cout << "    NO (truly unbounded) → DESIGN PROBLEM!\n";  
588     std::cout << "                Safety-critical systems MUST have bounded  
589     resources\n";  
590     std::cout << "    • Revisit requirements\n";  
591     std::cout << "    • Determine worst-case maximum\n";  
592     std::cout << "    • Add resource limits\n";  
593     std::cout << "    • Consider circular buffer pattern\n";  
594     std::cout << "\n";  
595     std::cout << "    ALTERNATIVE → Fixed-capacity container (custom)\n\n";  
596  
597     std::cout << "    Q: Do I need to insert/remove in the MIDDLE frequently?\n";  
598     std::cout << "\n";  
599     std::cout << "    YES (was thinking std::list) → RECONSIDER!\n";  
600     std::cout << "    • std::list forbidden in safety-critical systems\n";  
601     std::cout << "    • Alternatives:\n";  
602     std::cout << "        1. std::vector + erase/insert (usually fast  
603         enough)\n";  
604     std::cout << "        2. Circular buffer (if queue-like)\n";  
605     std::cout << "        3. Fixed-size priority queue\n";  
606     std::cout << "        4. Index-based linked list in std::array\n";  
607     std::cout << "\n";  
608     std::cout << "    NO → std::vector or std::array is fine\n\n";
```

```

608 std::cout << " Q: Do I need key-value mapping (was thinking std::map)?\n"
609     ;
610 std::cout << " \n";
611 std::cout << " YES → ALTERNATIVES (no std::map):\n";
612 std::cout << "      1. std::array of std::pair<Key, Value> +
613             binary_search\n";
614 std::cout << "      • Sort during initialization\n";
615 std::cout << "      • Use binary_search at runtime (O(log n))\n";
616 std::cout << "      • No allocation after init\n";
617 std::cout << " \n";
618 std::cout << "      2. Fixed-size hash table (compile-time)\n";
619 std::cout << "      • Perfect hashing (no collisions)\n";
620 std::cout << "      • O(1) lookup\n";
621 std::cout << "      • Requires design-time hash analysis\n";
622 std::cout << " \n";
623 std::cout << "      3. std::vector<pair> + sort + binary_search\n";
624 std::cout << "      • Sorted during initialization\n";
625 std::cout << "      • Read-only at runtime\n";
626 std::cout << "      • Good for configuration tables\n";
627 std::cout << " \n";
628 std::cout << "NO → Continue\n\n";
629
630 std::cout << "SUMMARY TABLE:\n\n";
631 std::cout << "          NEED           SAFE SOLUTION          AVOID
632 std::cout << "          \n";
633 std::cout << "          Fixed-size sequence    std::array          C array (
634             no bounds) \n";
635 std::cout << "          Bounded sequence     std::vector + reserve()  std:::
636             vector (default) \n";
637 std::cout << "          FIFO queue         Circular buffer        std:::
638             queue/std::list \n";
639 std::cout << "          LIFO stack         std::array + index    std:::
640             stack (default) \n";
641 std::cout << "          Priority queue      std::array + heap alg   std:::
642             priority_queue \n";
643 std::cout << "          Key-value map       sorted array + search  std::map
644             \n";
645 std::cout << "          Hash table          Fixed hash table      std:::
646             unordered_map \n";
647 std::cout << "          Sorted set          sorted array + search  std::set
648             \n";
649 std::cout << "          Linked list         Index-based in array  std::list
650             \n\n";
651
652 std::cout << "GOLDEN RULES:\n\n";
653 std::cout << "1. ALWAYS prefer std::array when size is known\n";
654 std::cout << "2. NEVER use node-based containers (list, map, set)\n";
655 std::cout << "3. NEVER use std::unordered_* (rehashing issue)\n";
656 std::cout << "4. IF using std::vector:\n";
657 std::cout << "  • Call reserve() during initialization\n";
658 std::cout << "  • Never exceed reserved capacity at runtime\n";

```

```
650     std::cout << " • Consider custom allocator for extra safety\n";
651     std::cout << "5. DOCUMENT maximum sizes for all containers\n";
652     std::cout << "6. VERIFY no runtime allocation (static analysis)\n";
653     std::cout << "7. TEST with memory allocation monitoring enabled\n";
654 }
655
656 } // namespace decision_guide
657
658 // =====
659 // MAIN
660 // =====
661
662 int main() {
663     std::cout << "\n" << std::string(80, '=') << "\n";
664     std::cout << "STL CONTAINERS FOR SAFETY-CRITICAL SYSTEMS\n";
665     std::cout << "ISO 26262 | DO-178C | MISRA C++ | AUTOSAR C++14\n";
666     std::cout << std::string(80, '=') << "\n";
667
668     container_classification::demonstrate();
669     containers_to_avoid::demonstrate();
670     safe_alternatives::demonstrate();
671     standards_summary::demonstrate();
672     decision_guide::demonstrate();
673
674     std::cout << "\n" << std::string(80, '=') << "\n";
675     std::cout << "FINAL ANSWER TO: Which STL containers to avoid?\n";
676     std::cout << std::string(80, '=') << "\n\n";
677
678     std::cout << " ABSOLUTELY FORBIDDEN in safety-critical systems:\n\n";
679     std::cout << " 1. std::list - Per-element heap allocation\n";
680     std::cout << " 2. std::forward_list - Per-element heap allocation\n";
681     std::cout << " 3. std::map - Per-node allocation (red-black tree)\n";
682     std::cout << " 4. std::multimap - Per-node allocation\n";
683     std::cout << " 5. std::set - Per-node allocation\n";
684     std::cout << " 6. std::multiset - Per-node allocation\n";
685     std::cout << " 7. std::unordered_map - Rehashing + per-bucket allocation
686                 \n";
686     std::cout << " 8. std::unordered_multimap - Rehashing + per-bucket
687                 allocation\n";
687     std::cout << " 9. std::unordered_set - Rehashing + per-bucket allocation
688                 \n";
688     std::cout << " 10. std::unordered_multiset - Rehashing + per-bucket
689                 allocation\n";
690     std::cout << " 11. std::deque - Complex multi-level allocation\n";
691     std::cout << " 12. std::string - Dynamic (use with custom allocator only
692                 )\n\n";
693
694     std::cout << " YES, you CAN use containers with CUSTOM ALLOCATORS:\n\n";
695     std::cout << " • std::vector<T, CustomAllocator>\n";
696     std::cout << " • Pre-allocated pool-based allocator\n";
697     std::cout << " • Static memory pool (no heap)\n";
698     std::cout << " • Bounded capacity enforced\n";
699     std::cout << " • Allocation during initialization phase only\n\n";
```

```
699     std::cout << "  SAFEST CHOICE (no allocator needed):\n\n";
700     std::cout << "  •    std::array<T, N> - Stack or static storage\n";
701     std::cout << "  •    std::span<T> (C++20) - Non-owning view\n";
702     std::cout << "  •    C++17 std::string_view - String view\n\n";
703
704     std::cout << "  REMEMBER:\n";
705     std::cout << "    If heap is the issue, custom allocators can help,\n";
706     std::cout << "    but std::array is ALWAYS the safest choice when size is
707           known!\n\n";
708
709     std::cout << std::string(80, '=')
710     return 0;
711 }
```

65 Source Code: SearchAnagramsDictionary.cpp

File: src/SearchAnagramsDictionary.cpp

Repository: [View on GitHub](#)

```
1 // Example program
2 #include <iostream>
3 #include <string>
4
5 #include <algorithm>
6 #include <functional>
7 #include <iterator>
8
9 #include <vector>
10 #include <set>
11 #include <map>
12
13 using Pair_t = std::multimap< std::string, std::string> ;
14 using MMAPIterator = std::multimap<std::string, std::string>::iterator ;
15
16 std::set<std::string> mDictionary = { "act", "ant", "art", "bat", "bet",
17     "boss", "cat", "cap", "cop", "dear", "dog",
18     "dip", "ear", "end", "eel", "fad", "fat", "fog", "gap", "god", "hat", "hit",
19     "hot", "ink", "irk", "jot", "jab",
20     "lap", "lip", "lot", "man", "nan", "nat", "net", "pat", "pet", "tap", "tar",
21     "ten", "rat", "woo", "yoo", "zoo" };
22
23 int main()
24 {
25     Pair_t Pairs = {};
26     std::vector<std::string> emptyVectors = {};
27
28     //std::cout << "All words in the mDictionary are :" << std::endl;
29     for(const auto& it : mDictionary) {
30
31         std::string sortedWord = it;
32         std::sort(sortedWord.begin(), sortedWord.end());
33
34         Pairs.emplace(std::make_pair(sortedWord, it));
35
36         //std::cout << "for word " << it << ", sorted word = " << sortedWord <<
37         //std::endl;
38     }
39
40     for(auto& obj : Pairs) {
41
42         std::cout << "unsorted word = " << obj.second << ", sorted word : " <<
43             obj.first << std::endl;
44     }
45
46     for(auto& obj : Pairs) {
47
48         std::pair <MMAPIterator, MMAPIterator> equalPairs = Pairs.equal_range(
```

```
        obj.first);

45     if(equalPairs.second != equalPairs.first)
46     {
47         std::cout << "for the word = " << obj.second << ", its anagrams
48             are : ";
49
50         for (MMAPIterator it=equalPairs.first; it!=equalPairs.second; ++it
51             )
52         {
53             if(obj.second != it->second) {
54                 std::cout << it->second << ", ";
55             }
56
57             //std::cout << it->first << " : " << it->second << ", ";
58         }
59
60         std::cout << std::endl;
61     } else {
62         std::cout << "for the word = " << obj.second << " there are no
63             anagrams!";
64     }
65 }
```

66 Source Code: SinglyLinkedList.cpp

File: src/SinglyLinkedList.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <string.h>
4 /*
5     pHead
6     |
7     |
8     +---+-----+      +---+-----+      +---+-----+
9     | 1  | next ----->| 2  | next----->| 3 | NULL |
10    +---+-----+      +---+-----+      +---+-----+
11 */
12 extern "C" {
13 struct info;
14 typedef struct info{
15     char name[20];
16     int age;
17     info *next;
18 } personal_info_t;
19
20 info* pHead = NULL; //by default first node will be point to nothing
21
22 extern "C" void deleteNode(info* p); //Forward declaration
23
24 extern "C" void deleteNodeByName(info** pH, const char* name) {
25     info *prevNode, *currNode = *pH;
26
27     while(currNode->next != NULL) {
28
29         if(strcmp(currNode->name, name) == 0) {
30             std::cout << "found the match, will delete node named " <<
31 currNode->name << std::endl;
32             deleteNode(prevNode);
33             return;
34         }
35         prevNode = currNode;
36         currNode = currNode->next;
37     }
38
39     if(currNode->next == NULL) {
40         if(strcmp(currNode->name, name) == 0) {
41             std::cout << currNode->name << " is the last node...." << std::
42 endl;
43             memset((void*) currNode, 0, sizeof(info));
44             free((info *) currNode);
45             prevNode->next = NULL;
46         }
47         else {
48             std::cout << "cannot find the matching name " << name << std::endl
49         ;
50     }
51 }
```

```
48     }
49 }
50 }
51
52 extern "C" void deleteNode(info* p) {
53     info* pNode = p->next;
54     std::cout << pNode->name << " is followed by " << pNode->name << std::endl;
55     pNode->next = pNode->next;
56     memset((void*) pNode, 0, sizeof(info));
57     free((info *) pNode);
58     pNode = pNode->next;
59     std::cout << pNode->name << " is followed by " << pNode->name << std::endl;
60 }
61 extern "C" void createNode(info** pH, const char* name, const int age) {
62     info* pNewNode = (info*) malloc(sizeof(info));
63     if(pNewNode != NULL) {
64         strcpy(pNewNode->name, name);
65         pNewNode->age = age;
66         pNewNode->next= NULL;
67     }
68     else {
69         return;
70     }
71
72     if(*pH == NULL) {
73         pNewNode->next= NULL;
74         *pH = pNewNode;
75         std::cout << (*pH)->name << " is Head, pointing to memory address 0x"
76             << std::hex << std::to_string((size_t)pH) << std::endl;
77     }
78     else {
79         info* pNode = *pH;
80         while(pNode->next != NULL) { pNode = pNode->next; }
81         pNode->next= pNewNode;
82     }
83 }
84 extern "C" const char* getName(const info* i) { return i->name; }
85 extern "C" const int getAge(const info* i) { return i->age; }
86 };
87
88 void print(info* pH) {
89     std::cout << getName(pH) << " is aged " << std::to_string(getAge(pH)) << "
90         followed by:" << std::endl;
91
92     info* pNode = pH;
93     while(pNode->next != NULL){
94         pNode = pNode->next;
95         std::cout << getName(pNode) << " aged " << getAge(pNode) << std::endl;
96     }
97
98 int main() {
99     createNode(&pHead, "AungBu", 20);
```

```
100    createNode(&pHead, "Sar Oo", 30);
101    createNode(&pHead, "AhBang", 25);
102    createNode(&pHead, "AhLain", 27);
103    createNode(&pHead, "Ahmedi", 28);
104
105    print(pHead);
106
107    deleteNodeByName(&pHead, "Sar Oo");
108    deleteNodeByName(&pHead, "AhLain");
109
110    print(pHead);
111
112    return 0;
113
114 }
```

67 Source Code: StopTokenExample.cpp

File: src/StopTokenExample.cpp

Repository: [View on GitHub](#)

```
1 // StopTokenExample.cpp
2 // Demonstrates std::stop_token (C++20) for graceful thread cancellation
3 // Shows the difference between old-style atomic flags and modern stop_token
4 //
5 // KEY CONCEPTS:
6 // 1. std::jthread - Automatically joins, supports stop_token
7 // 2. std::stop_token - Cooperative cancellation signal
8 // 3. std::stop_source - Controls stop requests
9 // 4. std::stop_callback - Actions on stop request
10 //
11 // USE CASES:
12 // REST/Monitor threads (non-critical)
13 // Worker threads in thread pools
14 // Background tasks that need graceful shutdown
15 // Any interruptible operation
16 //
17 // ADVANTAGES OVER atomic<bool>:
18 // Standard, type-safe
19 // Callback support (cleanup on stop)
20 // Works with condition_variable_any
21 // No manual join() needed with jthread
22 // Cannot be accidentally set to true
23
24 #include <iostream>
25 #include <thread>
26 #include <stop_token>
27 #include <mutex>
28 #include <condition_variable>
29 #include <queue>
30 #include <vector>
31 #include <atomic>
32 #include <chrono>
33 #include <string>
34 #include <sstream>
35 #include <iomanip>
36 #include <functional>
37
38 using namespace std::chrono_literals;
39
40 //
41 =====
42 // SECTION 1: Old Style vs New Style - Comparison
43 // =====
44
45 namespace old_vs_new {
```

```
46 // OLD STYLE: Using atomic<bool> for cancellation
47 class OldStyleThread {
48 private:
49     std::atomic<bool> stop_flag_{false};
50     std::thread thread_;
51     std::mutex mutex_;
52     std::condition_variable cv_;
53
54 public:
55     void start() {
56         thread_ = std::thread([this] {
57             std::cout << " [Old Style] Thread started\n";
58
59             while (!stop_flag_.load()) {
60                 std::unique_lock<std::mutex> lock(mutex_);
61
62                 // Problem: Can't easily interrupt cv.wait()
63                 // Must use wait_for() with timeout
64                 if (cv_.wait_for(lock, 100ms, [this] { return stop_flag_.load();
65                     (); })) {
66                     break;
67                 }
68
69                 std::cout << " [Old Style] Working...\n";
70             }
71
72             std::cout << " [Old Style] Thread stopped\n";
73         });
74     }
75
76     void stop() {
77         stop_flag_ = true;
78         cv_.notify_all();
79         if (thread_.joinable()) {
80             thread_.join(); // Manual join required
81         }
82     }
83
84 // NEW STYLE: Using std::jthread with stop_token
85 class NewStyleThread {
86 private:
87     std::jthread thread_; // Automatically joins on destruction
88     std::mutex mutex_;
89     std::condition_variable_any cv_; // Note: _any variant for stop_token
90
91 public:
92     void start() {
93         thread_ = std::jthread([this](std::stop_token stoken) {
94             std::cout << " [New Style] Thread started\n";
95
96             while (!stoken.stop_requested()) {
97                 std::unique_lock<std::mutex> lock(mutex_);
```

```
99         // Can be interrupted immediately!
100        if (cv_.wait(lock, stoken, [] { return false; })) {
101            break; // Stop requested
102        }
103
104        std::cout << " [New Style] Working...\\n";
105    }
106
107    std::cout << " [New Style] Thread stopped\\n";
108);
109}
110
111 void stop() {
112     thread_.request_stop(); // Signal stop
113     // No manual join() needed - jthread does it automatically!
114 }
115};
116
117 void demonstrate() {
118     std::cout << "\\n" << std::string(70, '=') << "\\n";
119     std::cout << "==== SECTION 1: Old Style vs New Style ===\\n";
120     std::cout << std::string(70, '=') << "\\n\\n";
121
122     std::cout << "1. Old style with atomic<bool>:\\n";
123 {
124     OldStyleThread old_thread;
125     old_thread.start();
126     std::this_thread::sleep_for(250ms);
127     std::cout << " [Main] Requesting stop...\\n";
128     old_thread.stop();
129 }
130
131     std::cout << "\\n2. New style with stop_token:\\n";
132 {
133     NewStyleThread new_thread;
134     new_thread.start();
135     std::this_thread::sleep_for(250ms);
136     std::cout << " [Main] Requesting stop...\\n";
137     new_thread.stop();
138 }
139
140     std::cout << "\\n ADVANTAGES of stop_token:\\n";
141     std::cout << " • Type-safe (can't accidentally set to wrong value)\\n";
142     std::cout << " • Works with condition_variable_any for immediate
143         interruption\\n";
144     std::cout << " • jthread automatically joins\\n";
145     std::cout << " • Standard interface for cancellation\\n";
146 }
147} // namespace old_vs_new
148
149// =====
```

```
150 // SECTION 2: REST Service with stop_token (Non-Critical Thread)
151 //
152 =====
153
154 namespace rest_service_example {
155
156 class RESTService {
157 private:
158     std::jthread thread_;
159     std::mutex mutex_;
160     std::condition_variable_any cv_;
161     std::queue<std::string> request_queue_;
162     int request_count_ = 0;
163
164 public:
165     void start() {
166         thread_ = std::jthread([this](std::stop_token stoken) {
167             std::cout << "    [REST] Service started (non-critical thread)\n";
168
169             // Register callback for cleanup
170             std::stop_callback callback(stoken, [this] {
171                 std::cout << "    [REST] Stop requested, cleaning up...\n";
172                 std::lock_guard<std::mutex> lock(mutex_);
173                 std::cout << "    [REST] Processed " << request_count_
174                     << " requests before stop\n";
175             });
176
177             try {
178                 while (!stoken.stop_requested()) {
179                     std::unique_lock<std::mutex> lock(mutex_);
180
181                     // Wait for requests or stop signal
182                     bool stop = cv_.wait(lock, stoken, [this] {
183                         return !request_queue_.empty();
184                     });
185
186                     if (stop) {
187                         std::cout << "    [REST] Stop signal received during
188                             wait\n";
189                         break;
190                     }
191
192                     // Process request
193                     if (!request_queue_.empty()) {
194                         std::string request = request_queue_.front();
195                         request_queue_.pop();
196                         lock.unlock();
197
198                         handle_request(request, stoken);
199                     }
200             }
201         });
202     }
203 }
```

```
201     }
202     catch (const std::exception& e) {
203         std::cerr << "  [REST] Exception: " << e.what() << "\n";
204         std::cerr << "  [REST] Non-critical thread exiting (core
205             services OK)\n";
206     }
207
208     std::cout << "  [REST] Service stopped gracefully\n";
209 }
210
211 void handle_request(const std::string& request, std::stop_token stoken) {
212     std::cout << "  [REST] Handling request: " << request << "\n";
213
214     // Simulate processing with interruptible sleep
215     for (int i = 0; i < 5; ++i) {
216         if (stoken.stop_requested()) {
217             std::cout << "  [REST] Request handling interrupted\n";
218             return;
219         }
220
221         std::this_thread::sleep_for(100ms);
222     }
223
224     ++request_count_;
225     std::cout << "  [REST] Request completed (total: " << request_count_
226         << ")\n";
227
228     // Simulate occasional error in REST service
229     if (request.find("CAUSE_ERROR") != std::string::npos) {
230         throw std::runtime_error("REST service error (non-critical)");
231     }
232
233     void submit_request(const std::string& request) {
234         std::lock_guard<std::mutex> lock(mutex_);
235         request_queue_.push(request);
236         cv_.notify_one();
237     }
238
239     void stop() {
240         std::cout << "  [Main] Requesting REST service stop...\n";
241         thread_.request_stop();
242         // jthread automatically joins
243     }
244
245     bool is_running() const {
246         return thread_.joinable() && !thread_.get_stop_token().stop_requested
247             ();
248     }
249
250     void demonstrate() {
251         std::cout << "\n" << std::string(70, '=') << "\n";
```

```
252     std::cout << "==== SECTION 2: REST Service with stop_token ===\n";
253     std::cout << std::string(70, '=') << "\n\n";
254
255     RESTService rest;
256     rest.start();
257
258     std::cout << "Submitting requests...\n";
259     rest.submit_request("GET /api/users");
260     rest.submit_request("POST /api/data");
261
262     std::this_thread::sleep_for(300ms);
263
264     std::cout << "\nSimulating graceful shutdown...\n";
265     rest.stop();
266
267     std::cout << "\n REST service stopped gracefully\n";
268     std::cout << " Core services (database, cache) would continue running\n";
269 }
270
271 } // namespace rest_service_example
272
273 /**
274 // SECTION 3: Monitoring Service with stop_token
275 /**
276 =====
277
278 namespace monitor_service_example {
279
280 class MonitorService {
281 private:
282     std::jthread thread_;
283     std::atomic<int> health_checks_{0};
284
285 public:
286     void start() {
287         thread_ = std::jthread([this](std::stop_token stoken) {
288             std::cout << " [Monitor] Service started (non-critical)\n";
289
290             // Cleanup callback
291             std::stop_callback cleanup(stoken, [this] {
292                 std::cout << " [Monitor] Performed " << health_checks_.load()
293                             << " health checks\n";
294             });
295
296             while (!stoken.stop_requested()) {
297                 // Perform health check
298                 ++health_checks_;
299                 std::cout << " [Monitor] Health check #" << health_checks_
300                     .load()
301                         << " - System OK\n";
```

```
301         // Interruptible sleep
302         auto wake_time = std::chrono::steady_clock::now() + 1s;
303         while (std::chrono::steady_clock::now() < wake_time) {
304             if (stoken.stop_requested()) {
305                 std::cout << "    [Monitor] Stop requested during sleep\n";
306                 return;
307             }
308             std::this_thread::sleep_for(100ms);
309         }
310     }
311
312     std::cout << "    [Monitor] Service stopped\n";
313 }
314
315 void stop() {
316     thread_.request_stop();
317 }
318
319 int get_health_checks() const {
320     return health_checks_.load();
321 }
322 };
323
324 void demonstrate() {
325     std::cout << "\n" << std::string(70, '=') << "\n";
326     std::cout << "==== SECTION 3: Monitoring Service with stop_token ===\n";
327     std::cout << std::string(70, '=') << "\n\n";
328
329     MonitorService monitor;
330     monitor.start();
331
332     std::cout << "Monitoring running...\n";
333     std::this_thread::sleep_for(2500ms);
334
335     std::cout << "\nStopping monitor service...\n";
336     monitor.stop();
337
338     std::cout << "\n Total health checks: " << monitor.get_health_checks() <<
339     "\n";
340 }
341
342 } // namespace monitor_service_example
343
344 /**
345 =====
346 // SECTION 4: Thread Pool with stop_token
347 // =====
348
349 namespace thread_pool_example {
```

```
349
350 class ThreadPool {
351 private:
352     std::vector<std::jthread> workers_;
353     std::queue<std::function<void()>> tasks_;
354     std::mutex mutex_;
355     std::condition_variable_any cv_;
356
357 public:
358     explicit ThreadPool(size_t num_threads) {
359         for (size_t i = 0; i < num_threads; ++i) {
360             workers_.emplace_back([this, i](std::stop_token stoken) {
361                 std::cout << " [Worker " << i << "] Started\n";
362
363                 while (!stoken.stop_requested()) {
364                     std::function<void()> task;
365
366                     {
367                         std::unique_lock<std::mutex> lock(mutex_);
368
369                         // Wait for task or stop signal
370                         bool stop = cv_.wait(lock, stoken, [this] {
371                             return !tasks_.empty();
372                         });
373
374                         if (stop) {
375                             std::cout << " [Worker " << i << "] Stop
376                             requested\n";
377                             break;
378                         }
379
380                         if (!tasks_.empty()) {
381                             task = std::move(tasks_.front());
382                             tasks_.pop();
383                         }
384
385                         if (task) {
386                             std::cout << " [Worker " << i << "] Executing task\n"
387                             ;
388                             task();
389                         }
390
391                         std::cout << " [Worker " << i << "] Stopped\n";
392                     });
393                 }
394             }
395
396             template<typename F>
397             void enqueue(F&& task) {
398                 {
399                     std::lock_guard<std::mutex> lock(mutex_);
400                     tasks_.emplace(std::forward<F>(task));
401                 }
402             }
403         }
404     }
405 }
```

```
401     }
402     cv_.notify_one();
403 }
404
405 void stop() {
406     std::cout << "[ThreadPool] Requesting stop for all workers...\n";
407     for (auto& worker : workers_) {
408         worker.request_stop();
409     }
410     cv_.notify_all();
411     // jthread automatically joins all threads
412 }
413
414 ~ThreadPool() {
415     stop();
416 }
417 };
418
419 void demonstrate() {
420     std::cout << "\n" << std::string(70, '=') << "\n";
421     std::cout << "==== SECTION 4: Thread Pool with stop_token ====\n";
422     std::cout << std::string(70, '=') << "\n\n";
423
424     ThreadPool pool(3);
425
426     std::cout << "Enqueueing tasks...\n";
427     for (int i = 1; i <= 5; ++i) {
428         pool.enqueue([i] {
429             std::cout << "    Task " << i << " processing...\n";
430             std::this_thread::sleep_for(200ms);
431             std::cout << "    Task " << i << " completed\n";
432         });
433     }
434
435     std::this_thread::sleep_for(1s);
436
437     std::cout << "\nStopping thread pool...\n";
438     pool.stop();
439
440     std::cout << "\n All workers stopped gracefully\n";
441 }
442
443 } // namespace thread_pool_example
444
445 /**
446 // =====
447 // SECTION 5: stop_callback - Cleanup on Stop
448 // =====
449
450 namespace stop_callback_example {
```

```
451 class ServiceWithCleanup {
452 private:
453     std::jthread thread_;
454
455 public:
456     void start() {
457         thread_ = std::jthread([](std::stop_token stoken) {
458             std::cout << "[Service] Started\n";
459
460             // Register multiple callbacks
461             std::stop_callback callback1(stoken, [] {
462                 std::cout << "[Cleanup 1] Closing network connections...\n";
463             });
464
465             std::stop_callback callback2(stoken, [] {
466                 std::cout << "[Cleanup 2] Flushing buffers...\n";
467             });
468
469             std::stop_callback callback3(stoken, [] {
470                 std::cout << "[Cleanup 3] Saving state...\n";
471             });
472
473             // Simulate work
474             int work_count = 0;
475             while (!stoken.stop_requested()) {
476                 ++work_count;
477                 std::cout << "[Service] Working... (" << work_count << ")\n";
478                 ;
479                 std::this_thread::sleep_for(500ms);
480             }
481
482             std::cout << "[Service] Stopped after " << work_count << " iterations\n";
483             // Callbacks execute here (in reverse order of registration)
484         });
485
486     void stop() {
487         thread_.request_stop();
488     }
489 };
490
491 void demonstrate() {
492     std::cout << "\n" << std::string(70, '=') << "\n";
493     std::cout << "==== SECTION 5: stop_callback for Cleanup ===\n";
494     std::cout << std::string(70, '=') << "\n\n";
495
496     ServiceWithCleanup service;
497     service.start();
498
499     std::this_thread::sleep_for(1500ms);
500
501     std::cout << "\nRequesting stop...\n";
502     service.stop();
```

```
503     std::cout << "\n Cleanup callbacks executed automatically\n";
504 }
505
506 } // namespace stop_callback_example
507
508 //
509 =====
510 // SECTION 6: Complete Microservices Example
511 //
512 =====
513
514 namespace microservices_example {
515
516 // Core service (critical - no stop_token, uses exception for abort)
517 class DatabaseService {
518 private:
519     std::thread thread_; // Regular thread, not jthread
520     std::atomic<bool> running_{false};
521
522 public:
523     void start() {
524         running_ = true;
525         thread_ = std::thread([this] {
526             std::cout << " [Database] CORE service started (critical)\n";
527
528             try {
529                 while (running_) {
530                     std::cout << " [Database] Processing transactions...\n";
531                     std::this_thread::sleep_for(500ms);
532
533                     // Simulate critical error (would call abort())
534                     // For demo, we just log it
535                 }
536             }
537             catch (const std::exception& e) {
538                 std::cerr << " [Database] CRITICAL ERROR: " << e.what() << "\n";
539                 std::cerr << " [Database] Would call abort() in real system\n";
540             }
541
542             std::cout << " [Database] Core service stopped\n";
543         });
544     }
545
546     void stop() {
547         running_ = false;
548         if (thread_.joinable()) {
549             thread_.join();
550         }
551     }
552 }
```

```
551 };
552
553 // Non-core service (non-critical - uses stop_token)
554 class MetricsService {
555 private:
556     std::jthread thread_;
557     std::atomic<int> metrics_collected_{0};
558
559 public:
560     void start() {
561         thread_ = std::jthread([this](std::stop_token stoken) {
562             std::cout << " [Metrics] NON-CORE service started (stop_token)\n"
563             ;
564
565             std::stop_callback cleanup(stoken, [this] {
566                 std::cout << " [Metrics] Collected " << metrics_collected_.load()
567                     << " metrics before stop\n";
568             });
569
570             while (!stoken.stop_requested()) {
571                 ++metrics_collected_;
572                 std::cout << " [Metrics] Collecting metric #"
573                     << metrics_collected_.load() << "\n";
574
575                 // Interruptible sleep
576                 auto wake_time = std::chrono::steady_clock::now() + 800ms;
577                 while (std::chrono::steady_clock::now() < wake_time) {
578                     if (stoken.stop_requested()) {
579                         return;
580                     }
581                     std::this_thread::sleep_for(100ms);
582                 }
583             }
584         });
585     }
586
587     void stop() {
588         std::cout << " [Metrics] Requesting graceful stop...\n";
589         thread_.request_stop();
590     }
591
592     void demonstrate() {
593         std::cout << "\n" << std::string(70, '=') << "\n";
594         std::cout << "==== SECTION 6: Complete Microservices Example ===\n";
595         std::cout << std::string(70, '=') << "\n\n";
596
597         DatabaseService database;
598         MetricsService metrics;
599
600         std::cout << "Starting services...\n";
601         database.start();
602         metrics.start();
603     }
604 }
```

```
603     std::this_thread::sleep_for(2s);
605
606     std::cout << "\n";
607     std::cout << "    Stopping NON-CORE service\n";
608     std::cout << "    (Metrics - uses stop_token)\n";
609     std::cout << "\n\n";
610
611     metrics.stop();
612
613     std::cout << "\n Metrics service stopped gracefully\n";
614     std::cout << " Database service (core) still running\n";
615
616     std::this_thread::sleep_for(1s);
617
618     std::cout << "\nStopping all services...\n";
619     database.stop();
620
621     std::cout << "\n All services stopped\n";
622 }
623
624 } // namespace microservices_example
625
626 // =====
627 // SECTION 7: Summary and Best Practices
628 //
629 // =====
630 void show_summary() {
631     std::cout << "\n" << std::string(70, '=') << "\n";
632     std::cout << "==== Summary: stop_token for Non-Core Threads ===\n";
633     std::cout << std::string(70, '=') << "\n\n";
634
635     std::cout << "                                     \n";
636     std::cout << "    THREAD TYPE           STOP MECHANISM\n";
637     std::cout << "                                     \n";
638     std::cout << "    Core (Critical)      abort() on exception\n";
639     std::cout << "                                     \n";
640     std::cout << "                                     std::thread + atomic<bool>\n";
641     std::cout << "                                     \n";
642     std::cout << "                                     Ensures entire process stops\n";
643     std::cout << "                                     \n";
644     std::cout << "    Non-Core               std::jthread + stop_token\n";
645     std::cout << "                                     \n";
646     std::cout << "    (REST, Monitor)       Graceful shutdown\n";
647     std::cout << "                                     \n";
648     std::cout << "                                     Core services continue running\n";
649     std::cout << "                                     \n\n";
```

```

646
647     std::cout << "WHY stop_token FOR NON-CORE THREADS:\n";
648     std::cout << "    Type-safe cancellation signal\n";
649     std::cout << "    Standard C++20 interface\n";
650     std::cout << "    Works with condition_variable_any for immediate
651         interruption\n";
652     std::cout << "    std::jthread automatically joins (RAII)\n";
653     std::cout << "    stop_callback for automatic cleanup\n";
654     std::cout << "    Cannot accidentally set wrong value (unlike bool)\n\n";
655
656     std::cout << "COMPARISON: atomic<bool> vs stop_token\n\n";
657
658     std::cout << "    atomic<bool> approach:\n";
659     std::cout << "        while (!stop_flag.load()) {\n";
660     std::cout << "            cv.wait_for(lock, 100ms, ...); // Needs timeout\n";
661     std::cout << "            // Check flag regularly\n";
662     std::cout << "        }\n";
663     std::cout << "        // Manual join() required\n\n";
664
665     std::cout << "    stop_token approach:\n";
666     std::cout << "        std::jthread thread([](std::stop_token stoken) {\n";
667     std::cout << "            while (!stoken.stop_requested()) {\n";
668     std::cout << "                cv.wait(lock, stoken, ...); // Immediate interrupt
669             !\n";
670     std::cout << "            }\n";
671     std::cout << "        });
672     std::cout << "        thread.request_stop(); // Automatic join on destruction
673             \n\n";
674
675     std::cout << "BEST PRACTICES:\n";
676     std::cout << " 1. Use stop_token for all non-critical threads\n";
677     std::cout << " 2. Use std::jthread (not std::thread) for automatic
678         joining\n";
679     std::cout << " 3. Use condition_variable_any (not condition_variable)\n";
680     std::cout << " 4. Check stop_requested() in loops\n";
681     std::cout << " 5. Use stop_callback for cleanup logic\n";
682     std::cout << " 6. Core services: use abort() for critical failures\n";
683     std::cout << " 7. Non-core services: graceful shutdown with stop_token\n
684             \n";
685
686 }
687
688 /**
689 =====
690 // MAIN FUNCTION
691 /**
692 =====

```

```
691
692 int main() {
693     std::cout << "\n";
694     std::cout << "                                         \n";
695     std::cout << "             std::stop_token for Non-Core Thread Cancellation\n";
696     std::cout << "                                         \n";
697     std::cout << "                                         C++20 Cooperative Cancellation\n";
698     std::cout << "                                         \n";
699
700     // Section 1: Old vs New
701     old_vs_new::demonstrate();
702
703     // Section 2: REST Service
704     rest_service_example::demonstrate();
705
706     // Section 3: Monitoring Service
707     monitor_service_example::demonstrate();
708
709     // Section 4: Thread Pool
710     thread_pool_example::demonstrate();
711
712     // Section 5: stop_callback
713     stop_callback_example::demonstrate();
714
715     // Section 6: Complete Example
716     microservices_example::demonstrate();
717
718     // Section 7: Summary
719     show_summary();
720
721     std::cout << "\n" << std::string(70, '=') << "\n";
722     std::cout << "All demonstrations completed!\n";
723     std::cout << std::string(70, '=') << "\n\n";
724
725     std::cout << "KEY TAKEAWAY:\n";
726     std::cout << "Use std::stop_token with std::jthread for graceful
727         cancellation\n";
728     std::cout << "of non-critical threads (REST, monitoring, metrics).\n";
729     std::cout << "Core threads should still use abort() for critical failures
730         .\n\n";
731
732     return 0;
733 }
```

68 Source Code: StructuredBindings.cpp

File: src/StructuredBindings.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <string>
3 #include <vector>
4 #include <map>
5 #include <tuple>
6 #include <array>
7 #include <set>
8 #include <utility>
9 #include <algorithm>
10
11 // =====
12 // 1. BASIC STRUCTURED BINDINGS WITH PAIR
13 // =====
14 void example_basic_structured_bindings() {
15     std::cout << "\n==== 1. BASIC STRUCTURED BINDINGS WITH PAIR ===" << std::endl;
16
17     std::pair<int, std::string> person{25, "Alice"};
18
19     // Old way (C++11/14)
20     int age_old = person.first;
21     std::string name_old = person.second;
22     std::cout << "Old way: " << name_old << " is " << age_old << " years old"
23         << std::endl;
24
25     // New way with structured bindings (C++17)
26     auto [age, name] = person;
27     std::cout << "Structured binding: " << name << " is " << age << " years
28         old" << std::endl;
29 }
30
31 // =====
32 // 2. STRUCTURED BINDINGS WITH TUPLE
33 // =====
34 void example_tuple_bindings() {
35     std::cout << "\n==== 2. STRUCTURED BINDINGS WITH TUPLE ===" << std::endl;
36
37     std::tuple<int, double, std::string, bool> data{42, 3.14, "Hello", true};
38
39     // Structured binding with tuple
40     auto [num, pi, text, flag] = data;
41
42     std::cout << "Number: " << num << std::endl;
43     std::cout << "Pi: " << pi << std::endl;
44     std::cout << "Text: " << text << std::endl;
45     std::cout << "Flag: " << std::boolalpha << flag << std::endl;
46 }
```

```
47 // 3. STRUCTURED BINDINGS WITH ARRAYS
48 // =====
49 void example_array_bindings() {
50     std::cout << "\n==== 3. STRUCTURED BINDINGS WITH ARRAYS ===" << std::endl;
51
52     // C-array
53     int c_array[3] = {10, 20, 30};
54     auto [a, b, c] = c_array;
55     std::cout << "C-array elements: " << a << ", " << b << ", " << c << std::
56         endl;
57
58     // std::array
59     std::array<std::string, 3> std_array = {"Red", "Green", "Blue"};
60     auto [color1, color2, color3] = std_array;
61     std::cout << "Colors: " << color1 << ", " << color2 << ", " << color3 <<
62         std::endl;
63 }
64
65 // =====
66 // 4. STRUCTURED BINDINGS WITH STRUCTS
67 // =====
68 struct Point {
69     int x;
70     int y;
71     int z;
72 };
73
74 struct Employee {
75     std::string name;
76     int id;
77     double salary;
78 };
79
80 void example_struct_bindings() {
81     std::cout << "\n==== 4. STRUCTURED BINDINGS WITH STRUCTS ===" << std::endl;
82
83     Point p{10, 20, 30};
84     auto [x, y, z] = p;
85     std::cout << "Point coordinates: x=" << x << ", y=" << y << ", z=" << z <<
86         std::endl;
87
88     Employee emp{"John Doe", 12345, 75000.50};
89     auto [emp_name, emp_id, emp_salary] = emp;
90     std::cout << "Employee: " << emp_name << " (ID: " << emp_id
91         << ", Salary: $" << emp_salary << ")" << std::endl;
92 }
93
94 // =====
95 // 5. STRUCTURED BINDINGS WITH MAP ITERATION
96 // =====
97 void example_map_iteration() {
98     std::cout << "\n==== 5. STRUCTURED BINDINGS WITH MAP ITERATION ===" << std
99         ::endl;
100 }
```

```
97     std::map<std::string, int> age_map = {
98         {"Alice", 30},
99         {"Bob", 25},
100        {"Charlie", 35}
101    };
102
103    // Old way
104    std::cout << "Old way:" << std::endl;
105    for (const auto& pair : age_map) {
106        std::cout << " " << pair.first << " is " << pair.second << " years
107        old" << std::endl;
108    }
109
110    // New way with structured bindings
111    std::cout << "With structured bindings:" << std::endl;
112    for (const auto& [name, age] : age_map) {
113        std::cout << " " << name << " is " << age << " years old" << std::
114        endl;
115    }
116
117 // =====
118 // 6. STRUCTURED BINDINGS WITH REFERENCES
119 // =====
120 void example_reference_bindings() {
121     std::cout << "\n== 6. STRUCTURED BINDINGS WITH REFERENCES ==" << std::
122         endl;
123
124     std::pair<int, std::string> data{100, "Original"};
125
126     // Non-reference binding (copy)
127     auto [val1, str1] = data;
128     val1 = 200;
129     str1 = "Modified Copy";
130     std::cout << "Original after copy modification: "
131         << data.first << ", " << data.second << std::endl;
132
133     // Reference binding
134     auto& [val2, str2] = data;
135     val2 = 300;
136     str2 = "Modified Reference";
137     std::cout << "Original after reference modification: "
138         << data.first << ", " << data.second << std::endl;
139
140 // =====
141 // 7. STRUCTURED BINDINGS WITH CONST
142 // =====
143 void example_const_bindings() {
144     std::cout << "\n== 7. STRUCTURED BINDINGS WITH CONST ==" << std::endl;
145
146     const std::pair<int, std::string> data{42, "Constant"};
147
148     // Const structured binding
```

```
148     const auto& [value, text] = data;
149     std::cout << "Const binding: " << value << ", " << text << std::endl;
150
151     // value = 100; // ERROR: cannot modify const
152 }
153
154 // =====
155 // 8. STRUCTURED BINDINGS WITH FUNCTION RETURNS
156 // =====
157 std::tuple<int, double, std::string> get_data() {
158     return {42, 3.14159, "Function Return"};
159 }
160
161 std::pair<bool, std::string> validate_input(int value) {
162     if (value > 0) {
163         return {true, "Valid"};
164     } else {
165         return {false, "Invalid: must be positive"};
166     }
167 }
168
169 void example_function_return_bindings() {
170     std::cout << "\n==== 8. STRUCTURED BINDINGS WITH FUNCTION RETURNS ===" <<
171             std::endl;
172
173     auto [num, pi, message] = get_data();
174     std::cout << "From function: " << num << ", " << pi << ", " << message <<
175             std::endl;
176
177     auto [is_valid, error_msg] = validate_input(10);
178     std::cout << "Validation: " << std::boolalpha << is_valid << " - " <<
179             error_msg << std::endl;
180
181
182 // =====
183 // 9. STRUCTURED BINDINGS WITH NESTED STRUCTURES
184 // =====
185 struct Address {
186     std::string street;
187     std::string city;
188     int zipcode;
189 };
190
191 struct Person {
192     std::string name;
193     int age;
194     Address address;
195 };
196
197 void example_nested_bindings() {
```

```
198     std::cout << "\n==== 9. STRUCTURED BINDINGS WITH NESTED STRUCTURES ===" <<
199         std::endl;
200
200     Person person{"John Smith", 30, {"123 Main St", "Springfield", 12345}};
201
202     auto [name, age, address] = person;
203     auto [street, city, zipcode] = address;
204
205     std::cout << "Person: " << name << ", Age: " << age << std::endl;
206     std::cout << "Address: " << street << ", " << city << " " << zipcode <<
207         std::endl;
208 }
209
210 // =====
211 // 10. STRUCTURED BINDINGS WITH STL ALGORITHMS
212 // =====
213 void example_algorithms_with_bindings() {
214     std::cout << "\n==== 10. STRUCTURED BINDINGS WITH STL ALGORITHMS ===" <<
215         std::endl;
216
217     std::vector<std::pair<std::string, int>> scores = {
218         {"Alice", 95},
219         {"Bob", 87},
220         {"Charlie", 92},
221         {"David", 88}
222     };
223
224     // Find student with highest score
225     auto max_it = std::max_element(scores.begin(), scores.end(),
226         [] (const auto& a, const auto& b) {
227             auto [name1, score1] = a;
228             auto [name2, score2] = b;
229             return score1 < score2;
230         });
231
232     if (max_it != scores.end()) {
233         auto [top_student, top_score] = *max_it;
234         std::cout << "Top student: " << top_student << " with score " <<
235             top_score << std::endl;
236     }
237
238     // Print all with structured bindings
239     std::cout << "All scores:" << std::endl;
240     std::for_each(scores.begin(), scores.end(),
241         [] (const auto& entry) {
242             auto [name, score] = entry;
243             std::cout << " " << name << ":" << score << std::endl;
244         });
245 }
246
247 // =====
248 // 11. STRUCTURED BINDINGS WITH INSERT OPERATIONS
249 // =====
250 void example_insert_bindings() {
```

```
248     std::cout << "\n==== 11. STRUCTURED BINDINGS WITH INSERT OPERATIONS ===" <<
249         std::endl;
250
250     std::map<int, std::string> id_map;
251
252     // Insert returns pair<iterator, bool>
253     auto [it1, inserted1] = id_map.insert({1, "First"});
254     std::cout << "Insert 1: " << (inserted1 ? "Success" : "Failed") << std::endl;
255
256     auto [it2, inserted2] = id_map.insert({1, "Duplicate"});
257     std::cout << "Insert duplicate 1: " << (inserted2 ? "Success" : "Failed")
258         << std::endl;
259
260     auto [it3, inserted3] = id_map.insert({2, "Second"});
261     std::cout << "Insert 2: " << (inserted3 ? "Success" : "Failed") << std::endl;
262
263     std::cout << "Map contents:" << std::endl;
264     for (const auto& [id, value] : id_map) {
265         std::cout << " " << id << ":" << value << std::endl;
266     }
267
268 // =====
269 // 12. STRUCTURED BINDINGS WITH MULTIPLE RETURNS
270 // =====
271 struct Stats {
272     double mean;
273     double median;
274     double stddev;
275 };
276
277 Stats calculate_stats(const std::vector<int>& data) {
278     double sum = 0;
279     for (int val : data) sum += val;
280     double mean = sum / data.size();
281
282     return {mean, static_cast<double>(data[data.size()/2]), 10.5}; // simplified
283 }
284
285 void example_multiple_return_values() {
286     std::cout << "\n==== 12. STRUCTURED BINDINGS WITH MULTIPLE RETURNS ===" <<
287         std::endl;
288
289     std::vector<int> dataset = {10, 20, 30, 40, 50};
290
291     auto [mean, median, stddev] = calculate_stats(dataset);
292
293     std::cout << "Statistics:" << std::endl;
294     std::cout << " Mean: " << mean << std::endl;
295     std::cout << " Median: " << median << std::endl;
296     std::cout << " Std Dev: " << stddev << std::endl;
```

```
296 }
297
298 // =====
299 // MAIN FUNCTION
300 // =====
301 int main() {
302     std::cout << "\n=====\n" << std::
303         endl;
304     std::cout << "      C++17 STRUCTURED BINDINGS EXAMPLES" << std::endl;
305     std::cout << "=====\n" << std::
306         endl;
307     example_basic_structured_bindings();
308     example_tuple_bindings();
309     example_array_bindings();
310     example_struct_bindings();
311     example_map_iteration();
312     example_reference_bindings();
313     example_const_bindings();
314     example_function_return_bindings();
315     example_nested_bindings();
316     example_algorithms_with_bindings();
317     example_insert_bindings();
318     example_multiple_return_values();
319
320     std::cout << "\n=====\n" << std::
321         endl;
322     std::cout << "      ALL EXAMPLES COMPLETED" << std::endl;
323     std::cout << "=====\n" << std::
324         endl;
325
326     return 0;
327 }
```

69 Source Code: SystemInteractionAndParsing.cpp

File: src/SystemInteractionAndParsing.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // SYSTEM INTERACTION, FILESYSTEM, STRING_VIEW, AND REGEX
3 // =====
4 // This example demonstrates modern C++ for system programming:
5 //
6 // TOPICS COVERED:
7 // 1. Executing external commands (popen, system)
8 // 2. std::filesystem for file operations (C++17)
9 // 3. std::string_view for efficient parsing (C++17)
10 // 4. std::regex for pattern matching (C++11)
11 // 5. Parsing Linux tool output (ps, df, lsof, etc.)
12 // 6. Running bash and Python scripts from C++
13 // 7. File streams (ifstream, ofstream, fstream)
14 // 8. String streams (ostringstream, istringstream)
15 // 9. Stream manipulators and formatting
16 // 10. Binary I/O and stream state handling
17 // 11. Error handling with std::error_code
18 // 12. Thread synchronization (mutex, lock_guard, unique_lock)
19 // 13. File locking for concurrent access
20 // 14. Best practices for system integration
21 // 15. Security considerations
22 // 16. Cross-platform considerations
23 // =====
24
25 #include <iostream>
26 #include <iomanip>
27 #include <string>
28 #include <string_view>
29 #include <vector>
30 #include <map>
31 #include <regex>
32 #include <filesystem>
33 #include <fstream>
34 #include <sstream>
35 #include <array>
36 #include <memory>
37 #include <algorithm>
38 #include <cstdio>
39 #include <cstdlib>
40 #include <stdexcept>
41 #include <chrono>
42 #include <ctime>
43 #include <mutex>
44 #include <shared_mutex>
45 #include <thread>
46 #include <condition_variable>
47 #include <atomic>
48
49 namespace fs = std::filesystem;
```

```
50 // =====
51 // SECTION 1: BASIC COMMAND EXECUTION
52 // =====
53
54
55 // Execute command and capture output
56 std::string execute_command(std::string_view command) {
57     std::array<char, 128> buffer;
58     std::string result;
59
60     // popen is safer than system() - doesn't invoke shell if not needed
61     std::unique_ptr<FILE, decltype(&pclose)> pipe(
62         popen(command.data(), "r"), pclose);
63
64     if (!pipe) {
65         throw std::runtime_error("popen() failed!");
66     }
67
68     while (fgets(buffer.data(), buffer.size(), pipe.get()) != nullptr) {
69         result += buffer.data();
70     }
71
72     return result;
73 }
74
75 // Execute command with return code
76 struct CommandResult {
77     std::string output;
78     int return_code;
79     bool success;
80 };
81
82 CommandResult execute_command_with_status(std::string_view command) {
83     CommandResult result;
84
85     std::array<char, 256> buffer;
86     std::string output;
87
88     FILE* pipe = popen(command.data(), "r");
89     if (!pipe) {
90         return {.output = "", .return_code = -1, .success = false};
91     }
92
93     while (fgets(buffer.data(), buffer.size(), pipe) != nullptr) {
94         output += buffer.data();
95     }
96
97     int status = pclose(pipe);
98     result.output = output;
99     result.return_code = WEXITSTATUS(status);
100    result.success = (result.return_code == 0);
101
102    return result;
103 }
```

```
104 void demonstrate_basic_execution() {
105     std::cout << "\n==== 1. BASIC COMMAND EXECUTION ===" << std::endl;
106
107     // Simple command
108     std::cout << "\n1.1 Current directory:" << std::endl;
109     std::string pwd = execute_command("pwd");
110     std::cout << "    " << pwd;
111
112     // Command with pipes
113     std::cout << "1.2 Count files in current directory:" << std::endl;
114     std::string count = execute_command("ls -1 | wc -l");
115     std::cout << "    Files: " << count;
116
117     // With status check
118     std::cout << "1.3 Execute with status check:" << std::endl;
119     auto result = execute_command_with_status("echo 'Hello from shell'");
120     std::cout << "    Output: " << result.output;
121     std::cout << "    Return code: " << result.return_code << std::endl;
122     std::cout << "    Success: " << std::boolalpha << result.success << std::endl;
123
124     std::cout << "\n KEY POINTS:" << std::endl;
125     std::cout << " • Use popen() to capture output" << std::endl;
126     std::cout << " • Check return codes for errors" << std::endl;
127     std::cout << " • pclose() is critical - use RAII" << std::endl;
128
129 }
130
131 // =====
132 // SECTION 2: std::string_view FOR EFFICIENT PARSING
133 // =====
134
135 // Parse process info using string_view (no copies!)
136 struct ProcessInfo {
137     std::string pid;
138     std::string user;
139     std::string cpu;
140     std::string mem;
141     std::string command;
142 };
143
144 std::vector<std::string_view> split_string_view(std::string_view str, char delimiter) {
145     std::vector<std::string_view> tokens;
146     size_t start = 0;
147
148     while (start < str.size()) {
149         // Skip leading delimiters
150         while (start < str.size() && str[start] == delimiter) {
151             ++start;
152         }
153
154         if (start >= str.size()) break;
155     }
156 }
```

```
156     // Find end of token
157     size_t end = str.find(delimiter, start);
158     if (end == std::string_view::npos) {
159         end = str.size();
160     }
161
162     tokens.push_back(str.substr(start, end - start));
163     start = end + 1;
164 }
165
166 return tokens;
167 }
168
169 // Efficient parsing with string_view - no memory allocations for substrings!
170 std::vector<ProcessInfo> parse_ps_output(std::string_view output) {
171     std::vector<ProcessInfo> processes;
172
173     size_t line_start = 0;
174     size_t line_end = output.find('\n');
175
176     // Skip header line
177     if (line_end != std::string_view::npos) {
178         line_start = line_end + 1;
179     }
180
181     while (line_start < output.size()) {
182         line_end = output.find('\n', line_start);
183         if (line_end == std::string_view::npos) {
184             line_end = output.size();
185         }
186
187         std::string_view line = output.substr(line_start, line_end -
188             line_start);
188         if (line.empty()) {
189             line_start = line_end + 1;
190             continue;
191         }
192
193         auto tokens = split_string_view(line, ' ');
194         if (tokens.size() >= 5) {
195             ProcessInfo info;
196             info.pid = std::string(tokens[0]);
197             info.user = std::string(tokens[1]);
198             info.cpu = std::string(tokens[2]);
199             info.mem = std::string(tokens[3]);
200
201             // Command is rest of line - find position of 5th token in
202             // original output
202             size_t token4_pos = line.find(tokens[4]);
203             if (token4_pos != std::string_view::npos) {
204                 size_t cmd_offset = line_start + token4_pos;
205                 info.command = std::string(output.substr(cmd_offset, line_end
206                     - cmd_offset));
206             }
207 }
```

```

207         processes.push_back(info);
208     }
209
210     line_start = line_end + 1;
211 }
212
213
214     return processes;
215 }
216
217 void demonstrate_string_view_parsing() {
218     std::cout << "\n== 2. std::string_view PARSING ==" << std::endl;
219
220     // Get process list
221     std::string ps_output = execute_command("ps aux | head -20");
222
223     std::cout << "\n2.1 Parsing ps output with string_view (zero-copy):" <<
224         std::endl;
225     auto processes = parse_ps_output(ps_output);
226
227     std::cout << "    Found " << processes.size() << " processes" << std::endl;
228     std::cout << "\n    Top 5 by CPU:" << std::endl;
229
230     // Sort by CPU
231     std::sort(processes.begin(), processes.end(),
232               [] (const ProcessInfo& a, const ProcessInfo& b) {
233                   return std::stod(a.cpu) > std::stod(b.cpu);
234               });
235
236     for (size_t i = 0; i < std::min(size_t(5), processes.size()); i++) {
237         std::cout << "    " << processes[i].pid << " "
238             << processes[i].cpu << "% CPU "
239             << processes[i].command.substr(0, 50) << std::endl;
240     }
241
242     std::cout << "\n string_view benefits:" << std::endl;
243     std::cout << " • No memory allocations during parsing" << std::endl;
244     std::cout << " • Fast substring operations" << std::endl;
245     std::cout << " • Perfect for tokenizing large outputs" << std::endl;
246 }
247 // =====
248 // SECTION 3: std::regex FOR PATTERN MATCHING
249 // =====
250
251 // Parse network interface info with regex
252 struct NetworkInterface {
253     std::string name;
254     std::string ip_address;
255     std::string netmask;
256     std::string status;
257 };
258
259 std::vector<NetworkInterface> parse_ifconfig_with_regex(std::string_view

```

```
    output) {
260     std::vector<NetworkInterface> interfaces;
261
262     // Regex patterns
263     std::regex iface_pattern(R"((\w+):\s+flags=.+)");
264     std::regex inet_pattern(R"(inet\s+(\d+\.\d+\.\d+\.\d+)\s+netmask\s+(\S+))");
265     std::regex status_pattern(R"(status:\s+(\w+))");
266
267     std::string output_str(output);
268     std::istringstream iss(output_str);
269     std::string line;
270
271     NetworkInterface current_iface;
272     bool has_current = false;
273
274     while (std::getline(iss, line)) {
275         std::smatch match;
276
277         // Check for interface name
278         if (std::regex_search(line, match, iface_pattern)) {
279             // Save previous interface
280             if (has_current && !current_iface.ip_address.empty()) {
281                 interfaces.push_back(current_iface);
282             }
283
284             // Start new interface
285             current_iface = NetworkInterface{};
286             current_iface.name = match[1].str();
287             has_current = true;
288         }
289         // Check for IP address
290         else if (has_current && std::regex_search(line, match, inet_pattern))
291             {
292                 current_iface.ip_address = match[1].str();
293                 current_iface.netmask = match[2].str();
294             }
295         // Check for status
296         else if (has_current && std::regex_search(line, match, status_pattern))
297             {
298                 current_iface.status = match[1].str();
299             }
300
301         // Don't forget last interface
302         if (has_current && !current_iface.ip_address.empty()) {
303             interfaces.push_back(current_iface);
304         }
305
306         return interfaces;
307     }
308
309 // Parse log files with regex
310 struct LogEntry {
```

```
310     std::string timestamp;
311     std::string level;
312     std::string message;
313 };
314
315 std::vector<LogEntry> parse_log_with_regex(std::string_view log_content) {
316     std::vector<LogEntry> entries;
317
318     // Match: [2024-01-15 10:30:45] ERROR: Something went wrong
319     std::regex log_pattern(R"(\[\d{4}-\d{2}-\d{2}\s+\d{2}:\d{2}:\d{2})\]\s+(\w+):\s+(.+))");
320
321     std::string log_str(log_content);
322     std::istringstream iss(log_str);
323     std::string line;
324
325     while (std::getline(iss, line)) {
326         std::smatch match;
327         if (std::regex_search(line, match, log_pattern)) {
328             entries.push_back({
329                 .timestamp = match[1].str(),
330                 .level = match[2].str(),
331                 .message = match[3].str()
332             });
333         }
334     }
335
336     return entries;
337 }
338
339 void demonstrate_regex_parsing() {
340     std::cout << "\n==== 3. std::regex PATTERN MATCHING ===" << std::endl;
341
342     // Network interface parsing
343     std::cout << "\n3.1 Parsing network interfaces with regex:" << std::endl;
344     std::string ifconfig_output = execute_command("ifconfig 2>/dev/null || ip
345         addr 2>/dev/null || echo 'No network tools available'");
346
347     auto interfaces = parse_ifconfig_with_regex(ifconfig_output);
348     for (const auto& iface : interfaces) {
349         std::cout << "    Interface: " << iface.name << std::endl;
350         std::cout << "        IP: " << iface.ip_address << std::endl;
351         std::cout << "        Netmask: " << iface.netmask << std::endl;
352         if (!iface.status.empty()) {
353             std::cout << "        Status: " << iface.status << std::endl;
354         }
355     }
356
357     // Create sample log for parsing
358     std::cout << "\n3.2 Parsing log files with regex:" << std::endl;
359     std::string sample_log =
360         "[2024-01-15 10:30:45] INFO: Application started\n"
361         "[2024-01-15 10:30:46] DEBUG: Loading configuration\n"
362         "[2024-01-15 10:30:47] ERROR: Database connection failed\n"
```

```
362     " [2024-01-15 10:30:48] WARN: Retrying connection\n"
363     " [2024-01-15 10:30:50] INFO: Connection established\n";
364
365     auto log_entries = parse_log_with_regex(sample_log);
366
367     std::cout << "    Found " << log_entries.size() << " log entries:" << std::endl;
368     for (const auto& entry : log_entries) {
369         std::cout << "      [" << entry.timestamp << "] "
370                 << entry.level << ":" << entry.message << std::endl;
371     }
372
373     // Filter errors
374     std::cout << "\n      Errors only:" << std::endl;
375     for (const auto& entry : log_entries) {
376         if (entry.level == "ERROR") {
377             std::cout << "          " << entry.message << std::endl;
378         }
379     }
380
381     std::cout << "\n      regex use cases:" << std::endl;
382     std::cout << " • Structured text parsing (logs, config)" << std::endl;
383     std::cout << " • Validation (emails, IPs, dates)" << std::endl;
384     std::cout << " • Extraction from unstructured output" << std::endl;
385 }
386
387 // =====
388 // SECTION 4: std::filesystem OPERATIONS
389 // =====
390
391 void demonstrate_filesystem() {
392     std::cout << "\n==== 4. std::filesystem OPERATIONS ===" << std::endl;
393
394     std::error_code ec;
395
396     // Current path
397     std::cout << "\n4.1 Current path:" << std::endl;
398     fs::path current = fs::current_path(ec);
399     std::cout << "      " << current << std::endl;
400
401     // Create temporary test directory
402     fs::path test_dir = fs::temp_directory_path(ec) / "cpp_test_dir";
403     std::cout << "\n4.2 Creating test directory:" << std::endl;
404     std::cout << "      " << test_dir << std::endl;
405
406     if (fs::create_directories(test_dir, ec)) {
407         std::cout << "          Created" << std::endl;
408     } else {
409         std::cout << "          Already exists or error: " << ec.message() << std::endl;
410     }
411
412     // Create test files
413     std::cout << "\n4.3 Creating test files:" << std::endl;
```

```
414     for (int i = 0; i < 3; i++) {
415         fs::path file = test_dir / ("test_file_" + std::to_string(i) + ".txt")
416         ;
417         std::ofstream ofs(file);
418         ofs << "Test content " << i << "\n";
419         ofs << "Line 2 of file " << i << "\n";
420         std::cout << "    Created: " << file.filename() << std::endl;
421     }
422
423     // Iterate directory
424     std::cout << "\n4.4 Directory contents:" << std::endl;
425     for (const auto& entry : fs::directory_iterator(test_dir, ec)) {
426         std::cout << "    " << entry.path().filename()
427             << " (" << fs::file_size(entry, ec) << " bytes)" << std::
428                 endl;
429     }
430
431     // File info
432     std::cout << "\n4.5 File properties:" << std::endl;
433     auto first_file = test_dir / "test_file_0.txt";
434     if (fs::exists(first_file, ec)) {
435         std::cout << "    Size: " << fs::file_size(first_file, ec) << " bytes"
436             << std::endl;
437         std::cout << "    Is regular file: " << fs::is_regular_file(first_file,
438             ec) << std::endl;
439         std::cout << "    Is directory: " << fs::is_directory(first_file, ec)
440             << std::endl;
441
442         auto ftime = fs::last_write_time(first_file, ec);
443         std::cout << "    Last modified: " << std::chrono::system_clock::
444             to_time_t(
445                 std::chrono::file_clock::to_sys(ftime)) << " (unix timestamp)" <<
446                 std::endl;
447     }
448
449     // Path operations
450     std::cout << "\n4.6 Path operations:" << std::endl;
451     fs::path example = "/home/user/documents/file.txt";
452     std::cout << "    Full path: " << example << std::endl;
453     std::cout << "    Filename: " << example.filename() << std::endl;
454     std::cout << "    Stem: " << example.stem() << std::endl;
455     std::cout << "    Extension: " << example.extension() << std::endl;
456     std::cout << "    Parent: " << example.parent_path() << std::endl;
457
458     // Cleanup
459     std::cout << "\n4.7 Cleanup:" << std::endl;
460     std::uintmax_t removed = fs::remove_all(test_dir, ec);
461     std::cout << "    Removed " << removed << " files/directories" << std::endl
462         ;
463
464     std::cout << "\n    filesystem features:" << std::endl;
465     std::cout << "    • Cross-platform path handling" << std::endl;
466     std::cout << "    • Iterator for directory traversal" << std::endl;
467     std::cout << "    • Error codes for exception-free errors" << std::endl;
```

```
460 }
461
462 // =====
463 // SECTION 5: RUNNING BASH SCRIPTS
464 // =====
465
466 void create_test_bash_script(const fs::path& script_path) {
467     std::ofstream script(script_path);
468     script << "#!/bin/bash\n";
469     script << "# Test bash script called from C++\n\n";
470     script << "echo \"Script started with $# arguments\"\n";
471     script << "echo \"Arguments: $@\n\n";
472     script << "# Process arguments\n";
473     script << "for arg in \"$@\"; do\n";
474     script << "    echo \" - Processing: $arg\"\n";
475     script << "done\n\n";
476     script << "# Return some data\n";
477     script << "echo \"Hostname: $(hostname)\"\n";
478     script << "echo \"User: $(whoami)\"\n";
479     script << "echo \"Date: $(date +%Y-%m-%d)\"\n";
480     script << "\n";
481     script << "exit 0\n";
482
483     fs::permissions(script_path,
484                     fs::perms::owner_all | fs::perms::group_read | fs::perms::
485                     others_read,
486                     fs::perm_options::add);
487 }
488
489 void demonstrate_bash_scripts() {
490     std::cout << "\n== 5. RUNNING BASH SCRIPTS ==" << std::endl;
491
492     std::error_code ec;
493     fs::path temp_dir = fs::temp_directory_path(ec);
494     fs::path script_path = temp_dir / "test_script.sh";
495
496     std::cout << "\n5.1 Creating bash script:" << std::endl;
497     std::cout << "    " << script_path << std::endl;
498
499     create_test_bash_script(script_path);
500
501     // Execute script with arguments
502     std::cout << "\n5.2 Executing script with arguments:" << std::endl;
503     std::string command = "bash " + script_path.string() + " arg1 arg2 arg3";
504     std::string output = execute_command(command);
505     std::cout << output;
506
507     // Parse script output with string_view
508     std::cout << "\n5.3 Parsing script output:" << std::endl;
509     std::regex hostname_pattern(R"(Hostname:\s+(\S+))");
510     std::regex user_pattern(R"(User:\s+(\S+))");
511     std::regex date_pattern(R"(Date:\s+(\S+))");
512
513     std::smatch match;
```

```
513     std::string output_str(output);
514
515     if (std::regex_search(output_str, match, hostname_pattern)) {
516         std::cout << "    Hostname: " << match[1].str() << std::endl;
517     }
518     if (std::regex_search(output_str, match, user_pattern)) {
519         std::cout << "    User: " << match[1].str() << std::endl;
520     }
521     if (std::regex_search(output_str, match, date_pattern)) {
522         std::cout << "    Date: " << match[1].str() << std::endl;
523     }
524
525     // Cleanup
526     fs::remove(script_path, ec);
527
528     std::cout << "\n Script execution:" << std::endl;
529     std::cout << " • Use bash explicitly for portability" << std::endl;
530     std::cout << " • Pass arguments safely (avoid injection)" << std::endl;
531     std::cout << " • Parse structured output with regex" << std::endl;
532 }
533
534 // =====
535 // SECTION 6: RUNNING PYTHON SCRIPTS
536 // =====
537
538 void create_test_python_script(const fs::path& script_path) {
539     std::ofstream script(script_path);
540     script << "#!/usr/bin/env python3\n";
541     script << "import sys\n";
542     script << "import json\n";
543     script << "import platform\n\n";
544     script << "def main():\n";
545     script << "    # Get system info\n";
546     script << "    info = {\n";
547     script << "        'python_version': sys.version.split()[0],\n";
548     script << "        'platform': platform.system(),\n";
549     script << "        'architecture': platform.machine(),\n";
550     script << "        'arguments': sys.argv[1:]\n";
551     script << "    }\n";
552     script << "    \n";
553     script << "    # Output as JSON for easy parsing\n";
554     script << "    print(json.dumps(info, indent=2))\n\n";
555     script << "if __name__ == '__main__':\n";
556     script << "    main()\n";
557
558     fs::permissions(script_path,
559                     fs::perms::owner_all | fs::perms::group_read | fs::perms::
560                     others_read,
561                     fs::perm_options::add);
562 }
563
564 void demonstrate_python_scripts() {
565     std::cout << "\n==== 6. RUNNING PYTHON SCRIPTS ===" << std::endl;
566 }
```

```

566     std::error_code ec;
567     fs::path temp_dir = fs::temp_directory_path(ec);
568     fs::path script_path = temp_dir / "test_script.py";
569
570     std::cout << "\n6.1 Creating Python script:" << std::endl;
571     std::cout << "    " << script_path << std::endl;
572
573     create_test_python_script(script_path);
574
575     // Execute Python script
576     std::cout << "\n6.2 Executing Python script:" << std::endl;
577     std::string command = "python3 " + script_path.string() + " data1 data2";
578     auto result = execute_command_with_status(command);
579
580     if (result.success) {
581         std::cout << "    Script executed successfully" << std::endl;
582         std::cout << "\n6.3 JSON Output:\n" << result.output << std::endl;
583
584         // Parse JSON output with regex (simple approach)
585         std::cout << "6.4 Extracting data:" << std::endl;
586         std::regex version_pattern("\"python_version\"\\s*:\\s*\"([^\"]+)\"");
587         std::regex platform_pattern("\"platform\"\\s*:\\s*\"([^\"]+)\"");
588         std::regex arch_pattern("\"architecture\"\\s*:\\s*\"([^\"]+)\"");
589
590         std::smatch match;
591         if (std::regex_search(result.output, match, version_pattern)) {
592             std::cout << "    Python version: " << match[1].str() << std::endl;
593         }
594         if (std::regex_search(result.output, match, platform_pattern)) {
595             std::cout << "    Platform: " << match[1].str() << std::endl;
596         }
597         if (std::regex_search(result.output, match, arch_pattern)) {
598             std::cout << "    Architecture: " << match[1].str() << std::endl;
599         }
600     } else {
601         std::cout << "    Script failed with code: " << result.return_code <<
602             std::endl;
603     }
604
605     // Cleanup
606     fs::remove(script_path, ec);
607
608     std::cout << "\n Python integration:" << std::endl;
609     std::cout << " • Use JSON for structured data exchange" << std::endl;
610     std::cout << " • Check return codes" << std::endl;
611     std::cout << " • Python for quick prototyping/data processing" << std::endl;
612
613 // =====
614 // SECTION 7: PARSING LINUX TOOL OUTPUT
615 // =====
616
617 struct DiskInfo {

```

```
618     std::string filesystem;
619     std::string size;
620     std::string used;
621     std::string available;
622     std::string use_percent;
623     std::string mounted_on;
624 };
625
626 std::vector<DiskInfo> parse_df_output(std::string_view output) {
627     std::vector<DiskInfo> disks;
628
629     size_t line_start = 0;
630     size_t line_end = output.find('\n');
631
632     // Skip header
633     if (line_end != std::string_view::npos) {
634         line_start = line_end + 1;
635     }
636
637     while (line_start < output.size()) {
638         line_end = output.find('\n', line_start);
639         if (line_end == std::string_view::npos) {
640             line_end = output.size();
641         }
642
643         std::string_view line = output.substr(line_start, line_end -
644                                         line_start);
644         if (line.empty()) {
645             line_start = line_end + 1;
646             continue;
647         }
648
649         auto tokens = split_string_view(line, ' ');
650         if (tokens.size() >= 6) {
651             DiskInfo info;
652             info.filesystem = std::string(tokens[0]);
653             info.size = std::string(tokens[1]);
654             info.used = std::string(tokens[2]);
655             info.available = std::string(tokens[3]);
656             info.use_percent = std::string(tokens[4]);
657             info.mounted_on = std::string(tokens[5]);
658             disks.push_back(info);
659         }
660
661         line_start = line_end + 1;
662     }
663
664     return disks;
665 }
666
667 void demonstrate_linux_tools() {
668     std::cout << "\n==== 7. PARSING LINUX TOOL OUTPUT ===" << std::endl;
669
670     // df command
```

```
671     std::cout << "\n7.1 Disk usage (df -h):" << std::endl;
672     std::string df_output = execute_command("df -h 2>/dev/null | head -10");
673     auto disks = parse_df_output(df_output);
674
675     for (const auto& disk : disks) {
676         if (disk.filesystem.find("/dev/") == 0) { // Real devices only
677             std::cout << "    " << disk.mounted_on
678             << ":" << disk.used << "/" << disk.size
679             << " (" << disk.use_percent << ")" << std::endl;
680         }
681     }
682
683     // Memory info
684     std::cout << "\n7.2 Memory usage:" << std::endl;
685     std::string mem_output = execute_command("free -h | grep Mem");
686     std::regex mem_pattern(R"(Mem:\s+(\S+)\s+(\S+)\s+(\S+))");
687     std::smatch match;
688     if (std::regex_search(mem_output, match, mem_pattern)) {
689         std::cout << "    Total: " << match[1].str() << std::endl;
690         std::cout << "    Used: " << match[2].str() << std::endl;
691         std::cout << "    Free: " << match[3].str() << std::endl;
692     }
693
694     // CPU info
695     std::cout << "\n7.3 CPU information:" << std::endl;
696     std::string cpu_output = execute_command("lscpu 2>/dev/null | grep -E 'Model name|CPU\\(s\\\\)|Thread'");
697
698     std::istringstream iss(cpu_output);
699     std::string line;
700     while (std::getline(iss, line)) {
701         if (!line.empty()) {
702             std::cout << "    " << line << std::endl;
703         }
704     }
705
706     std::cout << "\n Linux tools:" << std::endl;
707     std::cout << " • Rich ecosystem of system tools" << std::endl;
708     std::cout << " • Standardized output formats" << std::endl;
709     std::cout << " • Combine with grep/awk for filtering" << std::endl;
710 }
711
712 // =====
713 // SECTION 8: FILE STREAMS - ifstream, ofstream, fstream
714 // =====
715
716 void demonstrate_file_streams() {
717     std::cout << "\n== 8. FILE STREAMS (ifstream, ofstream, fstream) ==" <<
718         std::endl;
719
720     std::error_code ec;
721     fs::path temp_dir = fs::temp_directory_path(ec);
722     fs::path test_file = temp_dir / "stream_test.txt";
```

```
723 // 8.1 Writing with ofstream
724 std::cout << "\n8.1 Writing with ofstream:" << std::endl;
725 {
726     std::ofstream ofs(test_file);
727     if (!ofs) {
728         std::cout << "      Failed to open file for writing" << std::endl;
729         return;
730     }
731
732     ofs << "Line 1: Hello, World!\n";
733     ofs << "Line 2: Modern C++ Streams\n";
734     ofs << "Line 3: Numbers: " << 42 << ", " << 3.14159 << "\n";
735     ofs << "Line 4: Boolean: " << std::boolalpha << true << "\n";
736
737     std::cout << "      Wrote 4 lines to " << test_file.filename() << std::endl;
738 } // File automatically closed when ofs goes out of scope
739
740 // 8.2 Reading with ifstream
741 std::cout << "\n8.2 Reading with ifstream (line by line):" << std::endl;
742 {
743     std::ifstream ifs(test_file);
744     if (!ifs) {
745         std::cout << "      Failed to open file for reading" << std::endl;
746         return;
747     }
748
749     std::string line;
750     int line_num = 1;
751     while (std::getline(ifs, line)) {
752         std::cout << "[" << line_num++ << "] " << line << std::endl;
753     }
754 }
755
756 // 8.3 Reading entire file
757 std::cout << "\n8.3 Reading entire file at once:" << std::endl;
758 {
759     std::ifstream ifs(test_file);
760     std::string content((std::istreambuf_iterator<char>(ifs)),
761                         std::istreambuf_iterator<char>());
762     std::cout << "      File size: " << content.size() << " bytes" << std::endl;
763     std::cout << "      First 50 chars: " << content.substr(0, 50) << "..." << std::endl;
764 }
765
766 // 8.4 Appending to file
767 std::cout << "\n8.4 Appending with std::ios::app:" << std::endl;
768 {
769     std::ofstream ofs(test_file, std::ios::app); // Append mode
770     ofs << "Line 5: Appended line\n";
771     std::cout << "      Appended one line" << std::endl;
772 }
773
```

```
774 // 8.5 Random access with fstream
775 std::cout << "\n8.5 Random access with fstream:" << std::endl;
776 {
777     std::fstream fs(test_file, std::ios::in | std::ios::out);
778
779     // Seek to position
780     fs.seekg(0, std::ios::end);
781     std::streampos file_size = fs.tellg();
782     std::cout << "    File size: " << file_size << " bytes" << std::endl;
783
784     // Go back to start
785     fs.seekg(0, std::ios::beg);
786
787     // Read first line
788     std::string first_line;
789     std::getline(fs, first_line);
790     std::cout << "    First line: " << first_line << std::endl;
791
792     // Current position
793     std::cout << "    Current position: " << fs.tellg() << std::endl;
794 }
795
796 // 8.6 Stream state checking
797 std::cout << "\n8.6 Stream state checking:" << std::endl;
798 {
799     std::ifstream ifs(test_file);
800
801     std::cout << "    Initial state:" << std::endl;
802     std::cout << "        good(): " << ifs.good() << std::endl;
803     std::cout << "        eof(): " << ifs.eof() << std::endl;
804     std::cout << "        fail(): " << ifs.fail() << std::endl;
805     std::cout << "        bad(): " << ifs.bad() << std::endl;
806
807     // Read until EOF
808     std::string line;
809     while (std::getline(ifs, line)) {
810         // Reading...
811     }
812
813     std::cout << "    After reading to EOF:" << std::endl;
814     std::cout << "        eof(): " << ifs.eof() << std::endl;
815     std::cout << "        good(): " << ifs.good() << std::endl;
816
817     // Clear error state
818     ifs.clear();
819     std::cout << "    After clear():" << std::endl;
820     std::cout << "        good(): " << ifs.good() << std::endl;
821 }
822
823 // Cleanup
824 fs::remove(test_file, ec);
825
826 std::cout << "\n File stream tips:" << std::endl;
827 std::cout << " • RAI - files auto-close when stream destroyed" << std::endl;
```

```
        endl;
828     std::cout << " • Check state with good(), fail(), bad(), eof()" << std::endl;
829     std::cout << " • Use seekg()/tellg() for reading position" << std::endl;
830     std::cout << " • Use seekp()/tellp() for writing position" << std::endl;
831 }
832
833 // =====
834 // SECTION 9: STRING STREAMS - ostringstream, istringstream
835 // =====
836
837 struct LogRecord {
838     std::string timestamp;
839     std::string level;
840     int thread_id;
841     std::string message;
842 };
843
844 void demonstrate_string_streams() {
845     std::cout << "\n== 9. STRING STREAMS (ostringstream, istringstream) =="
846             << std::endl;
847
848     // 9.1 ostringstream - building strings
849     std::cout << "\n9.1 Building strings with ostringstream:" << std::endl;
850     {
851         std::ostringstream oss;
852         oss << "System report:\n";
853         oss << " CPU cores: " << 8 << "\n";
854         oss << " Memory: " << 16.5 << " GB\n";
855         oss << " Load: " << std::fixed << std::setprecision(2) << 0.6789 << "
856             \n";
857
858         std::string report = oss.str();
859         std::cout << report;
860     }
861
862     // 9.2 istringstream - parsing strings
863     std::cout << "\n9.2 Parsing with istringstream:" << std::endl;
864     {
865         std::string data = "2024-01-15 ERROR 12345 Database connection failed"
866             ;
867         std::istringstream iss(data);
868
869         LogRecord record;
870         iss >> record.timestamp >> record.level >> record.thread_id;
871         std::getline(iss, record.message); // Rest is message
872
873         // Trim leading space from message
874         if (!record.message.empty() && record.message[0] == ' ')
875             record.message = record.message.substr(1);
876
877         std::cout << " Parsed log record:" << std::endl;
878         std::cout << " Timestamp: " << record.timestamp << std::endl;
```

```
877     std::cout << "      Level: " << record.level << std::endl;
878     std::cout << "      Thread: " << record.thread_id << std::endl;
879     std::cout << "      Message: " << record.message << std::endl;
880 }
881
882 // 9.3 Parsing CSV
883 std::cout << "\n9.3 Parsing CSV with istringstream:" << std::endl;
884 {
885     std::string csv = "John,Doe,30,Engineer\nJane,Smith,28,Designer\nBob,
886     Johnson,35,Manager";
887     std::istringstream iss(csv);
888     std::string line;
889
890     while (std::getline(iss, line)) {
891         std::istringstream line_stream(line);
892         std::string first, last, age, role;
893
894         std::getline(line_stream, first, ',');
895         std::getline(line_stream, last, ',');
896         std::getline(line_stream, age, ',');
897         std::getline(line_stream, role, ',');
898
899         std::cout << "    " << first << " " << last
900             << " (" << age << ") - " << role << std::endl;
901     }
902 }
903
904 // 9.4 Number conversion with stringstream
905 std::cout << "\n9.4 Type conversions:" << std::endl;
906 {
907     // String to number
908     std::string num_str = "42.5";
909     std::istringstream iss(num_str);
910     double value;
911     iss >> value;
912     std::cout << "    String \"<< num_str << "\" -> double: " << value <<
913         std::endl;
914
915     // Number to string (alternative to std::to_string with formatting)
916     std::ostringstream oss;
917     oss << std::fixed << std::setprecision(3) << 3.14159265;
918     std::cout << "    double 3.14159265 -> string: \"<< oss.str() << \"\""
919         << std::endl;
920
921     // Hex conversion
922     oss.str(""); // Clear
923     oss.clear(); // Clear state
924     oss << "0x" << std::hex << 255;
925     std::cout << "    int 255 -> hex string: \"<< oss.str() << \"\" <<
926         std::endl;
927 }
928
929 // 9.5 Building complex formatted strings
930 std::cout << "\n9.5 Complex string formatting:" << std::endl;
```

```
927 {
928     std::ostringstream oss;
929
930     auto now = std::chrono::system_clock::now();
931     auto now_time_t = std::chrono::system_clock::to_time_t(now);
932
933     oss << "
934             SYSTEM STATUS REPORT
935             "
936     oss << " Time: " << std::put_time(std::localtime(&now_time_t), "%Y-%m-%d %H:%M:%S") << "
937             "
938     oss << " Status: " << std::left << std::setw(22) << "Running" << "
939             "
940     oss << " Uptime: " << std::right << std::setw(10) << "99.9%" << "
941             "
942     oss << "
943             "
944     std::cout << "\n String stream benefits:" << std::endl;
945     std::cout << " • Type-safe string building" << std::endl;
946     std::cout << " • Parsing with >> operator" << std::endl;
947     std::cout << " • Full stream manipulator support" << std::endl;
948     std::cout << " • Reusable: clear() + str(\"\\\") to reset" << std::endl;
949 }
950
951 // =====
952 // SECTION 10: STREAM MANIPULATORS AND FORMATTING
953 // =====
954
955 void demonstrate_stream_manipulators() {
956     std::cout << "\n== 10. STREAM MANIPULATORS ==" << std::endl;
957
958     // 10.1 Numeric formatting
959     std::cout << "\n10.1 Numeric formatting:" << std::endl;
960     {
961         double pi = 3.14159265358979;
962         int num = 255;
963
964         std::cout << " Default: " << pi << std::endl;
965         std::cout << " Fixed (6 decimals): " << std::fixed << pi << std::
966             endl;
967         std::cout << " Scientific: " << std::scientific << pi << std::endl;
968         std::cout << std::defaultfloat; // Reset to default
969
970         std::cout << " Precision 3: " << std::setprecision(3) << pi << std::
971             endl;
972         std::cout << " Precision 10: " << std::setprecision(10) << pi << std
973             ::endl;
974
975         std::cout << " Decimal: " << std::dec << num << std::endl;
976         std::cout << " Hex: 0x" << std::hex << num << std::endl;
977         std::cout << " Octal: 0" << std::oct << num << std::endl;
```

```
975     std::cout << std::dec; // Reset to decimal
976 }
977
978 // 10.2 Width and alignment
979 std::cout << "\n10.2 Width and alignment:" << std::endl;
980 {
981     std::cout << "    |" << std::setw(15) << "Right" << "|" << std::endl;
982     std::cout << "    |" << std::left << std::setw(15) << "Left" << "|" <<
983         std::endl;
984     std::cout << "    |" << std::internal << std::setw(15) << -123 << "|" <<
985         std::endl;
986     std::cout << std::right; // Reset
987 }
988
989 // 10.3 Fill character
990 std::cout << "\n10.3 Fill character:" << std::endl;
991 {
992     std::cout << "    " << std::setfill('*') << std::setw(20) << "Title" <<
993         std::setfill(' ') << std::endl;
994     std::cout << "    " << std::setfill('0') << std::setw(8) << 42 << std::
995         setfill(' ') << std::endl;
996     std::cout << "    " << std::setfill('-') << std::setw(30) << "" << std::
997         setfill(' ') << std::endl;
998 }
999
1000 // 10.4 Boolean formatting
1001 std::cout << "\n10.4 Boolean formatting:" << std::endl;
1002 {
1003     bool flag = true;
1004     std::cout << "    Default: " << flag << std::endl;
1005     std::cout << "    Boolalpha: " << std::boolalpha << flag << std::endl;
1006     std::cout << std::noboolalpha; // Reset
1007 }
1008
1009 // 10.5 Sign formatting
1010 std::cout << "\n10.5 Sign formatting:" << std::endl;
1011 {
1012     int pos = 42, neg = -42;
1013     std::cout << "    Default: " << pos << ", " << neg << std::endl;
1014     std::cout << "    Showpos: " << std::showpos << pos << ", " << neg <<
1015         std::endl;
1016     std::cout << std::noshowpos; // Reset
1017 }
1018
1019 // 10.6 Table formatting example
1020 std::cout << "\n10.6 Table formatting:" << std::endl;
1021 {
1022     struct Product {
1023         std::string name;
1024         double price;
1025         int quantity;
1026     };
1027
1028     std::vector<Product> products = {
```

```
1023     {"Widget", 29.99, 15},
1024     {"Gadget", 149.50, 8},
1025     {"Doohickey", 9.95, 42}
1026 };
1027
1028     std::cout << "           " << std::endl;
1029     std::cout << "     " << std::left << std::setw(15) << "Product"
1030             << "     " << std::right << std::setw(8) << "Price"
1031             << "     " << std::setw(8) << "Qty" << "     " << std::endl;
1032     std::cout << "           " << std::endl;
1033
1034     for (const auto& p : products) {
1035         std::cout << "     " << std::left << std::setw(15) << p.name
1036             << "     $" << std::right << std::setw(7) << std::fixed
1037             << std::setprecision(2) << p.price
1038             << "     " << std::setw(8) << p.quantity << "     " << std::endl;
1039     }
1040
1041     std::cout << "           " << std::endl;
1042 }
1043
1044 std::cout << "\n Manipulator categories:" << std::endl;
1045 std::cout << " • Numeric: fixed, scientific, precision, hex, oct, dec"
1046             << std::endl;
1047 std::cout << " • Alignment: setw, left, right, internal, setfill" << std::endl;
1048 std::cout << " • Boolean: boolalpha, noboolalpha" << std::endl;
1049 std::cout << " • Sign: showpos, noshowpos, showbase" << std::endl;
1050 }
1051 // =====
1052 // SECTION 11: BINARY I/O
1053 // =====
1054
1055 struct BinaryRecord {
1056     int id;
1057     double value;
1058     char name[32];
1059 };
1060
1061 void demonstrate_binary_io() {
1062     std::cout << "\n== 11. BINARY I/O ==" << std::endl;
1063
1064     std::error_code ec;
1065     fs::path temp_dir = fs::temp_directory_path(ec);
1066     fs::path binary_file = temp_dir / "binary_data.bin";
1067
1068     // 11.1 Writing binary data
1069     std::cout << "\n11.1 Writing binary data:" << std::endl;
1070     {
1071         std::ofstream ofs(binary_file, std::ios::binary);
1072
1073         BinaryRecord records[] = {
```

```
1074     {1, 3.14159, "Record One"},  
1075     {2, 2.71828, "Record Two"},  
1076     {3, 1.41421, "Record Three"}  
1077 };  
1078  
1079     for (const auto& record : records) {  
1080         ofs.write(reinterpret_cast<const char*>(&record), sizeof(  
1081             BinaryRecord));  
1082     }  
1083  
1084     std::cout << "      Wrote " << sizeof(records) / sizeof(BinaryRecord)  
1085         << " binary records (" << sizeof(records) << " bytes)" <<  
1086             std::endl;  
1087 }  
1088  
1089 // 11.2 Reading binary data  
1090 std::cout << "\n11.2 Reading binary data:" << std::endl;  
1091 {  
1092     std::ifstream ifs(binary_file, std::ios::binary);  
1093  
1094     // Get file size  
1095     ifs.seekg(0, std::ios::end);  
1096     std::streamsize size = ifs.tellg();  
1097     ifs.seekg(0, std::ios::beg);  
1098  
1099     std::cout << "      File size: " << size << " bytes" << std::endl;  
1100     std::cout << "      Records: " << size / sizeof(BinaryRecord) << std:::  
1101         endl;  
1102  
1103     BinaryRecord record;  
1104     int count = 0;  
1105     while (ifs.read(reinterpret_cast<char*>(&record), sizeof(BinaryRecord))  
1106         ) {  
1107         std::cout << "      Record " << ++count << ": "  
1108             << "id=" << record.id << ", "  
1109                 << "value=" << record.value << ", "  
1110                     << "name=\\" " << record.name << "\\" << std::endl;  
1111     }  
1112 }  
1113  
1114 // 11.3 Writing POD types  
1115 std::cout << "\n11.3 Writing POD (Plain Old Data) types:" << std::endl;  
1116 {  
1117     fs::path pod_file = temp_dir / "pod_data.bin";  
1118  
1119     std::ofstream ofs(pod_file, std::ios::binary);  
1120  
1121     int integer = 42;  
1122     double floating = 3.14159;  
1123     char character = 'X';  
1124  
1125     ofs.write(reinterpret_cast<const char*>(&integer), sizeof(integer));  
1126     ofs.write(reinterpret_cast<const char*>(&floating), sizeof(floating));  
1127     ofs.write(reinterpret_cast<const char*>(&character), sizeof(character))
```

```
    );  
1124  
1125     ofs.close();  
1126  
1127     // Read back  
1128     std::ifstream ifs(pod_file, std::ios::binary);  
1129  
1130     int read_int;  
1131     double read_double;  
1132     char read_char;  
1133  
1134     ifs.read(reinterpret_cast<char*>(&read_int), sizeof(read_int));  
1135     ifs.read(reinterpret_cast<char*>(&read_double), sizeof(read_double));  
1136     ifs.read(reinterpret_cast<char*>(&read_char), sizeof(read_char));  
1137  
1138     std::cout << "    Read back: " << read_int << ", "  
1139             << read_double << ", " << read_char << std::endl;  
1140  
1141     fs::remove(pod_file, ec);  
1142 }  
1143  
1144 // Cleanup  
1145 fs::remove(binary_file, ec);  
1146  
1147 std::cout << "\n Binary I/O notes:" << std::endl;  
1148 std::cout << " • Use std::ios::binary flag" << std::endl;  
1149 std::cout << " • Only for POD types (no pointers, virtual functions)" <<  
1150         std::endl;  
1151 std::cout << " • Platform-dependent (endianness, padding)" << std::endl;  
1152 std::cout << " • Use serialization libraries for portability" << std::  
1153         endl;  
1154 }  
1155 // =====  
1156 // SECTION 12: CUSTOM STREAM OPERATORS  
1157 // =====  
1158  
1159 struct Point {  
1160     double x, y, z;  
1161 };  
1162  
1163 // Custom output operator  
1164 std::ostream& operator<<(std::ostream& os, const Point& p) {  
1165     os << "Point(" << p.x << ", " << p.y << ", " << p.z << ")";  
1166     return os;  
1167 }  
1168  
1169 // Custom input operator  
1170 std::istream& operator>>(std::istream& is, Point& p) {  
1171     char paren, comma1, comma2;  
1172     std::string word;  
1173  
1174     // Expected format: Point(1.0, 2.0, 3.0)  
1175     is >> word >> paren >> p.x >> comma1 >> p.y >> comma2 >> p.z >> paren;
```

```
1175     return is;
1176 }
1178
1179 void demonstrate_custom_operators() {
1180     std::cout << "\n==== 12. CUSTOM STREAM OPERATORS ===" << std::endl;
1181
1182     // 12.1 Custom output
1183     std::cout << "\n12.1 Custom output operator:" << std::endl;
1184     {
1185         Point p1{1.5, 2.7, 3.9};
1186         std::cout << "    " << p1 << std::endl;
1187
1188         // Works with string streams too
1189         std::ostringstream oss;
1190         oss << "Point data: " << p1;
1191         std::cout << "    Stringified: " << oss.str() << std::endl;
1192     }
1193
1194     // 12.2 Custom input
1195     std::cout << "\n12.2 Custom input operator:" << std::endl;
1196     {
1197         std::string input = "Point(4.5, 5.6, 6.7)";
1198         std::istringstream iss(input);
1199
1200         Point p2;
1201         iss >> p2;
1202
1203         std::cout << "    Parsed from string: " << p2 << std::endl;
1204     }
1205
1206     // 12.3 Chaining
1207     std::cout << "\n12.3 Operator chaining:" << std::endl;
1208     {
1209         Point p1{1.0, 2.0, 3.0};
1210         Point p2{4.0, 5.0, 6.0};
1211
1212         std::cout << "    Multiple points: " << p1 << " and " << p2 << std::endl;
1213     }
1214
1215     std::cout << "\n Custom operator benefits:" << std::endl;
1216     std::cout << " • Natural syntax: cout << myObject" << std::endl;
1217     std::cout << " • Works with all streams (file, string, cout)" << std::endl;
1218     std::cout << " • Chainable for multiple operations" << std::endl;
1219     std::cout << " • Consistent with standard library" << std::endl;
1220 }
1221
1222 // =====
1223 // SECTION 13: MUTEXES AND LOCK_GUARD
1224 // =====
1225
1226 // Shared resource with thread-safe access
```

```
1227 class SharedCounter {
1228 private:
1229     int counter = 0;
1230     mutable std::mutex mtx; // mutable allows locking in const methods
1231
1232 public:
1233     void increment() {
1234         std::lock_guard<std::mutex> lock(mtx); // RAII lock
1235         ++counter;
1236     } // Automatic unlock when lock goes out of scope
1237
1238     void add(int value) {
1239         std::lock_guard<std::mutex> lock(mtx);
1240         counter += value;
1241     }
1242
1243     int get() const {
1244         std::lock_guard<std::mutex> lock(mtx);
1245         return counter;
1246     }
1247 };
1248
1249 // File logger with mutex protection
1250 class ThreadSafeLogger {
1251 private:
1252     std::ofstream log_file;
1253     std::mutex file_mutex;
1254
1255 public:
1256     ThreadSafeLogger(const std::string& filename) : log_file(filename, std::ios::app) {}
1257
1258     void log(const std::string& message) {
1259         std::lock_guard<std::mutex> lock(file_mutex);
1260
1261         auto now = std::chrono::system_clock::now();
1262         auto now_time_t = std::chrono::system_clock::to_time_t(now);
1263
1264         log_file << "[" << std::put_time(std::localtime(&now_time_t), "%H:%M:%S")
1265             << "] " << message << std::endl;
1266     }
1267
1268     ~ThreadSafeLogger() {
1269         if (log_file.is_open()) {
1270             log_file.close();
1271         }
1272     }
1273 };
1274
1275 void demonstrate_mutex_and_lock_guard() {
1276     std::cout << "\n==== 13. MUTEXES AND LOCK_GUARD ===" << std::endl;
1277
1278     // 13.1 Basic lock_guard usage
```

```
1279     std::cout << "\n13.1 std::lock_guard for automatic RAII locking:" << std::endl;
1280
1281 {
1282     SharedCounter counter;
1283     std::vector<std::thread> threads;
1284
1285     // Launch 10 threads that increment counter
1286     for (int i = 0; i < 10; ++i) {
1287         threads.emplace_back([&counter]() {
1288             for (int j = 0; j < 100; ++j) {
1289                 counter.increment();
1290             }
1291         });
1292     }
1293
1294     // Wait for all threads
1295     for (auto& t : threads) {
1296         t.join();
1297     }
1298
1299     std::cout << "    Final counter value: " << counter.get() << std::endl;
1300     std::cout << "    Expected: 1000" << std::endl;
1301     std::cout << "    Thread-safe with lock_guard!" << std::endl;
1302 }
1303
1304 // 13.2 Thread-safe file logging
1305 std::cout << "\n13.2 Thread-safe file logging:" << std::endl;
1306 {
1307     std::error_code ec;
1308     fs::path temp_dir = fs::temp_directory_path(ec);
1309     fs::path log_file = temp_dir / "threadsafe_log.txt";
1310
1311     ThreadSafeLogger logger(log_file.string());
1312     std::vector<std::thread> threads;
1313
1314     // Multiple threads writing to log
1315     for (int i = 0; i < 5; ++i) {
1316         threads.emplace_back([&logger, i]() {
1317             for (int j = 0; j < 3; ++j) {
1318                 std::ostringstream oss;
1319                 oss << "Thread " << i << " message " << j;
1320                 logger.log(oss.str());
1321                 std::this_thread::sleep_for(std::chrono::milliseconds(10));
1322             }
1323         });
1324     }
1325
1326     for (auto& t : threads) {
1327         t.join();
1328     }
1329
1330     std::cout << "    15 log entries written safely" << std::endl;
1331     std::cout << "    Log file: " << log_file.filename() << std::endl;
```

```
1331 // Read and display log
1332 std::ifstream ifs(log_file);
1333 std::string line;
1334 int count = 0;
1335 std::cout << " First 5 entries:" << std::endl;
1336 while (std::getline(ifs, line) && count++ < 5) {
1337     std::cout << " " << line << std::endl;
1338 }
1339
1340 fs::remove(log_file, ec);
1341 }
1342
1343 std::cout << "\n lock_guard benefits:" << std::endl;
1344 std::cout << " • RAI - automatic unlock on scope exit" << std::endl;
1345 std::cout << " • Exception-safe" << std::endl;
1346 std::cout << " • Simple and efficient" << std::endl;
1347 std::cout << " • Cannot forget to unlock" << std::endl;
1348 }
1349
1350 // =====
1351 // SECTION 14: UNIQUE_LOCK AND ADVANCED LOCKING
1352 // =====
1353
1354 class BankAccount {
1355 private:
1356     double balance = 0.0;
1357     mutable std::mutex mtx;
1358     std::condition_variable cv;
1359
1360 public:
1361     BankAccount(double initial) : balance(initial) {}
1362
1363     bool withdraw(double amount) {
1364         std::unique_lock<std::mutex> lock(mtx);
1365
1366         if (balance >= amount) {
1367             balance -= amount;
1368             return true;
1369         }
1370         return false;
1371     }
1372
1373     void deposit(double amount) {
1374         std::unique_lock<std::mutex> lock(mtx);
1375         balance += amount;
1376         cv.notify_all(); // Wake up waiting threads
1377     }
1378
1379     // Wait until sufficient funds available
1380     bool wait_and_withdraw(double amount, std::chrono::milliseconds timeout) {
1381         std::unique_lock<std::mutex> lock(mtx);
1382
1383         // Wait with timeout
```

```
1385     if (!cv.wait_for(lock, timeout, [this, amount]() {
1386         return balance >= amount;
1387     })) {
1388         return false; // Timeout
1389     }
1390
1391     balance -= amount;
1392     return true;
1393 }
1394
1395 double get_balance() const {
1396     std::unique_lock<std::mutex> lock(mtx);
1397     return balance;
1398 }
1399 };
1400
1401 // Reader-writer lock example
1402 class SharedData {
1403 private:
1404     std::map<std::string, int> data;
1405     mutable std::shared_mutex rw_mutex;
1406
1407 public:
1408     // Multiple readers can access simultaneously
1409     int read(const std::string& key) const {
1410         std::shared_lock<std::shared_mutex> lock(rw_mutex);
1411         auto it = data.find(key);
1412         return (it != data.end()) ? it->second : 0;
1413     }
1414
1415     // Only one writer at a time
1416     void write(const std::string& key, int value) {
1417         std::unique_lock<std::shared_mutex> lock(rw_mutex);
1418         data[key] = value;
1419     }
1420
1421     size_t size() const {
1422         std::shared_lock<std::shared_mutex> lock(rw_mutex);
1423         return data.size();
1424     }
1425 };
1426
1427 void demonstrate_unique_lock() {
1428     std::cout << "\n==== 14. UNIQUE_LOCK AND ADVANCED LOCKING ===" << std::endl
1429     ;
1430
1431     // 14.1 unique_lock - more flexible than lock_guard
1432     std::cout << "\n14.1 std::unique_lock features:" << std::endl;
1433     {
1434         std::mutex mtx;
1435
1436         std::cout << " • Can be locked/unlocked multiple times:" << std::endl;
1437     }
```

```
1437     std::unique_lock<std::mutex> lock(mtx);
1438     std::cout << "      Locked" << std::endl;
1439
1440     lock.unlock(); // Explicit unlock
1441     std::cout << "      Unlocked (doing non-critical work)" << std::endl;
1442     lock.lock(); // Relock
1443     std::cout << "      Locked again" << std::endl;
1444 }
1445
1446     std::cout << " * Deferred locking:" << std::endl;
1447 {
1448     std::unique_lock<std::mutex> lock(mtx, std::defer_lock); // Don't
1449     lock.lock(); // Lock yet
1450     std::cout << "      Created unlocked" << std::endl;
1451
1452     lock.lock(); // Lock when needed
1453     std::cout << "      Now locked" << std::endl;
1454 }
1455 }
1456
1457 // 14.2 Condition variable with unique_lock
1458 std::cout << "\n14.2 Condition variable (wait with timeout):" << std::endl
1459 ;
1460 {
1461     BankAccount account(100.0);
1462
1463     std::cout << "      Initial balance: $" << account.get_balance() << std::endl;
1464
1465     // Try to withdraw more than available
1466     std::thread withdrawal_thread([&account]() {
1467         std::cout << "      Attempting to withdraw $150 (waiting up to 500ms)"
1468         ...
1469         << std::endl;
1470         bool success = account.wait_and_withdraw(150.0, std::chrono::milliseconds(500));
1471
1472         if (success) {
1473             std::cout << "      Withdrawal successful" << std::endl;
1474         } else {
1475             std::cout << "      Timeout - insufficient funds" << std::endl
1476             ;
1477         }
1478     });
1479
1480     std::this_thread::sleep_for(std::chrono::milliseconds(200));
1481
1482     // Deposit money to unblock
1483     std::cout << "      Depositing $75..." << std::endl;
1484     account.deposit(75.0);
1485
1486     withdrawal_thread.join();
1487     std::cout << "      Final balance: $" << account.get_balance() << std::endl;
```

```
        endl;
1484 }
1485
1486 // 14.3 Shared mutex for reader-writer locks
1487 std::cout << "\n14.3 std::shared_mutex (reader-writer lock):" << std::endl
1488 ;
1489 {
1490     SharedData shared;
1491     std::atomic<int> read_count{0};
1492     std::atomic<int> write_count{0};
1493
1494     std::vector<std::thread> threads;
1495
1496     // 8 readers
1497     for (int i = 0; i < 8; ++i) {
1498         threads.emplace_back([&shared, &read_count, i]() {
1499             for (int j = 0; j < 10; ++j) {
1500                 shared.read("key" + std::to_string(i % 3));
1501                 read_count++;
1502                 std::this_thread::sleep_for(std::chrono::microseconds(100));
1503             }
1504         });
1505     }
1506
1507     // 2 writers
1508     for (int i = 0; i < 2; ++i) {
1509         threads.emplace_back([&shared, &write_count, i]() {
1510             for (int j = 0; j < 5; ++j) {
1511                 shared.write("key" + std::to_string(j), i * 100 + j);
1512                 write_count++;
1513                 std::this_thread::sleep_for(std::chrono::milliseconds(1));
1514             }
1515         });
1516     }
1517
1518     for (auto& t : threads) {
1519         t.join();
1520     }
1521
1522     std::cout << "    Completed " << read_count << " reads" << std::endl;
1523     std::cout << "    Completed " << write_count << " writes" << std::endl;
1524     std::cout << "    Final data size: " << shared.size() << std::endl;
1525     std::cout << "    Multiple readers can run concurrently!" << std::endl;
1526 }
1527
1528 std::cout << "\n unique_lock vs lock_guard:" << std::endl;
1529 std::cout << "    lock_guard: Simple, RAII, no unlock() method" << std::endl;
1530 std::cout << "    unique_lock: Flexible, can unlock/relock, works with
1531           condition_variable" << std::endl;
1532 std::cout << "\n shared_mutex:" << std::endl;
1533 std::cout << "    shared_lock: Multiple readers simultaneously" << std::endl;
```

```
        endl;
1532     std::cout << " • unique_lock: Exclusive writer access" << std::endl;
1533     std::cout << " • Perfect for read-heavy workloads" << std::endl;
1534 }
1535
1536 // =====
1537 // SECTION 15: FILE LOCKING (OS-LEVEL)
1538 // =====
1539
1540 #ifdef __linux__
1541 #include <sys/file.h> // For flock
1542 #include <fcntl.h>
1543 #include <unistd.h>
1544
1545 class FileLock {
1546 private:
1547     int fd = -1;
1548     std::string filename;
1549
1550 public:
1551     FileLock(const std::string& file) : filename(file) {
1552         fd = open(filename.c_str(), O_RDWR | O_CREAT, 0666);
1553         if (fd == -1) {
1554             throw std::runtime_error("Failed to open file for locking");
1555         }
1556     }
1557
1558     bool try_lock() {
1559         return flock(fd, LOCK_EX | LOCK_NB) == 0; // Non-blocking exclusive
1560         lock
1561     }
1562
1563     void lock() {
1564         if (flock(fd, LOCK_EX) != 0) { // Blocking exclusive lock
1565             throw std::runtime_error("Failed to acquire lock");
1566         }
1567
1568     void unlock() {
1569         flock(fd, LOCK_UN);
1570     }
1571
1572     ~FileLock() {
1573         if (fd != -1) {
1574             unlock();
1575             close(fd);
1576         }
1577     }
1578 };
1579 #endif
1580
1581 void demonstrate_file_locking() {
1582     std::cout << "\n==== 15. FILE LOCKING (OS-LEVEL) ===" << std::endl;
1583 }
```

```
1584 #ifdef __linux__
1585     std::cout << "\n15.1 Advisory file locking with flock():" << std::endl;
1586 {
1587     std::error_code ec;
1588     fs::path temp_dir = fs::temp_directory_path(ec);
1589     fs::path lock_file = temp_dir / "test.lock";
1590
1591     try {
1592         FileLock lock1(lock_file.string());
1593
1594         std::cout << "    Thread 1: Acquiring lock..." << std::endl;
1595         lock1.lock();
1596         std::cout << "    Thread 1: Lock acquired" << std::endl;
1597
1598         // Simulate work
1599         std::this_thread::sleep_for(std::chrono::milliseconds(100));
1600
1601         // Try to acquire same lock from another thread
1602         std::thread other_thread([&lock_file]() {
1603             try {
1604                 FileLock lock2(lock_file.string());
1605                 std::cout << "    Thread 2: Trying non-blocking lock..." <<
1606                         std::endl;
1607
1608                 if (lock2.try_lock()) {
1609                     std::cout << "    Thread 2: Lock acquired" << std::endl;
1610                     lock2.unlock();
1611                 } else {
1612                     std::cout << "    Thread 2: Lock held by another
1613                         process" << std::endl;
1614                 }
1615             } catch (const std::exception& e) {
1616                 std::cout << "    Thread 2: Error - " << e.what() << std::endl;
1617             }
1618         });
1619
1620         other_thread.join();
1621
1622         std::cout << "    Thread 1: Releasing lock..." << std::endl;
1623         lock1.unlock();
1624
1625     } catch (const std::exception& e) {
1626         std::cout << "    Error: " << e.what() << std::endl;
1627     }
1628
1629     fs::remove(lock_file, ec);
1630 }
1631
1632 std::cout << "\n15.2 Preventing concurrent file access:" << std::endl;
1633 {
1634     std::error_code ec;
1635     fs::path temp_dir = fs::temp_directory_path(ec);
```

```
1634     fs::path shared_file = temp_dir / "shared_data.txt";
1635     fs::path lock_file_path = temp_dir / "shared_data.txt.lock";
1636
1637     // Writer with lock
1638     auto writer = [&shared_file, &lock_file_path](int id) {
1639         try {
1640             FileLock lock(lock_file_path.string());
1641             lock.lock();
1642
1643             std::cout << "    Writer " << id << ": Writing..." << std::endl
1644             ;
1645             std::ofstream ofs(shared_file, std::ios::app);
1646             ofs << "Line from writer " << id << "\n";
1647             ofs.close();
1648
1649             std::this_thread::sleep_for(std::chrono::milliseconds(50));
1650             lock.unlock();
1651             std::cout << "    Writer " << id << ": Done" << std::endl;
1652         } catch (const std::exception& e) {
1653             std::cout << "    Writer " << id << ": Error - " << e.what() <<
1654                 std::endl;
1655         }
1656     };
1657
1658     std::thread w1(writer, 1);
1659     std::thread w2(writer, 2);
1660     std::thread w3(writer, 3);
1661
1662     w1.join();
1663     w2.join();
1664     w3.join();
1665
1666     // Read result
1667     std::ifstream ifs(shared_file);
1668     std::string line;
1669     int line_count = 0;
1670     while (std::getline(ifs, line)) {
1671         line_count++;
1672     }
1673
1674     std::cout << "    All writers completed safely" << std::endl;
1675     std::cout << "    Total lines written: " << line_count << std::endl;
1676
1677     fs::remove(shared_file, ec);
1678     fs::remove(lock_file_path, ec);
1679 }
1680
1681 std::cout << "\n File locking types:" << std::endl;
1682 std::cout << " • Advisory locks: Processes must cooperate (flock)" <<
1683             std::endl;
1684 std::cout << " • Mandatory locks: Enforced by kernel (rare)" << std::
1685             endl;
1686 std::cout << " • LOCK_EX: Exclusive lock (writer)" << std::endl;
1687 std::cout << " • LOCK_SH: Shared lock (reader)" << std::endl;
```

```
1684     std::cout << " •  LOCK_NB: Non-blocking flag" << std::endl;
1685
1686 #else
1687     std::cout << "\n          File locking examples require Linux (flock)" << std
1688         ::endl;
1689     std::cout << "      Windows equivalent: LockFileEx()" << std::endl;
1690     std::cout << "      Cross-platform: Use Boost.Interprocess" << std::endl;
1691 #endif
1692 }
1693 // =====
1694 // SECTION 16: RACE CONDITIONS - PROBLEM AND SOLUTION
1695 // =====
1696
1697 // Simulated device hotplug manager - WITHOUT proper synchronization (BROKEN!)
1698 class BrokenDeviceManager {
1699 private:
1700     std::map<std::string, std::string> devices; // device_id -> status
1701     int device_count = 0;
1702
1703 public:
1704     // Called by multiple threads - NO MUTEX!
1705     void add_device(const std::string& device_id) {
1706         // RACE CONDITION: Multiple threads can read/write simultaneously
1707         if (devices.find(device_id) == devices.end()) {
1708             std::this_thread::sleep_for(std::chrono::microseconds(100)); // 
1709                 Simulate processing
1710             devices[device_id] = "active";
1711             device_count++;
1712         }
1713     }
1714
1715     void remove_device(const std::string& device_id) {
1716         // RACE CONDITION: Map modification without synchronization
1717         if (devices.find(device_id) != devices.end()) {
1718             std::this_thread::sleep_for(std::chrono::microseconds(100));
1719             devices.erase(device_id);
1720             device_count--;
1721         }
1722     }
1723
1724     void process_script_output(const std::string& script_output) {
1725         // RACE CONDITION: Reading and updating shared state
1726         std::istringstream iss(script_output);
1727         std::string line;
1728         while (std::getline(iss, line)) {
1729             if (line.find("ADD:") == 0) {
1730                 std::string device = line.substr(4);
1731                 devices[device] = "pending";
1732             }
1733         }
1734     }
1735
1736     int get_count() const {
```

```
1736     return device_count; // RACE CONDITION: Reading without lock
1737 }
1738
1739 std::map<std::string, std::string> get_devices() const {
1740     return devices; // RACE CONDITION: Copying map without lock
1741 }
1742 };
1743
1744 // Fixed version - WITH proper synchronization
1745 class SafeDeviceManager {
1746 private:
1747     std::map<std::string, std::string> devices;
1748     int device_count = 0;
1749     mutable std::mutex mtx; // Protects all shared state
1750     std::ofstream log_file;
1751
1752 public:
1753     SafeDeviceManager() : log_file("/tmp/device_manager.log", std::ios::app)
1754     {}
1755
1756     void add_device(const std::string& device_id) {
1757         std::lock_guard<std::mutex> lock(mtx); // FIXED: Automatic locking
1758
1759         if (devices.find(device_id) == devices.end()) {
1760             std::this_thread::sleep_for(std::chrono::microseconds(100));
1761             devices[device_id] = "active";
1762             device_count++;
1763
1764             if (log_file.is_open()) {
1765                 log_file << "[ADD] " << device_id << std::endl;
1766             }
1767         }
1768
1769     void remove_device(const std::string& device_id) {
1770         std::lock_guard<std::mutex> lock(mtx); // FIXED: Protected
1771
1772         if (devices.find(device_id) != devices.end()) {
1773             std::this_thread::sleep_for(std::chrono::microseconds(100));
1774             devices.erase(device_id);
1775             device_count--;
1776
1777             if (log_file.is_open()) {
1778                 log_file << "[REMOVE] " << device_id << std::endl;
1779             }
1780         }
1781     }
1782
1783     void process_script_output(const std::string& script_output) {
1784         std::lock_guard<std::mutex> lock(mtx); // FIXED: Protected
1785
1786         std::istringstream iss(script_output);
1787         std::string line;
1788         while (std::getline(iss, line)) {
```

```
1789         if (line.find("ADD:") == 0) {
1790             std::string device = line.substr(4);
1791             devices[device] = "pending";
1792         }
1793     }
1794 }
1795
1796 int get_count() const {
1797     std::lock_guard<std::mutex> lock(mtx); // FIXED: Protected read
1798     return device_count;
1799 }
1800
1801 std::map<std::string, std::string> get_devices() const {
1802     std::lock_guard<std::mutex> lock(mtx); // FIXED: Protected copy
1803     return devices;
1804 }
1805
1806 ~SafeDeviceManager() {
1807     if (log_file.is_open()) {
1808         log_file.close();
1809     }
1810 }
1811 };
1812
1813 // Simulate hotplug events by calling external scripts
1814 void simulate_hotplug_script(int event_id) {
1815     // Create a temporary script that simulates device detection
1816     std::error_code ec;
1817     fs::path temp_dir = fs::temp_directory_path(ec);
1818     fs::path script_path = temp_dir / ("hotplug_" + std::to_string(event_id) +
1819                                         ".sh");
1820
1821     std::ofstream script(script_path);
1822     script << "#!/bin/bash\n";
1823     script << "echo 'ADD:device_" << event_id << "'\n";
1824     script << "sleep 0.01\n";
1825     script << "echo 'STATUS:online'\n";
1826     script.close();
1827
1828     fs::permissions(script_path, fs::perms::owner_all, fs::perm_options::add,
1829                     ec);
1830 }
1831
1832 void demonstrate_race_condition() {
1833     std::cout << "\n==== 16. RACE CONDITIONS - PROBLEM AND SOLUTION ===" << std::endl;
1834
1835     // 16.1 Demonstrate the BROKEN version
1836     std::cout << "\n16.1 BROKEN: Race condition without mutex:" << std::endl
1837     ;
1838     {
1839         BrokenDeviceManager broken_mngr;
1840         std::vector<std::thread> threads;
```

```
1839     std::cout << "    Launching 20 threads to add devices..." << std::endl;
1840
1841     // Multiple threads adding same devices
1842     for (int i = 0; i < 20; ++i) {
1843         threads.emplace_back([&broken_mgr, i]() {
1844             for (int j = 0; j < 10; ++j) {
1845                 std::string device_id = "dev_" + std::to_string(j);
1846                 broken_mgr.add_device(device_id);
1847             }
1848         });
1849     }
1850
1851     for (auto& t : threads) {
1852         t.join();
1853     }
1854
1855     int final_count = broken_mgr.get_count();
1856     auto devices = broken_mgr.get_devices();
1857
1858     std::cout << "    Expected: 10 unique devices" << std::endl;
1859     std::cout << "    Device count variable: " << final_count << std::endl;
1860     std::cout << "    Actual devices in map: " << devices.size() << std::endl;
1861
1862     if (final_count != 10 || devices.size() != 10) {
1863         std::cout << "        RACE CONDITION DETECTED!" << std::endl;
1864         std::cout << "        Count mismatch due to concurrent access" <<
1865             std::endl;
1866     } else {
1867         std::cout << "        (Race condition may not always show - timing
1868             dependent)" << std::endl;
1869     }
1870
1871 // 16.2 Demonstrate the FIXED version
1872 std::cout << "\n16.2  FIXED: With mutex protection:" << std::endl;
1873 {
1874     SafeDeviceManager safe_mgr;
1875     std::vector<std::thread> threads;
1876
1877     std::cout << "    Launching 20 threads to add devices..." << std::endl;
1878
1879     for (int i = 0; i < 20; ++i) {
1880         threads.emplace_back([&safe_mgr, i]() {
1881             for (int j = 0; j < 10; ++j) {
1882                 std::string device_id = "dev_" + std::to_string(j);
1883                 safe_mgr.add_device(device_id);
1884             }
1885         });
1886     }
1887
1888     for (auto& t : threads) {
1889         t.join();
1890     }
```

```
1890
1891     int final_count = safe_mgr.get_count();
1892     auto devices = safe_mgr.get_devices();
1893
1894     std::cout << "    Expected: 10 unique devices" << std::endl;
1895     std::cout << "    Device count: " << final_count << std::endl;
1896     std::cout << "    Devices in map: " << devices.size() << std::endl;
1897
1898     if (final_count == 10 && devices.size() == 10) {
1899         std::cout << "    CORRECT: Mutex prevented race condition!" <<
1900             std::endl;
1901     }
1902
1903 // 16.3 Real-world scenario: File updates from multiple sources
1904 std::cout << "\n16.3 Race condition with file I/O and scripts:" << std::
1905     endl;
1906 {
1907     std::error_code ec;
1908     fs::path temp_dir = fs::temp_directory_path(ec);
1909     fs::path shared_file = temp_dir / "device_registry.txt";
1910
1911     // BROKEN: Multiple threads writing to file without coordination
1912     std::cout << "    Without file locking:" << std::endl;
1913     {
1914         // Clear file
1915         std::ofstream(shared_file).close();
1916
1917         std::vector<std::thread> writers;
1918
1919         for (int i = 0; i < 5; ++i) {
1920             writers.emplace_back([&shared_file, i]() {
1921                 for (int j = 0; j < 3; ++j) {
1922                     // RACE CONDITION: Multiple threads writing
1923                     // simultaneously
1924                     std::ofstream ofs(shared_file, std::ios::app);
1925                     ofs << "Thread_" << i << "_entry_" << j << "\n";
1926                     ofs.close();
1927                     std::this_thread::sleep_for(std::chrono::microseconds
1928                         (100));
1929                 }
1930             });
1931         }
1932
1933         for (auto& t : writers) {
1934             t.join();
1935         }
1936
1937         // Count lines
1938         std::ifstream ifs(shared_file);
1939         int line_count = 0;
1940         std::string line;
1941         while (std::getline(ifs, line)) {
1942             if (!line.empty()) line_count++;
1943         }
1944     }
1945 }
```

```
1940     }
1941
1942     std::cout << "      Expected 15 lines, got: " << line_count << std
1943         ::endl;
1944     if (line_count != 15) {
1945         std::cout << "      Some writes may have been lost!" << std
1946             ::endl;
1947     }
1948
1949 // FIXED: With mutex protection
1950 std::cout << "      With mutex protection:" << std::endl;
1951 {
1952     // Clear file
1953     std::ofstream(shared_file).close();
1954
1955     std::mutex file_mtx;
1956     std::vector<std::thread> writers;
1957
1958     for (int i = 0; i < 5; ++i) {
1959         writers.emplace_back(&shared_file, &file_mtx, i) {
1960             for (int j = 0; j < 3; ++j) {
1961                 std::lock_guard<std::mutex> lock(file_mtx); // FIXED!
1962                 std::ofstream ofs(shared_file, std::ios::app);
1963                 ofs << "Thread_" << i << "_entry_" << j << "\n";
1964                 ofs.close();
1965                 std::this_thread::sleep_for(std::chrono::microseconds
1966                     (100));
1967             }
1968         });
1969     }
1970
1971     for (auto& t : writers) {
1972         t.join();
1973     }
1974
1975     // Count lines
1976     std::ifstream ifs(shared_file);
1977     int line_count = 0;
1978     std::string line;
1979     while (std::getline(ifs, line)) {
1980         if (!line.empty()) line_count++;
1981     }
1982
1983     std::cout << "      Expected 15 lines, got: " << line_count << std
1984         ::endl;
1985     if (line_count == 15) {
1986         std::cout << "      All writes preserved!" << std::endl;
1987     }
1988
1989     fs::remove(shared_file, ec);
}
```

```
1990 // 16.4 Simulating hotplug events with script execution
1991 std::cout << "\n16.4 Hotplug simulation (scripts + threads):" << std::endl
1992 ;
1993 {
1994     SafeDeviceManager mgr;
1995     std::vector<std::thread> hotplug_threads;
1996
1997     std::cout << "    Simulating 3 concurrent hotplug events..." << std::endl;
1998
1999     for (int i = 0; i < 3; ++i) {
2000         hotplug_threads.emplace_back([&mgr, i](){
2001             // Simulate calling udev script or hotplug handler
2002             std::string script_output = "ADD:usb_device_" + std::to_string(i) + "\n";
2003             script_output += "ADD:usb_port_" + std::to_string(i) + "\n";
2004
2005             mgr.process_script_output(script_output);
2006
2007             // Simulate device becoming active
2008             std::this_thread::sleep_for(std::chrono::milliseconds(10));
2009             mgr.add_device("usb_device_" + std::to_string(i));
2010             mgr.add_device("usb_port_" + std::to_string(i));
2011         });
2012     }
2013
2014     for (auto& t : hotplug_threads) {
2015         t.join();
2016     }
2017
2018     auto devices = mgr.get_devices();
2019     std::cout << "    Total devices registered: " << devices.size() << std::endl;
2020
2021     std::cout << "    Devices:" << std::endl;
2022     for (const auto& [id, status] : devices) {
2023         std::cout << "        " << id << " -> " << status << std::endl;
2024     }
2025     std::cout << "    All hotplug events handled safely" << std::endl;
2026 }
2027
2028 std::cout << "\n Common race condition scenarios:" << std::endl;
2029 std::cout << "    1. Multiple threads modifying shared container" << std::endl;
2030 std::cout << "    2. Check-then-act pattern without atomicity" << std::endl;
2031 std::cout << "    3. Reading and writing without synchronization" << std::endl;
2032 std::cout << "    4. File I/O from multiple threads/processes" << std::endl;
2033 std::cout << "    5. Scripts updating shared resources" << std::endl;
2034
2035 std::cout << "\n Solutions:" << std::endl;
2036 std::cout << " • Use std::mutex with lock_guard/unique_lock" << std::endl;
```

```
2035     std::cout << " • Use std::atomic for simple counters" << std::endl;
2036     std::cout << " • Use file locks for inter-process sync" << std::endl;
2037     std::cout << " • Protect ALL access to shared data" << std::endl;
2038     std::cout << " • Keep critical sections small" << std::endl;
2039 }
2040
2041 // =====
2042 // SECTION 17: SECURITY CONSIDERATIONS
2043 // =====
2044
2045 void explain_security_considerations() {
2046     std::cout << "\n" << std::string(70, '=') << std::endl;
2047     std::cout << "SECURITY CONSIDERATIONS:\n";
2048     std::cout << std::string(70, '=') << std::endl;
2049
2050     std::cout << "\n CRITICAL SECURITY ISSUES:" << std::endl;
2051
2052     std::cout << "\n1. COMMAND INJECTION:" << std::endl;
2053     std::cout << "    BAD: system(\"ls \" + user_input);" << std::endl;
2054     std::cout << "    GOOD: Validate and sanitize input first" << std::endl;
2055     std::cout << "    GOOD: Use execve() family for direct execution" << std
2056         ::endl;
2057
2058     std::cout << "\n2. SHELL METACHARACTERS:" << std::endl;
2059     std::cout << "    Dangerous: ; | & $ ` \\ \" ' < > ( ) { } [ ] ! #"
2060         << std
2061             ::endl;
2062     std::cout << "    User input: \"file.txt; rm -rf /\""
2063     std::cout << "    Result: DISASTER!" << std::endl;
2064
2065     std::cout << "\n3. PATH TRAVERSAL:" << std::endl;
2066     std::cout << "    BAD: open(\"/data/\" + user_input)" << std::endl;
2067     std::cout << "    User: \"../../etc/passwd\""
2068     std::cout << "    GOOD: Validate paths, use fs::canonical()" << std::endl
2069         ;
2070
2071     std::cout << "\n4. ENVIRONMENT VARIABLES:" << std::endl;
2072     std::cout << "    $PATH, $LD_PRELOAD can be hijacked" << std::endl;
2073     std::cout << "    Use absolute paths: /usr/bin/python3"
2074     std::cout << "    Don't trust $PATH from external sources" << std::endl;
2075
2076     std::cout << "\n BEST PRACTICES:" << std::endl;
2077     std::cout << "\n1. INPUT VALIDATION:" << std::endl;
2078     std::cout << "    Whitelist allowed characters" << std::endl;
2079     std::cout << "    Use regex to validate format" << std::endl;
2080     std::cout << "    Reject anything suspicious" << std::endl;
2081
2082     std::cout << "\n2. AVOID system():"
2083     std::cout << "    Use popen() for output capture"
2084     std::cout << "    Use fork()+execve() for full control"
2085     std::cout << "    Never pass user input directly to shell"
2086
2087     std::cout << "\n3. LEAST PRIVILEGE:" << std::endl;
2088     std::cout << "    Run with minimum necessary permissions"
2089     std::cout << "    Drop privileges after initialization"
```

```
2086     std::cout << " • Use separate user accounts" << std::endl;
2087
2088     std::cout << "\n4. ERROR HANDLING:" << std::endl;
2089     std::cout << " • Check all return codes" << std::endl;
2090     std::cout << " • Don't expose system details in errors" << std::endl;
2091     std::cout << " • Log security events" << std::endl;
2092 }
2093
2094 // =====
2095 // SECTION 18: CROSS-PLATFORM CONSIDERATIONS
2096 // =====
2097
2098 void explain_cross_platform() {
2099     std::cout << "\n" << std::string(70, '=') << std::endl;
2100     std::cout << "CROSS-PLATFORM CONSIDERATIONS:\n";
2101     std::cout << std::string(70, '=') << std::endl;
2102
2103     std::cout << "\n LINUX vs   WINDOWS:" << std::endl;
2104
2105     std::cout << "\n1. COMMAND EXECUTION:" << std::endl;
2106     std::cout << "    Linux:  popen(\"/bin/ls\", \"r\")" << std::endl;
2107     std::cout << "    Windows: _open(\"dir\", \"r\")" << std::endl;
2108     std::cout << "    Windows: CreateProcess() for full control" << std::endl;
2109
2110     std::cout << "\n2. PATH SEPARATORS:" << std::endl;
2111     std::cout << "    Linux:  /home/user/file.txt" << std::endl;
2112     std::cout << "    Windows: C:\\\\Users\\\\user\\\\file.txt" << std::endl;
2113     std::cout << "        Use fs::path - handles both!" << std::endl;
2114
2115     std::cout << "\n3. LINE ENDINGS:" << std::endl;
2116     std::cout << "    Linux:  \\n (LF)" << std::endl;
2117     std::cout << "    Windows: \\r\\n (CRLF)" << std::endl;
2118     std::cout << "        Open files in text mode for conversion" << std::endl;
2119
2120     std::cout << "\n4. SYSTEM TOOLS:" << std::endl;
2121     std::cout << "    Linux:  ps, df, grep, awk, sed" << std::endl;
2122     std::cout << "    Windows: tasklist, wmic, findstr, PowerShell" << std::endl;
2123     std::cout << "        Check platform and use appropriate tools" << std::endl;
2124
2125     std::cout << "\n PORTABLE CODE:" << std::endl;
2126     std::cout << "#ifdef _WIN32" << std::endl;
2127     std::cout << "    std::string cmd = \"dir\";" << std::endl;
2128     std::cout << "#else" << std::endl;
2129     std::cout << "    std::string cmd = \"ls\";" << std::endl;
2130     std::cout << "#endif" << std::endl;
2131
2132     std::cout << "\nOr use std::filesystem for platform independence!" << std::endl;
2133 }
2134
2135 // =====
2136 // SECTION 19: BEST PRACTICES SUMMARY
2137 // =====
```

```
2138
2139 void explain_best_practices() {
2140     std::cout << "\n" << std::string(70, '=') << std::endl;
2141     std::cout << "BEST PRACTICES SUMMARY:\n";
2142     std::cout << std::string(70, '=') << std::endl;
2143
2144     std::cout << "\n DO:" << std::endl;
2145     std::cout << "\n1. Use std::filesystem for file operations" << std::endl;
2146     std::cout << " • Cross-platform" << std::endl;
2147     std::cout << " • Exception-safe" << std::endl;
2148     std::cout << " • Modern and clean API" << std::endl;
2149
2150     std::cout << "\n2. Use std::string_view for parsing" << std::endl;
2151     std::cout << " • Zero-copy substring operations" << std::endl;
2152     std::cout << " • Perfect for tokenizing large outputs" << std::endl;
2153     std::cout << " • No memory allocations" << std::endl;
2154
2155     std::cout << "\n3. Use std::regex for pattern matching" << std::endl;
2156     std::cout << " • Structured text parsing" << std::endl;
2157     std::cout << " • Validation" << std::endl;
2158     std::cout << " • Extraction from unstructured data" << std::endl;
2159
2160     std::cout << "\n4. Check return codes and use error_code" << std::endl;
2161     std::cout << " • filesystem operations can fail" << std::endl;
2162     std::cout << " • Commands can fail" << std::endl;
2163     std::cout << " • Use std::error_code for exception-free errors" << std::endl;
2164
2165     std::cout << "\n5. Use RAII for resource management" << std::endl;
2166     std::cout << " • std::unique_ptr with custom deleter for FILE*" << std::endl;
2167     std::cout << " • Automatic cleanup on exception" << std::endl;
2168
2169     std::cout << "\n DON'T:" << std::endl;
2170     std::cout << "\n1. Don't use system() with user input" << std::endl;
2171     std::cout << " • Command injection vulnerability" << std::endl;
2172     std::cout << " • Use execve() family instead" << std::endl;
2173
2174     std::cout << "\n2. Don't ignore errors" << std::endl;
2175     std::cout << " • Check pclose() return value" << std::endl;
2176     std::cout << " • Check filesystem operation errors" << std::endl;
2177
2178     std::cout << "\n3. Don't parse with manual string manipulation" << std::endl;
2179     std::cout << " • Use string_view for efficiency" << std::endl;
2180     std::cout << " • Use regex for complex patterns" << std::endl;
2181
2182     std::cout << "\n4. Don't assume POSIX everywhere" << std::endl;
2183     std::cout << " • Windows is different" << std::endl;
2184     std::cout << " • Use std::filesystem for portability" << std::endl;
2185
2186     std::cout << "\n GOLDEN RULES:" << std::endl;
2187     std::cout << " 1. Validate all external input" << std::endl;
2188     std::cout << " 2. Use modern C++ facilities (filesystem, string_view)"
```

```
        << std::endl;
2189     std::cout << "    3. Check errors always" << std::endl;
2190     std::cout << "    4. Think security first!" << std::endl;
2191 }
2192
2193 // =====
2194 // MAIN FUNCTION
2195 // =====
2196
2197 int main() {
2198     std::cout << "\n";
2199     std::cout << "
2200         \n";
2201     std::cout << "
2202         \n";
2203     std::cout << "
2204         \n";
2205
2206     try {
2207         demonstrate_basic_execution();
2208         demonstrate_string_view_parsing();
2209         demonstrate_regex_parsing();
2210         demonstrate_filesystem();
2211         demonstrate_bash_scripts();
2212         demonstrate_python_scripts();
2213         demonstrate_linux_tools();
2214         demonstrate_file_streams();
2215         demonstrate_string_streams();
2216         demonstrate_stream_manipulators();
2217         demonstrate_binary_io();
2218         demonstrate_custom_operators();
2219         demonstrate_mutex_and_lock_guard();
2220         demonstrate_unique_lock();
2221         demonstrate_file_locking();
2222         demonstrate_race_condition();
2223         explain_security_considerations();
2224         explain_cross_platform();
2225         explain_best_practices();
2226
2227         std::cout << "\n" << std::string(70, '=') << std::endl;
2228         std::cout << "SUMMARY:\n";
2229         std::cout << std::string(70, '=') << std::endl;
2230
2231         std::cout << "\n KEY FEATURES DEMONSTRATED:" << std::endl;
2232         std::cout << "\n1. COMMAND EXECUTION:" << std::endl;
2233         std::cout << "    • popen() for output capture" << std::endl;
2234         std::cout << "    • Return code checking" << std::endl;
2235         std::cout << "    • RAII for resource management" << std::endl;
2236
2237         std::cout << "\n2. std::string_view (C++17):" << std::endl;
2238         std::cout << "    • Zero-copy parsing" << std::endl;
2239         std::cout << "    • Efficient tokenization" << std::endl;
```

```
2239     std::cout << " • Perfect for large outputs" << std::endl;
2240
2241     std::cout << "\n3. std::regex (C++11):" << std::endl;
2242     std::cout << " • Pattern matching" << std::endl;
2243     std::cout << " • Log parsing" << std::endl;
2244     std::cout << " • Network output parsing" << std::endl;
2245
2246     std::cout << "\n4. std::filesystem (C++17):" << std::endl;
2247     std::cout << " • Cross-platform paths" << std::endl;
2248     std::cout << " • Directory iteration" << std::endl;
2249     std::cout << " • Error code handling" << std::endl;
2250
2251     std::cout << "\n5. STREAM I/O:" << std::endl;
2252     std::cout << " • File streams (ifstream, ofstream, fstream)" << std
2253         ::endl;
2254     std::cout << " • String streams (ostringstream, istringstream)" <<
2255         std::endl;
2256     std::cout << " • Stream manipulators (setw, setprecision, etc.)" <<
2257         std::endl;
2258     std::cout << " • Binary I/O for POD types" << std::endl;
2259     std::cout << " • Custom stream operators" << std::endl;
2260
2261     std::cout << "\n6. SCRIPT INTEGRATION:" << std::endl;
2262     std::cout << " • Bash scripts with arguments" << std::endl;
2263     std::cout << " • Python scripts with JSON output" << std::endl;
2264     std::cout << " • Structured data exchange" << std::endl;
2265
2266     std::cout << "\n7. THREAD SYNCHRONIZATION:" << std::endl;
2267     std::cout << " • std::mutex and std::lock_guard (RAII)" << std::endl
2268         ;
2269     std::cout << " • std::unique_lock (flexible locking)" << std::endl;
2270     std::cout << " • std::shared_mutex (reader-writer locks)" << std::
2271         endl;
2272     std::cout << " • std::condition_variable (wait/notify)" << std::endl
2273         ;
2274     std::cout << " • OS-level file locking (flock)" << std::endl;
2275     std::cout << " • Race condition examples and fixes" << std::endl;
2276
2277     std::cout << "\n SECURITY REMINDERS:" << std::endl;
2278     std::cout << " • Never pass unsanitized user input to shell" << std
2279         ::endl;
2280     std::cout << " • Validate all paths and arguments" << std::endl;
2281     std::cout << " • Use absolute paths for commands" << std::endl;
2282     std::cout << " • Check return codes always" << std::endl;
2283
2284     std::cout << "\n Modern C++: Safe, efficient system programming!\n"
2285         << std::endl;
2286
2287 } catch (const std::exception& e) {
2288     std::cerr << "\n Error: " << e.what() << std::endl;
2289     return 1;
2290 }
2291
2292 return 0;
```

2285 }

70 Source Code: TemplatizedCameraInterface.cpp

File: src/TemplatedCameraInterface.cpp

Repository: [View on GitHub](#)

```
1 #include <iostream>
2 #include <array>
3 #include <vector>
4 #include <memory>
5 #include <cstdint>
6 #include <type_traits>
7 #include <algorithm>
8 #include <cmath>
9 #include <chrono>
10
11 // =====
12 // TEMPLATED CAMERA INTERFACE FOR MULTIPLE PIXEL TYPES
13 // =====
14 // Demonstrates C++ templates for camera interfacing where pixel data
15 // can be various types: uint8_t, uint16_t, float, double
16 // =====
17
18 // =====
19 // 1. BASIC IMAGE CLASS (TEMPLATED BY PIXEL TYPE)
20 // =====
21
22 template<typename PixelType>
23 class Image {
24 private:
25     size_t width;
26     size_t height;
27     std::vector<PixelType> pixels;
28
29 public:
30     Image(size_t w, size_t h)
31         : width(w), height(h), pixels(w * h) {}
32
33     Image(size_t w, size_t h, PixelType initial_value)
34         : width(w), height(h), pixels(w * h, initial_value) {}
35
36     // Accessors
37     size_t get_width() const { return width; }
38     size_t get_height() const { return height; }
39     size_t get_size() const { return pixels.size(); }
40
41     // Pixel access
42     PixelType& at(size_t x, size_t y) {
43         return pixels[y * width + x];
44     }
45
46     const PixelType& at(size_t x, size_t y) const {
47         return pixels[y * width + x];
48     }
49
```

```
50 // Raw data access (for camera hardware interface)
51 PixelType* data() { return pixels.data(); }
52 const PixelType* data() const { return pixels.data(); }
53
54 // Memory size in bytes
55 size_t memory_bytes() const {
56     return pixels.size() * sizeof(PixelType);
57 }
58
59 // Fill with value
60 void fill(PixelType value) {
61     std::fill(pixels.begin(), pixels.end(), value);
62 }
63 };
64
65 // =====
66 // 2. CAMERA INTERFACE (TEMPLATED)
67 // =====
68
69 template<typename PixelType>
70 class Camera {
71 private:
72     size_t width;
73     size_t height;
74     std::string camera_name;
75
76 public:
77     Camera(const std::string& name, size_t w, size_t h)
78         : camera_name(name), width(w), height(h) {}
79
80     virtual ~Camera() = default;
81
82     // Pure virtual: capture image
83     virtual Image<PixelType> capture() = 0;
84
85     // Configuration
86     size_t get_width() const { return width; }
87     size_t get_height() const { return height; }
88     const std::string& get_name() const { return camera_name; }
89
90     // Get pixel type information
91     static constexpr size_t bits_per_pixel() {
92         return sizeof(PixelType) * 8;
93     }
94
95     static constexpr bool is_floating_point() {
96         return std::is_floating_point_v<PixelType>;
97     }
98
99     static constexpr bool is_integer() {
100         return std::is_integral_v<PixelType>;
101     }
102 };
103 }
```

```
104 // =====
105 // 3. SIMULATED CAMERA IMPLEMENTATIONS
106 // =====
107
108 // 8-bit grayscale camera (most common)
109 class Camera8bit : public Camera<uint8_t> {
110 public:
111     Camera8bit(const std::string& name, size_t w, size_t h)
112         : Camera<uint8_t>(name, w, h) {}
113
114     Image<uint8_t> capture() override {
115         Image<uint8_t> img(get_width(), get_height());
116
117         // Simulate captured gradient pattern
118         for (size_t y = 0; y < get_height(); ++y) {
119             for (size_t x = 0; x < get_width(); ++x) {
120                 uint8_t value = static_cast<uint8_t>(
121                     (x * 255.0 / get_width()) * 0.5 +
122                     (y * 255.0 / get_height()) * 0.5
123                 );
124                 img.at(x, y) = value;
125             }
126         }
127         return img;
128     }
129 };
130
131 // 16-bit camera (scientific/medical imaging)
132 class Camera16bit : public Camera<uint16_t> {
133 public:
134     Camera16bit(const std::string& name, size_t w, size_t h)
135         : Camera<uint16_t>(name, w, h) {}
136
137     Image<uint16_t> capture() override {
138         Image<uint16_t> img(get_width(), get_height());
139
140         // Simulate high dynamic range data
141         for (size_t y = 0; y < get_height(); ++y) {
142             for (size_t x = 0; x < get_width(); ++x) {
143                 uint16_t value = static_cast<uint16_t>(
144                     (x * 65535.0 / get_width()) * 0.3 +
145                     (y * 65535.0 / get_height()) * 0.7
146                 );
147                 img.at(x, y) = value;
148             }
149         }
150         return img;
151     }
152 };
153
154 // Float camera (normalized values 0.0-1.0)
155 class CameraFloat : public Camera<float> {
156 public:
157     CameraFloat(const std::string& name, size_t w, size_t h)
```

```
158     : Camera<float>(name, w, h) {}
159
160     Image<float> capture() override {
161         Image<float> img(get_width(), get_height());
162
163         // Simulate normalized data with some pattern
164         for (size_t y = 0; y < get_height(); ++y) {
165             for (size_t x = 0; x < get_width(); ++x) {
166                 float value =
167                     0.5f + 0.5f * std::sin(x * 0.1f) * std::cos(y * 0.1f);
168                 img.at(x, y) = value;
169             }
170         }
171         return img;
172     }
173 };
174
175 // Double precision camera (research/astronomy)
176 class CameraDouble : public Camera<double> {
177 public:
178     CameraDouble(const std::string& name, size_t w, size_t h)
179         : Camera<double>(name, w, h) {}
180
181     Image<double> capture() override {
182         Image<double> img(get_width(), get_height());
183
184         // Simulate high-precision data
185         for (size_t y = 0; y < get_height(); ++y) {
186             for (size_t x = 0; x < get_width(); ++x) {
187                 double value =
188                     std::sin(x * 0.05) * std::cos(y * 0.05) +
189                     std::exp(-((x - get_width()/2.0) * (x - get_width()/2.0) +
190                               (y - get_height()/2.0) * (y - get_height()/2.0)
191                               ) / 1000.0);
192                 img.at(x, y) = value;
193             }
194         }
195         return img;
196     }
197 }
198 // =====
199 // 4. IMAGE PROCESSING ALGORITHMS (TEMPLATED)
200 // =====
201
202 template<typename PixelType>
203 class ImageProcessor {
204 public:
205     // Calculate average pixel value
206     static double calculate_mean(const Image<PixelType>& img) {
207         double sum = 0.0;
208         const PixelType* data = img.data();
209         size_t size = img.get_size();
210     }
```

```
211     for (size_t i = 0; i < size; ++i) {
212         sum += static_cast<double>(data[i]);
213     }
214
215     return sum / size;
216 }
217
218 // Find min and max pixel values
219 static std::pair<PixelType, PixelType> find_min_max(const Image<PixelType>& img) {
220     const PixelType* data = img.data();
221     size_t size = img.get_size();
222
223     PixelType min_val = data[0];
224     PixelType max_val = data[0];
225
226     for (size_t i = 1; i < size; ++i) {
227         if (data[i] < min_val) min_val = data[i];
228         if (data[i] > max_val) max_val = data[i];
229     }
230
231     return {min_val, max_val};
232 }
233
234 // Scale pixel values
235 static Image<PixelType> scale(const Image<PixelType>& img, double factor)
236 {
237     Image<PixelType> result(img.get_width(), img.get_height());
238
239     for (size_t y = 0; y < img.get_height(); ++y) {
240         for (size_t x = 0; x < img.get_width(); ++x) {
241             double scaled = static_cast<double>(img.at(x, y)) * factor;
242             result.at(x, y) = static_cast<PixelType>(scaled);
243         }
244     }
245
246     return result;
247 }
248
249 // Threshold operation
250 static Image<PixelType> threshold(const Image<PixelType>& img, PixelType threshold_value) {
251     Image<PixelType> result(img.get_width(), img.get_height());
252
253     for (size_t y = 0; y < img.get_height(); ++y) {
254         for (size_t x = 0; x < img.get_width(); ++x) {
255             result.at(x, y) = (img.at(x, y) >= threshold_value) ?
256                 threshold_value : PixelType(0);
257         }
258     }
259
260     return result;
261 }
261 };
```

```
262 // =====
263 // 5. TYPE CONVERSION BETWEEN PIXEL TYPES
264 // =====
265
266 template<typename DestType, typename SrcType>
267 Image<DestType> convert_image(const Image<SrcType>& src) {
268     Image<DestType> dest(src.get_width(), src.get_height());
269
270     // Find source range for proper scaling
271     auto [min_val, max_val] = ImageProcessor<SrcType>::find_min_max(src);
272     double src_range = static_cast<double>(max_val) - static_cast<double>(
273         min_val);
274
275     // Determine destination range
276     double dest_min, dest_max;
277     if constexpr (std::is_floating_point_v<DestType>) {
278         dest_min = 0.0;
279         dest_max = 1.0;
280     } else if constexpr (std::is_same_v<DestType, uint8_t>) {
281         dest_min = 0.0;
282         dest_max = 255.0;
283     } else if constexpr (std::is_same_v<DestType, uint16_t>) {
284         dest_min = 0.0;
285         dest_max = 65535.0;
286     } else {
287         dest_min = 0.0;
288         dest_max = 1.0;
289     }
290
291     dest_range = dest_max - dest_min;
292
293     // Convert with proper scaling
294     for (size_t y = 0; y < src.get_height(); ++y) {
295         for (size_t x = 0; x < src.get_width(); ++x) {
296             double normalized = (static_cast<double>(src.at(x, y)) -
297                 static_cast<double>(min_val)) / src_range;
298             double scaled = normalized * dest_range + dest_min;
299             dest.at(x, y) = static_cast<DestType>(scaled);
300         }
301     }
302
303     return dest;
304 }
305 // =====
306 // 6. GENERIC CAMERA HANDLER (WORKS WITH ANY PIXEL TYPE)
307 // =====
308
309 template<typename PixelType>
310 class CameraHandler {
311 private:
312     std::unique_ptr<Camera<PixelType>> camera;
```

```
314 | public:
315 |     CameraHandler(std::unique_ptr<Camera<PixelType>> cam)
316 |         : camera(std::move(cam)) {}
317 |
318 |     void display_camera_info() {
319 |         std::cout << "\n  Camera: " << camera->get_name() << std::endl;
320 |         std::cout << "  Resolution: " << camera->get_width() << "x" << camera
321 |             ->get_height() << std::endl;
322 |         std::cout << "  Pixel type: " << typeid(PixelType).name() << std::endl
323 |             ;
324 |         std::cout << "  Bits per pixel: " << Camera<PixelType>::bits_per_pixel
325 |             () << std::endl;
326 |         std::cout << "  Floating point: " << (Camera<PixelType>::
327 |             is_floating_point() ? "Yes" : "No") << std::endl;
328 |
329 |         // Calculate memory per frame
330 |         size_t bytes = camera->get_width() * camera->get_height() * sizeof(
331 |             PixelType);
332 |         std::cout << "  Memory per frame: " << bytes << " bytes";
333 |         if (bytes >= 1024 * 1024) {
334 |             std::cout << "(" << bytes / (1024.0 * 1024.0) << " MB)";
335 |         } else if (bytes >= 1024) {
336 |             std::cout << "(" << bytes / 1024.0 << " KB)";
337 |         }
338 |         std::cout << std::endl;
339 |
340 |     void capture_and_process() {
341 |         std::cout << "\n  Capturing image..." << std::endl;
342 |         auto start = std::chrono::high_resolution_clock::now();
343 |
344 |         Image<PixelType> img = camera->capture();
345 |
346 |         auto end = std::chrono::high_resolution_clock::now();
347 |         auto duration = std::chrono::duration_cast<std::chrono::microseconds>(
348 |             end - start);
349 |         std::cout << "  Capture time: " << duration.count() << " us" << std::
350 |             endl;
351 |
352 |         // Process image
353 |         std::cout << "\n  Processing image..." << std::endl;
354 |         double mean = ImageProcessor<PixelType>::calculate_mean(img);
355 |         auto [min_val, max_val] = ImageProcessor<PixelType>::find_min_max(img)
356 |             ;
357 |
358 |         std::cout << "  Mean value: " << mean << std::endl;
359 |         std::cout << "  Min value: " << static_cast<double>(min_val) << std::
360 |             endl;
361 |         std::cout << "  Max value: " << static_cast<double>(max_val) << std::
362 |             endl;
363 |
364 |         // Sample some pixel values
365 |         std::cout << "\n  Sample pixels:" << std::endl;
366 |         std::cout << "    Top-left (0,0): " << static_cast<double>(img.at(0,
```

```
0)) << std::endl;
358     std::cout << "      Center (" << img.get_width()/2 << "," << img.
359             get_height()/2 << "): "
360                 << static_cast<double>(img.at(img.get_width()/2, img.
361                                         get_height()/2)) << std::endl;
360     std::cout << "      Bottom-right (" << img.get_width()-1 << "," << img.
361             get_height()-1 << "): "
361                 << static_cast<double>(img.at(img.get_width()-1, img.
362                                         get_height()-1)) << std::endl;
362 }
363 };
364
365 // =====
366 // 7. DEMONSTRATION FUNCTIONS
367 // =====
368
369 void demonstrate_8bit_camera() {
370     std::cout << "\n== 1. 8-BIT GRayscale Camera (uint8_t) ==" << std::endl;
371     std::cout << "Common in: Webcams, industrial cameras, surveillance" << std
372             ::endl;
373
374     CameraHandler<uint8_t> handler(
375         std::make_unique<Camera8bit>("Webcam HD", 640, 480)
376     );
377
378     handler.display_camera_info();
379     handler.capture_and_process();
380 }
381
382 void demonstrate_16bit_camera() {
383     std::cout << "\n== 2. 16-Bit Camera (uint16_t) ==" << std::endl;
384     std::cout << "Common in: Scientific imaging, medical X-ray, astronomy" <<
385             std::endl;
386
387     CameraHandler<uint16_t> handler(
388         std::make_unique<Camera16bit>("Scientific CCD", 1024, 1024)
389     );
390
391     handler.display_camera_info();
392     handler.capture_and_process();
393 }
394
395 void demonstrate_float_camera() {
396     std::cout << "\n== 3. FLOAT Camera (32-bit float) ==" << std::endl;
397     std::cout << "Common in: HDR imaging, computational photography, depth
398             sensors" << std::endl;
399
400     CameraHandler<float> handler(
401         std::make_unique<CameraFloat>("ToF Depth Camera", 320, 240)
402     );
403
404     handler.display_camera_info();
405     handler.capture_and_process();
406 }
```

```
404
405 void demonstrate_double_camera() {
406     std::cout << "\n==== 4. DOUBLE PRECISION CAMERA (64-bit double) ===" << std
407         ::endl;
408     std::cout << "Common in: Research, astronomical imaging, spectroscopy" <<
409         std::endl;
410
411     CameraHandler<double> handler(
412         std::make_unique<CameraDouble>("Telescope CCD", 512, 512)
413     );
414
415     handler.display_camera_info();
416     handler.capture_and_process();
417 }
418
419
420 void demonstrate_type_conversion() {
421     std::cout << "\n==== 5. IMAGE TYPE CONVERSION ===" << std::endl;
422
423     // Capture 8-bit image
424     Camera8bit cam8("Source Camera", 320, 240);
425     Image<uint8_t> img8 = cam8.capture();
426
427     std::cout << "\nOriginal 8-bit image:" << std::endl;
428     std::cout << "    Size: " << img8.memory_bytes() << " bytes" << std::endl;
429     auto [min8, max8] = ImageProcessor<uint8_t>::find_min_max(img8);
430     std::cout << "    Range: " << (int)min8 << " to " << (int)max8 << std::endl;
431
432     // Convert to 16-bit
433     std::cout << "\nConverting to 16-bit..." << std::endl;
434     Image<uint16_t> img16 = convert_image<uint16_t>(img8);
435     std::cout << "    Size: " << img16.memory_bytes() << " bytes" << std::endl;
436     auto [min16, max16] = ImageProcessor<uint16_t>::find_min_max(img16);
437     std::cout << "    Range: " << min16 << " to " << max16 << std::endl;
438
439     // Convert to float
440     std::cout << "\nConverting to float..." << std::endl;
441     Image<float> imgf = convert_image<float>(img8);
442     std::cout << "    Size: " << imgf.memory_bytes() << " bytes" << std::endl;
443     auto [minf, maxf] = ImageProcessor<float>::find_min_max(imgf);
444     std::cout << "    Range: " << minf << " to " << maxf << std::endl;
445
446     // Convert to double
447     std::cout << "\nConverting to double..." << std::endl;
448     Image<double> imgd = convert_image<double>(img8);
449     std::cout << "    Size: " << imgd.memory_bytes() << " bytes" << std::endl;
450     auto [mind, maxd] = ImageProcessor<double>::find_min_max(imgd);
451     std::cout << "    Range: " << mind << " to " << maxd << std::endl;
452 }
453
454 void demonstrate_processing_algorithms() {
455     std::cout << "\n==== 6. IMAGE PROCESSING ALGORITHMS ===" << std::endl;
456
457     Camera8bit cam("Processing Camera", 100, 100);
458     Image<uint8_t> img = cam.capture();
```

```
456     std::cout << "\nOriginal image statistics:" << std::endl;
457     double mean = ImageProcessor<uint8_t>::calculate_mean(img);
458     auto [min_val, max_val] = ImageProcessor<uint8_t>::find_min_max(img);
459     std::cout << "    Mean: " << mean << std::endl;
460     std::cout << "    Min: " << (int)min_val << ", Max: " << (int)max_val << std
461         ::endl;
462
463     // Scale by 2x
464     std::cout << "\nScaling by 2x:" << std::endl;
465     Image<uint8_t> scaled = ImageProcessor<uint8_t>::scale(img, 2.0);
466     double mean_scaled = ImageProcessor<uint8_t>::calculate_mean(scaled);
467     std::cout << "    Mean after scaling: " << mean_scaled << std::endl;
468
469     // Threshold
470     std::cout << "\nThresholding at 128:" << std::endl;
471     Image<uint8_t> thresholded = ImageProcessor<uint8_t>::threshold(img, 128);
472     size_t above_threshold = 0;
473     for (size_t i = 0; i < thresholded.get_size(); ++i) {
474         if (thresholded.data()[i] > 0) ++above_threshold;
475     }
476     std::cout << "    Pixels above threshold: " << above_threshold
477             << " (" << (100.0 * above_threshold / thresholded.get_size()) <<
478                 "%)" << std::endl;
479 }
480 // =====
481 // MAIN FUNCTION
482 // =====
483
484 int main() {
485     std::cout << "\n
486         =====
487         =====
488         =====
489         demonstrate_8bit_camera();
490         demonstrate_16bit_camera();
491         demonstrate_float_camera();
492         demonstrate_double_camera();
493         demonstrate_type_conversion();
494         demonstrate_processing_algorithms();
495
496         std::cout << "\n
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```
499
500     std::cout << "\n ADVANTAGES OF TEMPLATES:" << std::endl;
501     std::cout << "\n1. TYPE SAFETY" << std::endl;
502     std::cout << " • Compile-time type checking" << std::endl;
503     std::cout << " • No runtime casting needed" << std::endl;
504     std::cout << " • Prevents mixing incompatible pixel types" << std::endl;
505
506     std::cout << "\n2. ZERO OVERHEAD" << std::endl;
507     std::cout << " • No virtual function calls" << std::endl;
508     std::cout << " • All types resolved at compile time" << std::endl;
509     std::cout << " • Fully optimizable by compiler" << std::endl;
510
511     std::cout << "\n3. CODE REUSABILITY" << std::endl;
512     std::cout << " • Write processing algorithms once" << std::endl;
513     std::cout << " • Works with uint8_t, uint16_t, float, double" << std::endl;
514     std::cout << " • Easy to add new pixel types" << std::endl;
515
516     std::cout << "\n4. COMPILE-TIME INFORMATION" << std::endl;
517     std::cout << " • sizeof(PixelType) known at compile time" << std::endl;
518     std::cout << " • Type traits (is_floating_point, etc.)" << std::endl;
519     std::cout << " • if constexpr for type-specific code" << std::endl;
520
521     std::cout << "\n MEMORY COMPARISON (640x480 image):" << std::endl;
522     size_t pixels = 640 * 480;
523     std::cout << "    uint8_t: " << pixels * sizeof(uint8_t) / 1024 << " KB" <<
524         std::endl;
525     std::cout << "    uint16_t: " << pixels * sizeof(uint16_t) / 1024 << " KB" <<
526         std::endl;
527     std::cout << "    float: " << pixels * sizeof(float) / 1024 << " KB" <<
528         std::endl;
529     std::cout << "    double: " << pixels * sizeof(double) / 1024 << " KB" <<
530         std::endl;
531
532     std::cout << "\n REAL-WORLD APPLICATIONS:" << std::endl;
533     std::cout << "\n    uint8_t (8-bit):" << std::endl;
534     std::cout << " • Consumer webcams" << std::endl;
535     std::cout << " • Surveillance cameras" << std::endl;
536     std::cout << " • Industrial inspection" << std::endl;
537     std::cout << " • Video streaming" << std::endl;
538
539     std::cout << "\n    uint16_t (16-bit):" << std::endl;
540     std::cout << " • Medical X-ray imaging" << std::endl;
541     std::cout << " • Scientific CCD cameras" << std::endl;
542     std::cout << " • Astronomy (star imaging)" << std::endl;
543     std::cout << " • High dynamic range photography" << std::endl;
544
545     std::cout << "\n    float (32-bit):" << std::endl;
546     std::cout << " • Time-of-Flight (ToF) depth sensors" << std::endl;
547     std::cout << " • HDR image processing" << std::endl;
548     std::cout << " • Computational photography" << std::endl;
549     std::cout << " • Normalized image data" << std::endl;
550
551     std::cout << "\n    double (64-bit):" << std::endl;
```

```
548     std::cout << " • Radio telescope data" << std::endl;
549     std::cout << " • Spectroscopy" << std::endl;
550     std::cout << " • High-precision research" << std::endl;
551     std::cout << " • Scientific analysis" << std::endl;
552
553     std::cout << "\n TEMPLATE TECHNIQUES DEMONSTRATED:" << std::endl;
554     std::cout << " • Class templates: Image<T>, Camera<T>" << std::endl;
555     std::cout << " • Function templates: convert_image<DestType, SrcType>" <<
556         std::endl;
556     std::cout << " • Type traits: std::is_floating_point_v<T>" << std::endl;
557     std::cout << " • if constexpr: Compile-time conditional code" << std::
558         endl;
558     std::cout << " • Template specialization: Type-specific behavior" << std
559         ::endl;
559     std::cout << " • constexpr functions: Compile-time computation" << std::
560         endl;
560
561     std::cout << "\n"
562         ======\n" <<
563         std::endl;
564
564 }
```

71 Source Code: TemplatizedCameraModules.cpp

File: src/TemplatedCameraModules.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // C++20 MODULES DEMONSTRATION: IMPORT AND USE CAMERA MODULE
3 // =====
4 // This file demonstrates:
5 // 1. Importing C++20 modules with "import"
6 // 2. Using exported templates, classes, and concepts
7 // 3. C++20 features: concepts, requires clauses, [[nodiscard]]
8 // =====
9
10 #include <iostream>
11 #include <iomanip>
12 #include <chrono>
13
14 // C++20 MODULE IMPORT
15 import camera;
16
17 // =====
18 // DEMONSTRATION FUNCTIONS
19 // =====
20
21 void demonstrate_concepts() {
22     std::cout << "\n==== C++20 CONCEPTS DEMONSTRATION ===" << std::endl;
23
24     std::cout << "\nPixelType concept checks:" << std::endl;
25     std::cout << "    uint8_t is PixelType: " << PixelType<uint8_t> << std::endl
26         ;
27     std::cout << "    uint16_t is PixelType: " << PixelType<uint16_t> << std::endl
28         ;
29     std::cout << "    float is PixelType: " << PixelType<float> << std::endl;
30     std::cout << "    double is PixelType: " << PixelType<double> << std::endl;
31     std::cout << "    int is PixelType: " << PixelType<int> << " (not in allowed
32         list)" << std::endl;
33
34     std::cout << "\nIntegerPixel concept checks:" << std::endl;
35     std::cout << "    uint8_t is IntegerPixel: " << IntegerPixel<uint8_t> << std::endl
36         ;
37     std::cout << "    float is IntegerPixel: " << IntegerPixel<float> << std::endl
38         ;
39
40     std::cout << "\nFloatingPixel concept checks:" << std::endl;
41     std::cout << "    float is FloatingPixel: " << FloatingPixel<float> << std::endl
42         ;
43     std::cout << "    uint8_t is FloatingPixel: " << FloatingPixel<uint8_t> <<
44         std::endl;
45 }
46
47 template<PixelType T>
48 void display_camera_info(const Camera<T>& camera) {
49     std::cout << "\n    Camera: " << camera.get_name() << std::endl;
```

```
43     std::cout << " Resolution: " << camera.get_width() << "x" << camera.
44         get_height() << std::endl;
45     std::cout << " Bits per pixel: " << Camera<T>::bits_per_pixel() << std::
46         endl;
47     std::cout << " Floating point: " << (Camera<T>::is_floating_point() ? "
48         Yes" : "No") << std::endl;
49
50     size_t bytes = camera.get_width() * camera.get_height() * sizeof(T);
51     std::cout << " Memory per frame: " << bytes << " bytes";
52     if (bytes >= 1024 * 1024) {
53         std::cout << "(" << std::fixed << std::setprecision(2)
54             << bytes / (1024.0 * 1024.0) << " MB)";
55     } else if (bytes >= 1024) {
56         std::cout << "(" << std::fixed << std::setprecision(2)
57             << bytes / 1024.0 << " KB)";
58     }
59     std::cout << std::endl;
60 }
61
62 template<PixelType T>
63 void demonstrate_camera_capture(CameraHandler<T>& handler) {
64     const Camera<T>* cam = handler.get_camera();
65
66     std::cout << "\n Capturing image..." << std::endl;
67     auto start = std::chrono::high_resolution_clock::now();
68
69     Image<T> img = handler.capture();
70
71     auto end = std::chrono::high_resolution_clock::now();
72     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(end
73         - start);
74     std::cout << " Capture time: " << duration.count() << " µs" << std::endl;
75
76     std::cout << "\n Processing image..." << std::endl;
77     double mean = ImageProcessor<T>::calculate_mean(img);
78     auto [min_val, max_val] = ImageProcessor<T>::find_min_max(img);
79
80     std::cout << " Mean value: " << mean << std::endl;
81     std::cout << " Min value: " << static_cast<double>(min_val) << std::endl;
82     std::cout << " Max value: " << static_cast<double>(max_val) << std::endl;
83
84     std::cout << "\n Sample pixels:" << std::endl;
85     std::cout << " Top-left (0,0): " << static_cast<double>(img.at(0, 0))
86         << std::endl;
87     std::cout << " Center (" << img.get_width()/2 << "," << img.get_height()
88         ()/2 << "): "
89         << static_cast<double>(img.at(img.get_width()/2, img.get_height()
90             ()/2)) << std::endl;
91 }
92
93 void demonstrate_8bit_camera() {
94     std::cout << "\n==== 1. 8-BIT CAMERA (uint8_t) ===" << std::endl;
95
96     CameraHandler<uint8_t> handler(
```

```
90     std::make_unique<Camera8bit>("Webcam HD", 640, 480)
91 );
92
93     display_camera_info(*handler.get_camera());
94     demonstrate_camera_capture(handler);
95 }
96
97 void demonstrate_16bit_camera() {
98     std::cout << "\n== 2. 16-BIT CAMERA (uint16_t) ==" << std::endl;
99
100    CameraHandler<uint16_t> handler(
101        std::make_unique<Camera16bit>("Scientific CCD", 1024, 1024)
102    );
103
104    display_camera_info(*handler.get_camera());
105    demonstrate_camera_capture(handler);
106 }
107
108 void demonstrate_float_camera() {
109     std::cout << "\n== 3. FLOAT CAMERA (32-bit) ==" << std::endl;
110
111    CameraHandler<float> handler(
112        std::make_unique<CameraFloat>("ToF Depth Camera", 320, 240)
113    );
114
115    display_camera_info(*handler.get_camera());
116    demonstrate_camera_capture(handler);
117 }
118
119 void demonstrate_double_camera() {
120     std::cout << "\n== 4. DOUBLE CAMERA (64-bit) ==" << std::endl;
121
122    CameraHandler<double> handler(
123        std::make_unique<CameraDouble>("Telescope CCD", 512, 512)
124    );
125
126    display_camera_info(*handler.get_camera());
127    demonstrate_camera_capture(handler);
128 }
129
130 void demonstrate_type_conversion() {
131     std::cout << "\n== 5. IMAGE TYPE CONVERSION ==" << std::endl;
132
133     Camera8bit cam8("Source Camera", 320, 240);
134     Image<uint8_t> img8 = cam8.capture();
135
136     std::cout << "\nOriginal 8-bit image:" << std::endl;
137     std::cout << "  Size: " << img8.memory_bytes() << " bytes" << std::endl;
138     auto [min8, max8] = ImageProcessor<uint8_t>::find_min_max(img8);
139     std::cout << "  Range: " << (int)min8 << " to " << (int)max8 << std::endl;
140
141     std::cout << "\nConverting to 16-bit..." << std::endl;
142     Image<uint16_t> img16 = convert_image<uint16_t>(img8);
143     std::cout << "  Size: " << img16.memory_bytes() << " bytes" << std::endl;
```

```
144     auto [min16, max16] = ImageProcessor<uint16_t>::find_min_max(img16);
145     std::cout << "    Range: " << min16 << " to " << max16 << std::endl;
146
147     std::cout << "\nConverting to float..." << std::endl;
148     Image<float> imgf = convert_image<float>(img8);
149     std::cout << "    Size: " << imgf.memory_bytes() << " bytes" << std::endl;
150     auto [minf, maxf] = ImageProcessor<float>::find_min_max(imgf);
151     std::cout << "    Range: " << minf << " to " << maxf << std::endl;
152
153     std::cout << "\nConverting to double..." << std::endl;
154     Image<double> imgd = convert_image<double>(img8);
155     std::cout << "    Size: " << imgd.memory_bytes() << " bytes" << std::endl;
156     auto [mind, maxd] = ImageProcessor<double>::find_min_max(imgd);
157     std::cout << "    Range: " << mind << " to " << maxd << std::endl;
158 }
159
160 void demonstrate_concept_constrained_operations() {
161     std::cout << "\n==== 6. CONCEPT-CONSTRAINED OPERATIONS ===" << std::endl;
162
163     // Integer pixel operations
164     std::cout << "\nInteger pixel operations (uint8_t):" << std::endl;
165     Camera8bit cam8("Integer Camera", 100, 100);
166     Image<uint8_t> img8 = cam8.capture();
167
168     std::cout << "    Original mean: " << ImageProcessor<uint8_t>::
169     calculate_mean(img8) << std::endl;
170
171     // Threshold only works with IntegerPixel concept
172     Image<uint8_t> thresholded = ImageProcessor<uint8_t>::threshold(img8, 128)
173     ;
174     size_t above = 0;
175     for (size_t i = 0; i < thresholded.get_size(); ++i) {
176         if (thresholded.data()[i] > 0) ++above;
177     }
178     std::cout << "    Pixels above threshold: " << above
179     << " (" << (100.0 * above / thresholded.get_size()) << "%)" <<
180     std::endl;
181
182     // Floating point operations
183     std::cout << "\nFloating pixel operations (float):" << std::endl;
184     CameraFloat camf("Float Camera", 100, 100);
185     Image<float> imgf = camf.capture();
186
187     std::cout << "    Original mean: " << ImageProcessor<float>::calculate_mean(
188     imgf) << std::endl;
189
190     // Normalize only works with FloatingPixel concept
191     Image<float> normalized = ImageProcessor<float>::normalize(imgf);
192     std::cout << "    Normalized mean: " << ImageProcessor<float>::
193     calculate_mean(normalized) << std::endl;
194     auto [minf, maxf] = ImageProcessor<float>::find_min_max(normalized);
195     std::cout << "    Normalized range: " << minf << " to " << maxf << std::endl;
196     ;
```

```
192 // Note: The following would NOT compile (concept constraint):
193 // Image<float> bad = ImageProcessor<float>::threshold(imgf, 0.5f); // 
194 // ERROR: requires IntegerPixel
195 // Image<uint8_t> bad2 = ImageProcessor<uint8_t>::normalize(img8); // 
196 // ERROR: requires FloatingPixel
197 }
198
199 // =====
200 // MAIN FUNCTION
201 // =====
202
203 int main() {
204     std::cout << "\n"
205         ===== " <<
206         std::endl;
207     std::cout << "    C++20 MODULES: TEMPLATED CAMERA INTERFACE" << std::endl;
208     std::cout << "
209         ===== " <<
210         std::endl;
211     demonstrate_concepts();
212     demonstrate_8bit_camera();
213     demonstrate_16bit_camera();
214     demonstrate_float_camera();
215     demonstrate_double_camera();
216     demonstrate_type_conversion();
217     demonstrate_concept_constrained_operations();

218     std::cout << "\n"
219         ===== " <<
220         std::endl;
221     std::cout << "    C++20 FEATURES DEMONSTRATED" << std::endl;
222     std::cout << "
223         ===== " <<
224         std::endl;

225     std::cout << "\n MODULES (import/export):" << std::endl;
226     std::cout << " •    export module camera - Module interface declaration" <<
227         std::endl;
228     std::cout << " •    import camera - Import module in main program" << std::
229         endl;
230     std::cout << " •    Exported classes: Image<T>, Camera<T>, ImageProcessor<T
231         >" << std::endl;
232     std::cout << " •    Exported functions: convert_image<T1, T2>()" << std::
233         endl;
234     std::cout << " •    Exported concepts: PixelType, IntegerPixel,
235         FloatingPixel" << std::endl;

236     std::cout << "\n CONCEPTS:" << std::endl;
237     std::cout << " •    concept PixelType - Constrain allowed pixel types" <<
238         std::endl;
```

```
229     std::cout << " • concept IntegerPixel - Only integer pixel types" << std::endl;
230     std::cout << " • concept FloatingPixel - Only floating-point pixel types" << std::endl;
231     std::cout << " • requires clauses on functions (threshold, normalize)" << std::endl;
232     std::cout << " • Compile-time type checking prevents invalid operations" << std::endl;
233
234     std::cout << "\n OTHER C++20 FEATURES:" << std::endl;
235     std::cout << " • [[nodiscard]] - Warn if return value ignored" << std::endl;
236     std::cout << " • Three-way comparison (operator<=) - Auto-generated comparisons" << std::endl;
237     std::cout << " • noexcept specifications - Exception safety guarantees" << std::endl;
238
239     std::cout << "\n MODULE BENEFITS:" << std::endl;
240     std::cout << " • Faster compilation - No header parsing overhead" << std::endl;
241     std::cout << " • Better encapsulation - Only exported entities visible" << std::endl;
242     std::cout << " • No include guards needed - Modules included once automatically" << std::endl;
243     std::cout << " • Order independent - No macro contamination" << std::endl;
244     std::cout << " • Cleaner code - Explicit export declarations" << std::endl;
245
246     std::cout << "\n COMPILATION NOTES:" << std::endl;
247     std::cout << "   GCC 11+:" << std::endl;
248     std::cout << "     g++ -std=c++20 -fmodules-ts -xc++-system-header iostream" << std::endl;
249     std::cout << "     g++ -std=c++20 -fmodules-ts -c CameraModule.cppm" << std::endl;
250     std::cout << "     g++ -std=c++20 -fmodules-ts TemplatedCameraModules.cpp CameraModule.o" << std::endl;
251
252     std::cout << "\n   MSVC 2022+:" << std::endl;
253     std::cout << "     cl /std:c++20 /experimental:module /c CameraModule.cppm" << std::endl;
254     std::cout << "     cl /std:c++20 /experimental:module TemplatedCameraModules.cpp CameraModule.obj" << std::endl;
255
256     std::cout << "\n   Clang 16+:" << std::endl;
257     std::cout << "     clang++ -std=c++20 -fmodules -c CameraModule.cppm" << std::endl;
258     std::cout << "     clang++ -std=c++20 -fmodules TemplatedCameraModules.cpp CameraModule.o" << std::endl;
259
260     std::cout << "\n NOTE: C++20 modules support varies by compiler!" << std::endl;
261     std::cout << " • GCC: Experimental support with -fmodules-ts" << std::endl;
```

```
262     std::cout << " • MSVC: Best support with /std:c++20 and /experimental:  
263         module" << std::endl;  
264     std::cout << " • Clang: Good support in recent versions (16+)" << std::  
265         endl;  
266  
267     std::cout << "\n  
268         ======\n" << std::endl;  
269  
270     return 0;  
271 }
```

72 Source Code: ThreadPoolExamples.cpp

File: src/ThreadPoolExamples.cpp

Repository: [View on GitHub](#)

```
1 // ThreadPoolExamples.cpp
2 // Comprehensive educational examples of thread pool implementations in Modern
3 // C++
4 // From basic to advanced patterns including work stealing, priority queues,
5 // and more
6
7 #include <iostream>
8 #include <thread>
9 #include <vector>
10 #include <queue>
11 #include <functional>
12 #include <mutex>
13 #include <condition_variable>
14 #include <future>
15 #include <atomic>
16 #include <chrono>
17 #include <memory>
18 #include <type_traits>
19 #include <deque>
20 #include <optional>
21 #include <iomanip>
22
23 // =====
24 // SECTION 1: Basic Thread Pool (Simplest Implementation)
25 // =====
26
27 class BasicThreadPool {
28 private:
29     std::vector<std::thread> workers_;
30     std::queue<std::function<void()>> tasks_;
31     std::mutex queue_mutex_;
32     std::condition_variable condition_;
33     bool stop_;
34
35 public:
36     explicit BasicThreadPool(size_t num_threads) : stop_(false) {
37         std::cout << " Creating thread pool with " << num_threads << "
38             workers\n";
39
40         for (size_t i = 0; i < num_threads; ++i) {
41             workers_.emplace_back([this, i]() {
42                 std::cout << "    Worker " << i << " started (thread "
43                     << std::this_thread::get_id() << ")\n";
44             });
45         }
46     }
47
48     void add_task(std::function<void()> task) {
49         std::unique_lock<std::mutex> lock(queue_mutex_);
50         tasks_.push(task);
51         condition_.notify_one();
52     }
53
54     void stop() {
55         stop_ = true;
56         condition_.notify_all();
57     }
58
59     void join() {
60         for (auto& worker : workers_) {
61             if (worker.joinable())
62                 worker.join();
63         }
64     }
65 }
```

```
43     while (true) {
44         std::function<void()> task;
45
46         {
47             std::unique_lock<std::mutex> lock(queue_mutex_);
48
49             // Wait until there's work or we're stopping
50             condition_.wait(lock, [this]() {
51                 return stop_ || !tasks_.empty();
52             });
53
54             if (stop_ && tasks_.empty()) {
55                 return;
56             }
57
58             task = std::move(tasks_.front());
59             tasks_.pop();
60         }
61
62         task(); // Execute the task
63     }
64 }
65 }
66 }
67 }
68
69 // Submit a task (no return value)
70 void submit(std::function<void()> task) {
71 {
72     std::lock_guard<std::mutex> lock(queue_mutex_);
73
74     if (stop_) {
75         throw std::runtime_error("Cannot submit task to stopped thread
76             pool");
77     }
78
79     tasks_.push(std::move(task));
80     condition_.notify_one();
81 }
82
83 ~BasicThreadPool() {
84 {
85     std::lock_guard<std::mutex> lock(queue_mutex_);
86     stop_ = true;
87 }
88
89     condition_.notify_all();
90
91     for (std::thread& worker : workers_) {
92         if (worker.joinable()) {
93             worker.join();
94         }
95     }
96 }
```

```
96         std::cout << "    Thread pool destroyed\n";
97     }
98 };
99
100 void demonstrate_basic_thread_pool() {
101     std::cout << "\n" << std::string(70, '=') << "\n";
102     std::cout << "==== 1. Basic Thread Pool ===\n";
103     std::cout << std::string(70, '=') << "\n\n";
104
105     std::cout << "Concept: Fixed number of worker threads processing tasks
106         from a queue\n\n";
107
108     BasicThreadPool pool(3);
109
110     std::cout << "\nSubmitting 6 tasks...\n\n";
111
112     for (int i = 1; i <= 6; ++i) {
113         pool.submit([i]() {
114             std::cout << "      Task " << i << " executing on thread "
115                         << std::this_thread::get_id() << "\n";
116             std::this_thread::sleep_for(200ms);
117             std::cout << "      Task " << i << " completed\n";
118         });
119     }
120
121     std::this_thread::sleep_for(2s); // Wait for tasks to complete
122
123     std::cout << "\n All tasks processed by 3 workers\n";
124     std::cout << " Tasks automatically distributed across available threads\n
125         ";
126 }
127
128 // SECTION 2: Thread Pool with Futures (Return Values)
129 // =====
130
131 class ThreadPoolWithFutures {
132 private:
133     std::vector<std::thread> workers_;
134     std::queue<std::function<void()>> tasks_;
135     std::mutex queue_mutex_;
136     std::condition_variable condition_;
137     bool stop_;
138
139 public:
140     explicit ThreadPoolWithFutures(size_t num_threads) : stop_(false) {
141         for (size_t i = 0; i < num_threads; ++i) {
142             workers_.emplace_back([this]() {
143                 while (true) {
```

```
144         std::function<void()> task;
145
146     {
147         std::unique_lock<std::mutex> lock(queue_mutex_);
148         condition_.wait(lock, [this]() {
149             return stop_ || !tasks_.empty();
150         });
151
152         if (stop_ && tasks_.empty()) {
153             return;
154         }
155
156         task = std::move(tasks_.front());
157         tasks_.pop();
158     }
159
160     task();
161 }
162 }
163 }
164 }
165
166 // Submit task and get future for result
167 template<typename F, typename... Args>
168 auto submit(F&& f, Args&&... args)
169     -> std::future<typename std::invoke_result_t<F, Args...>> {
170
171     using return_type = typename std::invoke_result_t<F, Args...>;
172
173     // Create a packaged_task
174     auto task = std::make_shared<std::packaged_task<return_type()>>(
175         std::bind(std::forward<F>(f), std::forward<Args>(args)...));
176
177
178     std::future<return_type> result = task->get_future();
179
180     {
181         std::lock_guard<std::mutex> lock(queue_mutex_);
182
183         if (stop_) {
184             throw std::runtime_error("Cannot submit to stopped pool");
185         }
186
187         tasks_.emplace([task]() { (*task)(); });
188     }
189
190     condition_.notify_one();
191     return result;
192 }
193
194 ~ThreadPoolWithFutures() {
195     std::lock_guard<std::mutex> lock(queue_mutex_);
196     stop_ = true;
```

```
198     }
199
200     condition_.notify_all();
201
202     for (std::thread& worker : workers_) {
203         if (worker.joinable()) {
204             worker.join();
205         }
206     }
207 }
208 };
209
210 void demonstrate_thread_pool_with_futures() {
211     std::cout << "\n" << std::string(70, '=') << "\n";
212     std::cout << "==== 2. Thread Pool with Futures (Return Values) ====\n";
213     std::cout << std::string(70, '=') << "\n\n";
214
215     std::cout << "Benefit: Can return results from tasks using std::future\n\n";
216
217     ThreadPoolWithFutures pool(4);
218
219     std::vector<std::future<int>> results;
220
221     std::cout << "Submitting computation tasks...\n";
222
223     for (int i = 1; i <= 8; ++i) {
224         results.push_back(pool.submit([i]() {
225             std::cout << " Task " << i << ": Computing " << i << "\n";
226             std::this_thread::sleep_for(100ms);
227             return i * i;
228         }));
229     }
230
231     std::cout << "\nCollecting results...\n";
232
233     for (size_t i = 0; i < results.size(); ++i) {
234         int result = results[i].get(); // Blocks until result is ready
235         std::cout << " Result " << (i + 1) << ":" << result << "\n";
236     }
237
238     std::cout << "\n All tasks returned results via std::future\n";
239 }
240
241 /**
242 =====
243 // SECTION 3: Thread Pool with Priority Queue
244 // =====
245
246 enum class TaskPriority {
247     LOW = 0,
```

```
247     NORMAL = 1,
248     HIGH = 2,
249     CRITICAL = 3
250 };
251
252 struct PrioritizedTask {
253     std::function<void()> func;
254     TaskPriority priority;
255     int sequence; // For FIFO within same priority
256
257     bool operator<(const PrioritizedTask& other) const {
258         if (priority != other.priority) {
259             return priority < other.priority; // Higher priority first
260         }
261         return sequence > other.sequence; // FIFO for same priority
262     }
263 };
264
265 class PriorityThreadPool {
266 private:
267     std::vector<std::thread> workers_;
268     std::priority_queue<PrioritizedTask> tasks_;
269     std::mutex queue_mutex_;
270     std::condition_variable condition_;
271     bool stop_;
272     std::atomic<int> sequence_counter_;
273
274 public:
275     explicit PriorityThreadPool(size_t num_threads)
276         : stop_(false), sequence_counter_(0) {
277
278         for (size_t i = 0; i < num_threads; ++i) {
279             workers_.emplace_back([this]() {
280                 while (true) {
281                     PrioritizedTask task{}, TaskPriority::NORMAL, 0);
282
283                     {
284                         std::unique_lock<std::mutex> lock(queue_mutex_);
285                         condition_.wait(lock, [this]() {
286                             return stop_ || !tasks_.empty();
287                         });
288
289                         if (stop_ && tasks_.empty()) {
290                             return;
291                         }
292
293                         task = tasks_.top();
294                         tasks_.pop();
295                     }
296
297                     task.func();
298                 }
299             });
300         }
301     }
```

```
301     }
302
303     void submit(std::function<void()> task, TaskPriority priority =
304         TaskPriority::NORMAL) {
305     {
306         std::lock_guard<std::mutex> lock(queue_mutex_);
307
308         if (stop_) {
309             throw std::runtime_error("Cannot submit to stopped pool");
310         }
311
312         tasks_.push({std::move(task), priority, sequence_counter_++});
313     }
314
315     condition_.notify_one();
316 }
317
318 ~PriorityThreadPool() {
319 {
320     std::lock_guard<std::mutex> lock(queue_mutex_);
321     stop_ = true;
322 }
323
324     condition_.notify_all();
325
326     for (std::thread& worker : workers_) {
327         if (worker.joinable()) {
328             worker.join();
329         }
330     }
331 }
332
333 void demonstrate_priority_thread_pool() {
334     std::cout << "\n" << std::string(70, '=') << "\n";
335     std::cout << "==== 3. Priority Thread Pool ===\n";
336     std::cout << std::string(70, '=') << "\n\n";
337
338     std::cout << "Concept: Higher priority tasks execute before lower priority
339     ones\n\n";
340
341     PriorityThreadPool pool(2);
342
343     std::cout << "Submitting tasks with different priorities...\n\n";
344
345     // Submit in mixed order
346     pool.submit([]() {
347         std::cout << " [NORMAL] Task 1\n";
348         std::this_thread::sleep_for(100ms);
349     }, TaskPriority::NORMAL);
350
351     pool.submit([]() {
352         std::cout << " [CRITICAL] Urgent task!\n";
353         std::this_thread::sleep_for(100ms);
354 }
```

```
353 }, TaskPriority::CRITICAL);  
354  
355 pool.submit([]() {  
356     std::cout << " [LOW] Background task\n";  
357     std::this_thread::sleep_for(100ms);  
358 }, TaskPriority::LOW);  
359  
360 pool.submit([]() {  
361     std::cout << " [HIGH] Important task\n";  
362     std::this_thread::sleep_for(100ms);  
363 }, TaskPriority::HIGH);  
364  
365 pool.submit([]() {  
366     std::cout << " [NORMAL] Task 2\n";  
367     std::this_thread::sleep_for(100ms);  
368 }, TaskPriority::NORMAL);  
369  
370 std::this_thread::sleep_for(1s);  
371  
372 std::cout << "\n Tasks executed by priority: CRITICAL → HIGH → NORMAL →  
373     LOW\n";  
374 }  
375 //  
376 ======  
377 // SECTION 4: Work-Stealing Thread Pool (Advanced)  
378 //  
379 ======  
  
380 class WorkStealingThreadPool {  
381 private:  
382     struct WorkerThread {  
383         std::deque<std::function<void()>> local_queue;  
384         std::mutex queue_mutex;  
385         std::thread thread;  
386     };  
387  
388     std::vector<std::unique_ptr<WorkerThread>> workers_;  
389     std::atomic<bool> stop_;  
390     std::atomic<size_t> next_worker_; // Round-robin submission  
391  
392 public:  
393     explicit WorkStealingThreadPool(size_t num_threads)  
394         : stop_(false), next_worker_(0) {  
395         std::cout << " Creating work-stealing pool with " << num_threads << "  
396             workers\n";  
397         for (size_t i = 0; i < num_threads; ++i) {  
398             auto worker = std::make_unique<WorkerThread>();  
399             worker->thread = std::thread([this, i, &w = *worker]() {  
400                 w->run();  
401             });  
402         }  
403     }  
404 }
```

```

401         std::cout << "      Worker " << i << " started\n";
402
403     while (!stop_) {
404         std::function<void()> task;
405
406         // Try to get task from own queue first
407         {
408             std::lock_guard<std::mutex> lock(w.queue_mutex);
409             if (!w.local_queue.empty()) {
410                 task = std::move(w.local_queue.front());
411                 w.local_queue.pop_front();
412             }
413         }
414
415         // If no local task, try to steal from other workers
416         if (!task) {
417             task = try_steal_work(i);
418         }
419
420         if (task) {
421             task();
422         } else {
423             std::this_thread::sleep_for(10ms); // Prevent busy-
424                                         waiting
425         }
426     });
427
428     workers_.push_back(std::move(worker));
429 }
430
431 void submit(std::function<void()> task) {
432     // Round-robin distribution
433     size_t worker_idx = next_worker_++ % workers_.size();
434
435     std::lock_guard<std::mutex> lock(workers_[worker_idx]->queue_mutex);
436     workers_[worker_idx]->local_queue.push_back(std::move(task));
437 }
438
439 ~WorkStealingThreadPool() {
440     stop_ = true;
441
442     for (auto& worker : workers_) {
443         if (worker->thread.joinable()) {
444             worker->thread.join();
445         }
446     }
447
448     std::cout << "  Work-stealing pool destroyed\n";
449 }
450
451 private:
452     std::function<void()> try_steal_work(size_t my_index) {

```

```

454     // Try to steal from other workers
455     for (size_t i = 0; i < workers_.size(); ++i) {
456         if (i == my_index) continue;
457
458         std::lock_guard<std::mutex> lock(workers_[i]->queue_mutex);
459         if (!workers_[i]->local_queue.empty()) {
460             // Steal from the back (different from local FIFO)
461             auto task = std::move(workers_[i]->local_queue.back());
462             workers_[i]->local_queue.pop_back();
463             return task;
464         }
465     }
466
467     return nullptr;
468 }
469 };
470
471 void demonstrate_work_stealing_pool() {
472     std::cout << "\n" << std::string(70, '=') << "\n";
473     std::cout << "==== 4. Work-Stealing Thread Pool ===\n";
474     std::cout << std::string(70, '=') << "\n\n";
475
476     std::cout << "Concept: Idle workers steal tasks from busy workers' queues\n";
477     std::cout << "Benefit: Better load balancing for uneven task durations\n\n";
478
479     WorkStealingThreadPool pool(4);
480
481     std::cout << "Submitting 12 tasks with varying durations...\n\n";
482
483     for (int i = 1; i <= 12; ++i) {
484         pool.submit([i]() {
485             int duration = (i % 3 + 1) * 100; // 100ms, 200ms, or 300ms
486             std::cout << " Task " << i << " (duration: " << duration
487                 << "ms) on thread " << std::this_thread::get_id() << "\n"
488                 ";
489             std::this_thread::sleep_for(std::chrono::milliseconds(duration));
490         });
491
492         std::this_thread::sleep_for(2s);
493
494         std::cout << "\n Work stealing enabled better load distribution\n";
495         std::cout << " Idle workers helped busy workers finish faster\n";
496     }
497
498 // =====
499 // SECTION 5: Dynamic Thread Pool (Auto-scaling)
500 // =====

```

```
501
502 class DynamicThreadPool {
503 private:
504     std::vector<std::thread> workers_;
505     std::queue<std::function<void()>> tasks_;
506     std::mutex queue_mutex_;
507     std::condition_variable condition_;
508     bool stop_;
509
510     size_t min_threads_;
511     size_t max_threads_;
512     std::atomic<size_t> active_threads_;
513     std::atomic<size_t> idle_threads_;
514
515 public:
516     DynamicThreadPool(size_t min_threads, size_t max_threads)
517         : stop_(false), min_threads_(min_threads), max_threads_(max_threads),
518           active_threads_(0), idle_threads_(0) {
519
520         std::cout << " Creating dynamic pool (min: " << min_threads
521             << ", max: " << max_threads << ")\n";
522
523         // Start with minimum threads
524         for (size_t i = 0; i < min_threads_; ++i) {
525             add_worker();
526         }
527     }
528
529     void submit(std::function<void()> task) {
530     {
531         std::lock_guard<std::mutex> lock(queue_mutex_);
532
533         if (stop_) {
534             throw std::runtime_error("Cannot submit to stopped pool");
535         }
536
537         tasks_.push(std::move(task));
538
539         // Auto-scale: add worker if all busy and below max
540         if (idle_threads_ == 0 && workers_.size() < max_threads_) {
541             std::cout << " Scaling up: adding worker (total: "
542                 << (workers_.size() + 1) << ")\n";
543             add_worker();
544         }
545     }
546
547     condition_.notify_one();
548 }
549
550 ~DynamicThreadPool() {
551 {
552     std::lock_guard<std::mutex> lock(queue_mutex_);
553     stop_ = true;
554 }
```

```
555     condition_.notify_all();
556
557     for (std::thread& worker : workers_) {
558         if (worker.joinable()) {
559             worker.join();
560         }
561     }
562
563     std::cout << "  Dynamic pool destroyed\n";
564 }
565
566
567 private:
568     void add_worker() {
569         workers_.emplace_back([this]() {
570             while (true) {
571                 std::function<void()> task;
572
573                 {
574                     std::unique_lock<std::mutex> lock(queue_mutex_);
575
576                     ++idle_threads_;
577
578                     condition_.wait(lock, [this]() {
579                         return stop_ || !tasks_.empty();
580                     });
581
582                     --idle_threads_;
583
584                     if (stop_ && tasks_.empty()) {
585                         return;
586                     }
587
588                     if (!tasks_.empty()) {
589                         task = std::move(tasks_.front());
590                         tasks_.pop();
591                     }
592                 }
593
594                 if (task) {
595                     ++active_threads_;
596                     task();
597                     --active_threads_;
598                 }
599             }
600         });
601     }
602 };
603
604 void demonstrate_dynamic_thread_pool() {
605     std::cout << "\n" << std::string(70, '=') << "\n";
606     std::cout << "==== 5. Dynamic Thread Pool (Auto-scaling) ===\n";
607     std::cout << std::string(70, '=') << "\n\n";
608 }
```

```
609     std::cout << "Concept: Pool grows/shrinks based on workload\n\n";
610
611     DynamicThreadPool pool(2, 6);
612
613     std::cout << "Phase 1: Light load (2 tasks)\n\n";
614
615     for (int i = 1; i <= 2; ++i) {
616         pool.submit([i]() {
617             std::cout << "  Light task " << i << "\n";
618             std::this_thread::sleep_for(200ms);
619         });
620     }
621
622     std::this_thread::sleep_for(500ms);
623
624     std::cout << "\nPhase 2: Heavy load (10 tasks)\n\n";
625
626     for (int i = 1; i <= 10; ++i) {
627         pool.submit([i]() {
628             std::cout << "  Heavy task " << i << "\n";
629             std::this_thread::sleep_for(300ms);
630         });
631         std::this_thread::sleep_for(50ms); // Gradual submission
632     }
633
634     std::this_thread::sleep_for(2s);
635
636     std::cout << "\n Pool automatically scaled up during heavy load\n";
637 }
638
639 // =====
640 // SECTION 6: Thread Pool Best Practices and Anti-Patterns
641 // =====
642
643 void demonstrate_best_practices() {
644     std::cout << "\n" << std::string(70, '=') << "\n";
645     std::cout << "==== 6. Thread Pool Best Practices ===\n";
646     std::cout << std::string(70, '=') << "\n\n";
647
648     std::cout << "  BEST PRACTICES:\n";
649     std::cout << "      \n\n";
650
651     std::cout << "1. Pool Size Selection:\n";
652     std::cout << "    CPU-bound: num_threads    std::thread::
653                 hardware_concurrency()\n";
654     std::cout << "    I/O-bound: num_threads > CPU cores (2x-4x)\n";
655     std::cout << "    Mixed:       Profile and tune based on workload\n\n";
656
657     std::cout << "2. Task Granularity:\n";
658     std::cout << "    Tasks should run for at least 1ms (avoid overhead)\n";
```

```
658     std::cout << "      Don't submit trivial tasks (e.g., single addition)\n";
659     std::cout << "      Batch small operations into larger tasks\n\n";
660
661     std::cout << "3. Exception Handling:\n";
662     std::cout << "      Tasks should catch their own exceptions\n";
663     std::cout << "      Use std::future to propagate exceptions\n";
664     std::cout << "      Uncaught exceptions terminate worker threads\n\n";
665
666     std::cout << "4. Shutdown:\n";
667     std::cout << "      Signal stop before destroying pool\n";
668     std::cout << "      Join all worker threads in destructor\n";
669     std::cout << "      Consider draining pending tasks gracefully\n\n";
670
671     std::cout << "5. Task Dependencies:\n";
672     std::cout << "      DEADLOCK RISK: Task waiting for another task in same
673         pool\n";
674     std::cout << "      Use separate pools for dependent tasks\n";
675     std::cout << "      Or ensure pool size > max dependency depth\n\n";
676
677     std::cout << "  ANTI-PATTERNS:\n";
678     std::cout << "      \n\n";
679
680     std::cout << "1. Too many pools: Creates thread explosion\n";
681     std::cout << "      One pool per operation type (100+ pools)\n";
682     std::cout << "      One global pool or few specialized pools\n\n";
683
684     std::cout << "2. Blocking in tasks:\n";
685     std::cout << "      Task calls blocking I/O (starves other tasks)\n";
686     std::cout << "      Use async I/O or separate I/O thread pool\n\n";
687
688     std::cout << "3. Long-running tasks:\n";
689     std::cout << "      Task runs for minutes/hours (blocks worker)\n";
690     std::cout << "      Break into smaller chunks or use dedicated thread\n\n";
691
692     std::cout << "4. Unbounded queue growth:\n";
693     std::cout << "      Submit faster than processing (memory exhaustion)\n";
694     std::cout << "      Use bounded queue with backpressure\n\n";
695 }
696 // =====
697 // SECTION 7: Real-World Example - Image Processing Pipeline
698 // =====
699
700 struct Image {
701     int id;
702     std::string name;
703     int processing_stage; // 0=load, 1=filter, 2=resize, 3=save
704 };
705
706 void demonstrate_real_world_example() {
```

```
707     std::cout << "\n" << std::string(70, '=') << "\n";
708     std::cout << "==== 7. Real-World Example: Image Processing Pipeline ===\n";
709     std::cout << std::string(70, '=') << "\n\n";
710
711     std::cout << "Pipeline: Load → Filter → Resize → Save\n";
712     std::cout << "Strategy: Use thread pool to parallelize each stage\n\n";
713
714     ThreadPoolWithFutures pool(std::thread::hardware_concurrency());
715
716     std::vector<Image> images = {
717         {1, "photo1.jpg", 0},
718         {2, "photo2.jpg", 0},
719         {3, "photo3.jpg", 0},
720         {4, "photo4.jpg", 0}
721     };
722
723     std::cout << "Processing " << images.size() << " images...\n\n";
724
725     // Stage 1: Load images
726     std::vector<std::future<Image>> loaded;
727     for (const auto& img : images) {
728         loaded.push_back(pool.submit([img]() {
729             std::cout << " [LOAD] " << img.name << "\n";
730             std::this_thread::sleep_for(100ms);
731             Image result = img;
732             result.processing_stage = 1;
733             return result;
734         }));
735     }
736
737     // Stage 2: Apply filters
738     std::vector<std::future<Image>> filtered;
739     for (auto& future : loaded) {
740         Image img = future.get();
741         filtered.push_back(pool.submit([img]() {
742             std::cout << " [FILTER] " << img.name << "\n";
743             std::this_thread::sleep_for(150ms);
744             Image result = img;
745             result.processing_stage = 2;
746             return result;
747         }));
748     }
749
750     // Stage 3: Resize
751     std::vector<std::future<Image>> resized;
752     for (auto& future : filtered) {
753         Image img = future.get();
754         resized.push_back(pool.submit([img]() {
755             std::cout << " [RESIZE] " << img.name << "\n";
756             std::this_thread::sleep_for(100ms);
757             Image result = img;
758             result.processing_stage = 3;
759             return result;
760         }));
761     }
```

```

761 }
762
763 // Stage 4: Save
764 std::vector<std::future<void>> saved;
765 for (auto& future : resized) {
766     Image img = future.get();
767     saved.push_back(pool.submit([img]() {
768         std::cout << " [SAVE] " << img.name << " -> output/" << img.name
769         << "\n";
770         std::this_thread::sleep_for(80ms);
771     }));
772 }
773
774 // Wait for all to complete
775 for (auto& future : saved) {
776     future.get();
777 }
778
779 std::cout << "\n Pipeline completed for all images\n";
780 std::cout << " Each stage parallelized using thread pool\n";
781 }
782 // -----
783 // SECTION 8: Comparison - When to Use What
784 // -----
785
786 void demonstrate_comparison() {
787     std::cout << "\n" << std::string(70, '=') << "\n";
788     std::cout << "==== 8. Thread Pool Comparison - When to Use What ===\n";
789     std::cout << std::string(70, '=') << "\n\n";
790
791     std::cout << "
792         Pool Type           Use Case          Pros/Cons
793         \n";
794     std::cout << "
795         Basic             Simple tasks      + Easy to
796         implement         \n";
797     std::cout << "
798         values            Fire-and-forget   - No return
799         \n";
800     std::cout << "
801         With Futures      Computational work + Return values
802         \n";
803     std::cout << "
804         \n";
805     std::cout << "
806         Priority          Need results      + Type-safe
807         order             \n";
808     std::cout << "
809         \n";
810     std::cout << "
811         Mixed importance  Real-time systems - More overhead
812         \n";
813     std::cout << "
814         \n";

```

```

803     std::cout << " Work-Stealing           Uneven task sizes      + Better load
804         balance\n";
805     std::cout << "
806         \n";
807     std::cout << "
808         Dynamic             Recursive tasks      - More complex
809             efficient \n";
810         std::cout << "
811             latency \n";
812         std::cout << "
813             \n\n";
814         std::cout << " ALTERNATIVES TO THREAD POOLS:\n";
815         std::cout << "
816             \n\n";
817         std::cout << "1. std::async:\n";
818             std::cout << "   Use when: One-off async operations, automatic thread
819                 management\n";
820             std::cout << "   Avoid when: High frequency task submission (creates many
821                 threads)\n\n";
822         std::cout << "2. std::thread:\n";
823             std::cout << "   Use when: Long-running background tasks, dedicated worker
824                 \n";
825             std::cout << "   Avoid when: Many short-lived tasks (thread creation
826                 overhead)\n\n";
827         std::cout << "3. ASIO/Boost.Asio:\n";
828             std::cout << "   Use when: I/O-bound operations, async networking\n";
829             std::cout << "   Avoid when: CPU-bound computations\n\n";
830         std::cout << "4. C++20 Coroutines:\n";
831             std::cout << "   Use when: Async I/O, cooperative multitasking\n";
832             std::cout << "   Avoid when: Heavy CPU computations\n\n";
833         std::cout << "5. TBB (Threading Building Blocks):\n";
834             std::cout << "   Use when: Need mature, production-ready parallel
835                 algorithms\n";
836             std::cout << "   Benefit: Work-stealing, parallel_for, parallel_reduce,
837                 etc.\n\n";
838     }
839     // =====
840
841 // MAIN FUNCTION
842 //
843 // =====
844
845
846
847
848 int main() {
849     std::cout << "\n";
850     std::cout << "
851         Thread Pool Implementations - Educational
852             Examples \n";

```

```
842     std::cout << "
843         ;
844         std::cout << "    From basic to advanced: Complete guide to C++ thread
845             pools          \n";
846         std::cout << "
847                         \n";
848         std::cout << "\nSystem Info: " << std::thread::hardware_concurrency()
849             << "    hardware threads available\n";
850
851         demonstrate_basic_thread_pool();
852         demonstrate_thread_pool_with_futures();
853         demonstrate_priority_thread_pool();
854         demonstrate_work_stealing_pool();
855         demonstrate_dynamic_thread_pool();
856         demonstrate_best_practices();
857         demonstrate_real_world_example();
858         demonstrate_comparison();
859
860         std::cout << "\n" << std::string(70, '=') << "\n";
861         std::cout << "All thread pool demonstrations completed!\n";
862         std::cout << "\nKEY TAKEAWAYS:\n";
863         std::cout << "    1. Thread pools reuse threads → avoid creation overhead\n"
864             ;
865         std::cout << "    2. Choose pool type based on workload characteristics\n";
866         std::cout << "    3. Use futures for tasks that return values\n";
867         std::cout << "    4. Profile before optimizing thread count\n";
868         std::cout << "    5. Watch for deadlocks with task dependencies\n";
869         std::cout << std::string(70, '=') << "\n\n";
870
871     return 0;
872 }
```

73 Source Code: TuplesAndStructuredBindings.cpp

File: src/TuplesAndStructuredBindings.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // COMPREHENSIVE TUPLES AND STRUCTURED BINDINGS
3 // =====
4 // This example demonstrates modern C++ tuple features and best practices.
5 //
6 // TOPICS COVERED:
7 // 1. Basic tuple operations (C++11)
8 // 2. std::tie and unpacking
9 // 3. Structured bindings (C++17)
10 // 4. std::apply (C++17)
11 // 5. Tuple comparison and algorithms
12 // 6. Tuple concatenation
13 // 7. std::tuple_cat
14 // 8. Real-world use cases
15 // 9. Performance considerations
16 // 10. When to use tuples vs structs
17 // =====
18
19 #include <iostream>
20 #include <string>
21 #include <tuple>
22 #include <vector>
23 #include <map>
24 #include <algorithm>
25 #include <numeric>
26
27 // =====
28 // SECTION 1: BASIC TUPLE OPERATIONS
29 // =====
30
31 void demonstrate_basic_tuples() {
32     std::cout << "\n== 1. BASIC TUPLE OPERATIONS ==" << std::endl;
33
34     // Creating tuples
35     std::tuple<int, std::string, double> person1{25, "Alice", 5.6};
36     auto person2 = std::make_tuple(30, "Bob", 6.0);
37
38     // Accessing elements with std::get
39     std::cout << "\nPerson 1: " << std::get<0>(person1) << " years, "
40             << std::get<1>(person1) << ", "
41             << std::get<2>(person1) << "ft" << std::endl;
42
43     // Accessing by type (C++14) - only if type is unique!
44     std::cout << "Name: " << std::get<std::string>(person1) << std::endl;
45
46     // Modifying elements
47     std::get<0>(person1) = 26;
48     std::cout << "After birthday: " << std::get<0>(person1) << " years" << std::endl;
```

```
49 // Tuple size
50 std::cout << "\nTuple size: " << std::tuple_size<decltype(person1)>::value
51     << std::endl;
52
53 std::cout << "\n KEY POINTS:" << std::endl;
54 std::cout << " • std::get<N>(tuple) - access by index (compile-time)" <<
55     std::endl;
56 std::cout << " • std::get<Type>(tuple) - access by type (if unique)" <<
57     std::endl;
58 std::cout << " • Zero runtime overhead vs struct" << std::endl;
59 }
60
61 // =====
62 // SECTION 2: std::tie AND UNPACKING
63 // =====
64
65 std::tuple<int, int, int> divide_full(int dividend, int divisor) {
66     return {dividend / divisor, dividend % divisor, dividend};
67 }
68
69 void demonstrate_tie() {
70     std::cout << "\n== 2. std::tie AND UNPACKING ==" << std::endl;
71
72     // Old way: extract tuple elements
73     auto result = divide_full(17, 5);
74     int quotient = std::get<0>(result);
75     int remainder = std::get<1>(result);
76     int original = std::get<2>(result);
77
78     std::cout << "\nOld way: 17 / 5 = " << quotient
79         << " remainder " << remainder << std::endl;
80
81     // Better: std::tie (C++11)
82     int q, r, o;
83     std::tie(q, r, o) = divide_full(17, 5);
84     std::cout << "With tie: 17 / 5 = " << q << " remainder " << r << std::endl
85         ;
86
87     // Ignore some values with std::ignore
88     std::tie(q, std::ignore, std::ignore) = divide_full(20, 3);
89     std::cout << "Quotient only: 20 / 3 = " << q << std::endl;
90
91     // Using tie for swap
92     int a = 10, b = 20;
93     std::cout << "\nBefore swap: a=" << a << ", b=" << b << std::endl;
94     std::tie(a, b) = std::tie(b, a);
95     std::cout << "After swap: a=" << a << ", b=" << b << std::endl;
96
97     std::cout << "\n std::tie benefits:" << std::endl;
98     std::cout << " • Unpack multiple return values" << std::endl;
99     std::cout << " • Use std::ignore for unwanted values" << std::endl;
100    std::cout << " • Create reference tuples" << std::endl;
101 }
```

```

99
100 // =====
101 // SECTION 3: STRUCTURED BINDINGS (C++17)
102 // =====
103
104 struct Sensor {
105     int id;
106     double temperature;
107     double humidity;
108     std::string location;
109 };
110
111 std::tuple<double, double, double> compute_statistics(const std::vector<double>& values) {
112     double sum = std::accumulate(values.begin(), values.end(), 0.0);
113     double mean = sum / values.size();
114     double min = *std::min_element(values.begin(), values.end());
115     double max = *std::max_element(values.begin(), values.end());
116     return {mean, min, max};
117 }
118
119 void demonstrate_structured_bindings() {
120     std::cout << "\n==== 3. STRUCTURED BINDINGS (C++17) ===" << std::endl;
121
122     // Structured bindings - most modern and readable!
123     auto [quotient, remainder, original] = divide_full(25, 7);
124     std::cout << "\n25 / 7 = " << quotient << " remainder " << remainder << std::endl;
125
126     // Works with pairs
127     std::map<std::string, int> scores{{"Alice", 95}, {"Bob", 87}};
128     for (const auto& [name, score] : scores) {
129         std::cout << name << ": " << score << " points" << std::endl;
130     }
131
132     // Works with structs
133     Sensor sensor{101, 22.5, 65.0, "Lab-A"};
134     auto [id, temp, humid, loc] = sensor;
135     std::cout << "\nSensor " << id << " at " << loc
136         << " : " << temp << "°C, " << humid << "% humidity" << std::endl;
137
138     // With functions
139     std::vector<double> temps{20.1, 22.5, 21.8, 23.0, 19.5};
140     auto [mean, min, max] = compute_statistics(temps);
141     std::cout << "\nTemperature stats: mean=" << mean
142         << ", min=" << min << ", max=" << max << std::endl;
143
144     std::cout << "\n BEST PRACTICE:" << std::endl;
145     std::cout << " • Use structured bindings (C++17) over std::tie" << std::endl;
146     std::cout << " • More readable, less verbose" << std::endl;
147     std::cout << " • Works with tuples, pairs, structs, arrays" << std::endl
148         ;
}

```

```
149
150 // =====
151 // SECTION 4: std::apply (C++17)
152 // =====
153
154 int add_three(int a, int b, int c) {
155     return a + b + c;
156 }
157
158 double multiply(double x, double y, double z) {
159     return x * y * z;
160 }
161
162 void demonstrate_apply() {
163     std::cout << "\n== 4. std::apply (C++17) ==" << std::endl;
164
165     // std::apply - call function with tuple as arguments
166     std::tuple<int, int, int> args{10, 20, 30};
167     int sum = std::apply(add_three, args);
168     std::cout << "\nsum of (10, 20, 30) = " << sum << std::endl;
169
170     std::tuple<double, double, double> factors{2.0, 3.0, 4.0};
171     double product = std::apply(multiply, factors);
172     std::cout << "product of (2.0, 3.0, 4.0) = " << product << std::endl;
173
174     // With lambdas
175     auto printer = [](auto... args) {
176         std::cout << "Values: ";
177         ((std::cout << args << " "), ...);
178         std::cout << std::endl;
179     };
180
181     std::apply(printer, std::make_tuple(1, "hello", 3.14, 'X'));
182
183     std::cout << "\n std::apply use cases:" << std::endl;
184     std::cout << " • Call function with tuple arguments" << std::endl;
185     std::cout << " • Forward arguments stored in tuple" << std::endl;
186     std::cout << " • Unpack tuple into function call" << std::endl;
187 }
188
189 // =====
190 // SECTION 5: TUPLE COMPARISON AND ALGORITHMS
191 // =====
192
193 void demonstrate_tuple_comparison() {
194     std::cout << "\n== 5. TUPLE COMPARISON ==" << std::endl;
195
196     std::tuple<int, std::string> t1{1, "apple"};
197     std::tuple<int, std::string> t2{1, "banana"};
198     std::tuple<int, std::string> t3{2, "apple"};
199
200     // Lexicographic comparison (left to right)
201     std::cout << "\nComparisons:" << std::endl;
202     std::cout << " (1, 'apple') < (1, 'banana'): "
```

```

203     << std::boolalpha << (t1 < t2) << std::endl;
204     std::cout << "    (1, 'apple') < (2, 'apple'): " << (t1 < t3) << std::endl;
205     std::cout << "    (1, 'banana') < (2, 'apple'): " << (t2 < t3) << std::endl
206     ;
207
208 // Sorting with tuples
209 std::vector<std::tuple<int, std::string, double>> students{
210     {85, "Charlie", 3.2},
211     {92, "Alice", 3.8},
212     {85, "Bob", 3.5},
213     {92, "David", 3.6}
214 };
215
216 std::cout << "\nBefore sort:" << std::endl;
217 for (const auto& [score, name, gpa] : students) {
218     std::cout << "    " << name << ":" << score << ", GPA " << gpa << std
219         ::endl;
220 }
221
222 // Sort by tuple (score desc, then name asc)
223 std::sort(students.begin(), students.end(),
224           [] (const auto& a, const auto& b) {
225               return std::tie(std::get<0>(b), std::get<1>(a)) <
226                   std::tie(std::get<0>(a), std::get<1>(b));
227           });
228
229 std::cout << "\nAfter sort (score desc, name asc):" << std::endl;
230 for (const auto& [score, name, gpa] : students) {
231     std::cout << "    " << name << ":" << score << ", GPA " << gpa << std
232         ::endl;
233 }
234
235 std::cout << "\n Tuple comparison:" << std::endl;
236 std::cout << " • Lexicographic (element by element)" << std::endl;
237 std::cout << " • Perfect for sorting by multiple keys" << std::endl;
238 std::cout << " • Use std::tie for custom comparison" << std::endl;
239 }
240
241 // =====
242 // SECTION 6: std::tuple_cat AND CONCATENATION
243 // =====
244 void demonstrate_tuple_cat() {
245     std::cout << "\n== 6. std::tuple_cat ==" << std::endl;
246
247     std::tuple<int, std::string> t1{42, "answer"};
248     std::tuple<double, char> t2{3.14, 'X'};
249
250     // Concatenate tuples
251     auto combined = std::tuple_cat(t1, t2);
252     auto [num, text, pi, letter] = combined;
253
254     std::cout << "\nCombined tuple: " << num << ", " << text
255         << ", " << pi << ", " << letter << std::endl;

```

```
254 // Combine multiple tuples
255 std::tuple<int> id{100};
256 std::tuple<std::string, std::string> name{"John", "Doe"};
257 std::tuple<int> age{30};
258
259 auto person = std::tuple_cat(id, name, age);
260 std::cout << "\nPerson: ID=" << std::get<0>(person)
261             << ", Name=" << std::get<1>(person) << " " << std::get<2>(person)
262             )
263             << ", Age=" << std::get<3>(person) << std::endl;
264
265 std::cout << "\n std::tuple_cat:" << std::endl;
266 std::cout << " • Concatenate multiple tuples" << std::endl;
267 std::cout << " • All done at compile-time" << std::endl;
268 std::cout << " • Zero runtime overhead" << std::endl;
269 }
270
271 // =====
272 // SECTION 7: REAL-WORLD USE CASE - PARTICLE SYSTEM
273 // =====
274
275 using State = std::tuple<double, double, double, double, double>;
276 using ParticleWeight = double;
277 using Particle = std::map<ParticleWeight, State>;
278 using Particles = std::vector<Particle>;
279
280 double compute_total_weight(const Particles& particles) {
281     double total = 0.0;
282     for (const auto& particle : particles) {
283         for (const auto& [weight, state] : particle) {
284             total += weight;
285         }
286     }
287     return total;
288 }
289
290 void print_particle_state(const State& state) {
291     auto [x, y, z, vx, vy] = state;
292     std::cout << "    Position(" << x << "," << y << "," << z << ") "
293                  << "Velocity(" << vx << "," << vy << ")" << std::endl;
294 }
295
296 void demonstrate_particle_system() {
297     std::cout << "\n== 7. REAL-WORLD: PARTICLE SYSTEM ==" << std::endl;
298
299     Particles particles;
300
301     // Create particles with weighted states
302     for (int i = 0; i < 4; i++) {
303         State state = std::make_tuple(i*1.0, i*1.1, i*1.2, i*0.5, i*0.6);
304         Particle particle;
305         particle.emplace(5.0 + i, state);
306         particles.push_back(particle);
```

```

307 }
308
309 std::cout << "\nParticle states:" << std::endl;
310 for (size_t i = 0; i < particles.size(); i++) {
311     for (const auto& [weight, state] : particles[i]) {
312         std::cout << "Particle " << i << " (weight=" << weight << "):" <<
313             std::endl;
314         print_particle_state(state);
315     }
316 }
317 double total_weight = compute_total_weight(particles);
318 std::cout << "\nTotal weight: " << total_weight << std::endl;
319
320 std::cout << "\n Why use tuples here:" << std::endl;
321 std::cout << " • Simple data aggregation" << std::endl;
322 std::cout << " • No need for named struct" << std::endl;
323 std::cout << " • Easy to decompose with structured bindings" << std::endl;
324 }
325
326 // =====
327 // SECTION 8: TUPLE VS STRUCT - WHEN TO USE EACH
328 // =====
329
330 void explain_tuple_vs_struct() {
331     std::cout << "\n" << std::string(70, '=') << std::endl;
332     std::cout << "TUPLE VS STRUCT - WHEN TO USE EACH:\n";
333     std::cout << std::string(70, '=') << std::endl;
334
335     std::cout << "\n USE TUPLES WHEN:" << std::endl;
336     std::cout << "\n1. RETURNING MULTIPLE VALUES:" << std::endl;
337     std::cout << "    std::tuple<int, int> divide(int a, int b) { ... }" <<
338         std::endl;
339     std::cout << " • Quick and easy multiple returns" << std::endl;
340     std::cout << " • Use structured bindings to unpack" << std::endl;
341
342     std::cout << "\n2. TEMPORARY DATA GROUPING:" << std::endl;
343     std::cout << " • Local scope only" << std::endl;
344     std::cout << " • No need for named type" << std::endl;
345     std::cout << " • One-off data combinations" << std::endl;
346
347     std::cout << "\n3. GENERIC PROGRAMMING:" << std::endl;
348     std::cout << " • Template metaprogramming" << std::endl;
349     std::cout << " • Variadic template arguments" << std::endl;
350     std::cout << " • Type computations" << std::endl;
351
352     std::cout << "\n4. QUICK PROTOTYPING:" << std::endl;
353     std::cout << " • Experimenting with data structures" << std::endl;
354     std::cout << " • Before defining proper types" << std::endl;
355
356     std::cout << "\n USE STRUCTS WHEN:" << std::endl;
357     std::cout << "\n1. NAMED SEMANTICS MATTER:" << std::endl;
358     std::cout << "    struct Person { int age; string name; double height; };"

```

```

        " << std::endl;
358     std::cout << " • Clear what each field means" << std::endl;
359     std::cout << " • Self-documenting code" << std::endl;
360
361     std::cout << "\n2. MEMBER FUNCTIONS NEEDED:" << std::endl;
362     std::cout << " • Methods to manipulate data" << std::endl;
363     std::cout << " • Encapsulation" << std::endl;
364     std::cout << " • Invariants to maintain" << std::endl;
365
366     std::cout << "\n3. PUBLIC API:" << std::endl;
367     std::cout << " • Library interfaces" << std::endl;
368     std::cout << " • Long-term maintainability" << std::endl;
369     std::cout << " • Clear documentation" << std::endl;
370
371     std::cout << "\n4. COMPLEX TYPES:" << std::endl;
372     std::cout << " • Many fields (>5)" << std::endl;
373     std::cout << " • Constructors needed" << std::endl;
374     std::cout << " • Relationships with other types" << std::endl;
375
376     std::cout << "\n ANTI-PATTERNS:" << std::endl;
377     std::cout << "\n DON'T: tuple<int, int, int, int, int, int>" << std
            ::endl;
378     std::cout << "    Too many fields - use struct!" << std::endl;
379     std::cout << "\n DON'T: Use tuples in public API" << std::endl;
380     std::cout << "    Hard to understand: get<2>(result) means what?" << std::
            endl;
381     std::cout << "\n DON'T: Store tuples long-term" << std::endl;
382     std::cout << "    Use proper named types for persistence" << std::endl;
383
384     std::cout << "\n GOLDEN RULE:" << std::endl;
385     std::cout << "    Tuples for quick local returns," << std::endl;
386     std::cout << "    Structs for everything else!" << std::endl;
387 }
388
389 // =====
390 // SECTION 9: PERFORMANCE CONSIDERATIONS
391 // =====
392
393 struct Point3D {
394     double x, y, z;
395 };
396
397 void demonstrate_performance() {
398     std::cout << "\n" << std::string(70, '=') << std::endl;
399     std::cout << "PERFORMANCE CONSIDERATIONS:\n";
400     std::cout << std::string(70, '=') << std::endl;
401
402     using TuplePoint = std::tuple<double, double, double>;
403
404     std::cout << "\n MEMORY LAYOUT:" << std::endl;
405     std::cout << "    struct Point3D: " << sizeof(Point3D) << " bytes" << std
            ::endl;
406     std::cout << "    tuple<d,d,d>:      " << sizeof(TuplePoint) << " bytes" <<
            std::endl;

```

```

407     std::cout << "      SAME SIZE - no overhead!" << std::endl;
408
409     std::cout << "\n RUNTIME PERFORMANCE:" << std::endl;
410     std::cout << "      Struct: point.x (direct access)" << std::endl;
411     std::cout << "      Tuple: std::get<0>(point) (compile-time index)" << std::endl;
412     std::cout << "      SAME SPEED - both inline to same code!" << std::endl;
413
414     std::cout << "\n COMPIILATION TIME:" << std::endl;
415     std::cout << "      Struct: Fast - simple type" << std::endl;
416     std::cout << "      Tuple: Slower - template instantiation" << std::endl;
417     std::cout << "      Tuples increase compile time slightly" << std::endl;
418
419     std::cout << "\n PERFORMANCE TIPS:" << std::endl;
420     std::cout << " • Tuples have ZERO runtime overhead" << std::endl;
421     std::cout << " • std::get<N> is compile-time constant" << std::endl;
422     std::cout << " • Use references to avoid copies" << std::endl;
423     std::cout << " • Move semantics work perfectly" << std::endl;
424 }
425
426 // =====
427 // SECTION 10: ADVANCED TECHNIQUES
428 // =====
429
430 // Tuple element type at index
431 template<size_t I, typename Tuple>
432 using tuple_element_t = typename std::tuple_element<I, Tuple>::type;
433
434 void demonstrate_advanced() {
435     std::cout << "\n==== 10. ADVANCED TECHNIQUES ===" << std::endl;
436
437     // Type introspection
438     using MyTuple = std::tuple<int, double, std::string>;
439
440     std::cout << "\nTuple type information:" << std::endl;
441     std::cout << "      Size: " << std::tuple_size_v<MyTuple> << std::endl;
442
443     // Get element types
444     using FirstType = tuple_element_t<0, MyTuple>;
445     using SecondType = tuple_element_t<1, MyTuple>;
446
447     std::cout << "      First element is int: "
448             << std::boolalpha << std::is_same_v<FirstType, int> << std::endl
449             ;
450     std::cout << "      Second element is double: "
451             << std::is_same_v<SecondType, double> << std::endl;
452
453     // Forward as tuple (perfect forwarding)
454     auto forward_example = [](&auto... args) {
455         auto tuple = std::forward_as_tuple(args...);
456         std::cout << "\n      Created reference tuple of size "
457                 << std::tuple_size_v<decltype(tuple)> << std::endl;
458     };

```

```
459 int x = 10;
460 double y = 20.5;
461 forward_example(x, y, std::string("test"));

462
463 std::cout << "\n Advanced features:" << std::endl;
464 std::cout << " • std::tuple_element - get element type" << std::endl;
465 std::cout << " • std::tuple_size - get tuple size" << std::endl;
466 std::cout << " • std::forward_as_tuple - create reference tuple" << std
        ::endl;
467 std::cout << " • Perfect for template metaprogramming" << std::endl;
468 }

469 // =====
470 // MAIN FUNCTION
471 // =====
472
473 int main() {
474     std::cout << "\n";
475     std::cout << "                                     \n";
476     std::cout << "             COMPREHENSIVE TUPLES AND STRUCTURED BINDINGS
        \n";
477     std::cout << "                                     \n";
478     std::cout << "                                     \n";
479     std::cout << "     Modern C++ techniques for heterogeneous data
        \n";
480     std::cout << "                                     \n";
481
482     demonstrate_basic_tuples();
483     demonstrate_tie();
484     demonstrate_structured_bindings();
485     demonstrate_apply();
486     demonstrate_tuple_comparison();
487     demonstrate_tuple_cat();
488     demonstrate_particle_system();
489     explain_tuple_vs_struct();
490     demonstrate_performance();
491     demonstrate_advanced();

492
493     std::cout << "\n" << std::string(70, '=') << std::endl;
494     std::cout << "SUMMARY:\n";
495     std::cout << std::string(70, '=') << std::endl;

496
497     std::cout << "\n KEY TAKEAWAYS:" << std::endl;
498     std::cout << "\n1. MODERN SYNTAX:" << std::endl;
499     std::cout << " • Prefer structured bindings (C++17) over std::tie" <<
        std::endl;
500     std::cout << " • Use std::apply for tuple-to-function unpacking" << std
        ::endl;
501     std::cout << " • auto [a, b, c] = func(); // Most readable!" << std::
        endl;

502
503     std::cout << "\n2. WHEN TO USE:" << std::endl;
504     std::cout << "     Multiple return values" << std::endl;
505     std::cout << "     Temporary data grouping" << std::endl;
```

```
506     std::cout << "      Generic programming" << std::endl;
507     std::cout << "      Public APIs (use structs)" << std::endl;
508     std::cout << "      Many fields (>5) (use structs)" << std::endl;
509
510     std::cout << "\n3. PERFORMANCE:" << std::endl;
511     std::cout << " • Zero runtime overhead vs struct" << std::endl;
512     std::cout << " • std::get<N> is compile-time" << std::endl;
513     std::cout << " • Slightly slower compilation" << std::endl;
514
515     std::cout << "\n4. BEST PRACTICES:" << std::endl;
516     std::cout << " • Keep tuples small (<= 5 elements)" << std::endl;
517     std::cout << " • Use for local/temporary data" << std::endl;
518     std::cout << " • Switch to struct when semantics matter" << std::endl;
519     std::cout << " • Document what tuple fields mean!" << std::endl;
520
521     std::cout << "\n Tuples: Quick and powerful for the right use cases!\n"
522             << std::endl;
523
524     return 0;
}
```

74 Source Code: VariadicTemplateRecursion.cpp

File: src/VariadicTemplateRecursion.cpp

Repository: [View on GitHub](#)

```
1 // =====
2 // VARIADIC TEMPLATES WITH COMPILE-TIME RECURSION
3 // =====
4 // This example demonstrates how variadic templates enable compile-time
5 // recursion and metaprogramming, eliminating runtime overhead.
6 //
7 // TOPICS COVERED:
8 // 1. Basic variadic template recursion
9 // 2. Compile-time computation (constexpr)
10 // 3. Type manipulation at compile-time
11 // 4. Fold expressions (C++17)
12 // 5. Practical use cases
13 // 6. Embedded systems applications
14 //
15 // KEY CONCEPT: Template recursion happens during compilation,
16 // resulting in ZERO runtime cost - perfect for embedded systems!
17 // =====
18
19 #include <iostream>
20 #include <string>
21 #include <type_traits>
22 #include <array>
23 #include <tuple>
24 #include <cstdint>
25 #include <limits>
26 #include <bitset>
27
28 // =====
29 // SECTION 1: BASIC VARIADIC RECURSION - COMPILE-TIME
30 // =====
31
32 // Base case: no arguments
33 void print_recursive() {
34     std::cout << std::endl;
35 }
36
37 // Recursive case: process first argument, recurse on rest
38 template<typename First, typename... Rest>
39 void print_recursive(First first, Rest... rest) {
40     std::cout << first << " ";
41     print_recursive(rest...); // Compile-time recursion
42 }
43
44 void demonstrate_basic_recursion() {
45     std::cout << "\n==== 1. BASIC VARIADIC RECURSION ===" << std::endl;
46
47     std::cout << "Printing: ";
48     print_recursive(1, "hello", 3.14, 'X', "world");
49 }
```

```
50     std::cout << "\n KEY POINT:" << std::endl;
51     std::cout << " • Compiler generates 5 functions at compile-time" << std
52         ::endl;
53     std::cout << " • Each function handles one argument type" << std::endl;
54     std::cout << " • Zero runtime overhead - all resolved at compile-time"
55         << std::endl;
56     std::cout << " • No loops, no vtables, no dynamic dispatch" << std::endl
57         ;
58 }
59
60 // =====
61 // SECTION 2: COMPILE-TIME COMPUTATION - SUM
62 // =====
63
64 // Base case
65 constexpr int sum() {
66     return 0;
67 }
68
69 // Recursive case
70 template<typename First, typename... Rest>
71 constexpr auto sum(First first, Rest... rest) {
72     return first + sum(rest...);
73 }
74
75 // Compile-time maximum
76 constexpr int max_value() {
77     return -2147483648; // INT_MIN
78 }
79
80 template<typename First, typename... Rest>
81 constexpr auto max_value(First first, Rest... rest) {
82     auto rest_max = max_value(rest...);
83     return (first > rest_max) ? first : rest_max;
84 }
85
86 void demonstrate_compile_time_computation() {
87     std::cout << "\n== 2. COMPILE-TIME COMPUTATION ==" << std::endl;
88
89     // These are computed at COMPILE TIME!
90     constexpr int total = sum(1, 2, 3, 4, 5);
91     constexpr int max_val = max_value(10, 25, 15, 30, 5);
92
93     std::cout << "sum(1,2,3,4,5) = " << total << " (computed at compile-time!)"
94         << std::endl;
95     std::cout << "max(10,25,15,30,5) = " << max_val << " (computed at compile-
96         time!)" << std::endl;
97
98     std::cout << "\n COST ANALYSIS:" << std::endl;
99     std::cout << " Runtime cost: ZERO" << std::endl;
100    std::cout << " Binary size: Just the constant values" << std::endl;
101    std::cout << " CPU cycles: ZERO (values are literals in binary)" << std
102        ::endl;
```

```
98 // Verify with static_assert (compile-time only!)
99 static_assert(sum(1, 2, 3, 4, 5) == 15, "Sum should be 15");
100 static_assert(max_value(10, 25, 15, 30, 5) == 30, "Max should be 30");
101 std::cout << "    static_assert passed - verified at compile-time!" <<
102     std::endl;
103 }
104 // =====
105 // SECTION 3: TYPE MANIPULATION - COMPILE-TIME
106 // =====
107
108 // Check if all types are integral
109 template<typename... Types>
110 struct all_integral;
111
112 // Base case: empty parameter pack
113 template<>
114 struct all_integral<> : std::true_type {};
115
116 // Recursive case
117 template<typename First, typename... Rest>
118 struct all_integral<First, Rest...> {
119     static constexpr bool value =
120         std::is_integral_v<First> && all_integral<Rest...>::value;
121 };
122
123 // Helper variable template (C++17)
124 template<typename... Types>
125 inline constexpr bool all_integral_v = all_integral<Types...>::value;
126
127 // Check if all types are the same
128 template<typename... Types>
129 struct all_same;
130
131 template<typename T>
132 struct all_same<T> : std::true_type {};
133
134 template<typename First, typename Second, typename... Rest>
135 struct all_same<First, Second, Rest...> {
136     static constexpr bool value =
137         std::is_same_v<First, Second> && all_same<Second, Rest...>::value;
138 };
139
140 template<typename... Types>
141 inline constexpr bool all_same_v = all_same<Types...>::value;
142
143 // Get size of largest type
144 template<typename... Types>
145 struct max_sizeof;
146
147 template<typename T>
148 struct max_sizeof<T> {
149     static constexpr size_t value = sizeof(T);
150 };
```

```
151
152 template<typename First, typename... Rest>
153 struct max_sizeof<First, Rest...> {
154     static constexpr size_t value =
155         (sizeof(First) > max_sizeof<Rest...>::value)
156             ? sizeof(First)
157             : max_sizeof<Rest...>::value;
158 };
159
160 template<typename... Types>
161 inline constexpr size_t max_sizeof_v = max_sizeof<Types...>::value;
162
163 void demonstrate_type_manipulation() {
164     std::cout << "\n==== 3. TYPE MANIPULATION AT COMPILE-TIME ===" << std::endl
165         ;
166
167     std::cout << "\nall_integral_v:" << std::endl;
168     std::cout << "    <int, long, short> = "
169         << std::boolalpha << all_integral_v<int, long, short> << std::endl;
170
171     std::cout << "    <int, double, char> = "
172         << all_integral_v<int, double, char> << std::endl;
173
174     std::cout << "\nall_same_v:" << std::endl;
175     std::cout << "    <int, int, int> = "
176         << all_same_v<int, int, int> << std::endl;
177     std::cout << "    <int, long, int> = "
178         << all_same_v<int, long, int> << std::endl;
179
180     std::cout << "\nmax_sizeof_v:" << std::endl;
181     std::cout << "    <char, int, long> = "
182         << max_sizeof_v<char, int, long> << " bytes" << std::endl;
183     std::cout << "    <double, int, float> = "
184         << max_sizeof_v<double, int, float> << " bytes" << std::endl;
185
186     std::cout << "\n ALL COMPUTED AT COMPILE-TIME!" << std::endl;
187     std::cout << "    No runtime type checking needed" << std::endl;
188     std::cout << "    Perfect for template constraints" << std::endl;
189 }
190
191 // =====
192 // SECTION 4: FOLD EXPRESSIONS (C++17) - SIMPLIFIED RECURSION
193 // =====
194
195 // Old way: explicit recursion
196 template<typename... Args>
197 constexpr auto sum_old_way(Args... args) {
198     return (args + ...); // Fold expression!
199 }
200
201 // Fold expressions for logical operations
202 template<typename... Args>
203 constexpr bool all_positive(Args... args) {
204     return ((args > 0) && ...); // Fold with &&
```

```

203 }
204
205 template<typename... Args>
206 constexpr bool any_negative(Args... args) {
207     return ((args < 0) || ...); // Fold with ||
208 }
209
210 // Fold for comma operator (call function for each)
211 template<typename... Args>
212 void print_all_fold(Args... args) {
213     ((std::cout << args << " "), ...);
214     std::cout << std::endl;
215 }
216
217 void demonstrate_fold_expressions() {
218     std::cout << "\n==== 4. FOLD EXPRESSIONS (C++17) ===" << std::endl;
219
220     std::cout << "\nArithmetic folds:" << std::endl;
221     std::cout << "    sum(1,2,3,4,5) = " << sum_old_way(1, 2, 3, 4, 5) << std::endl;
222
223     std::cout << "\nLogical folds:" << std::endl;
224     std::cout << "    all_positive(1,2,3) = "
225         << std::boolalpha << all_positive(1, 2, 3) << std::endl;
226     std::cout << "    all_positive(1,-2,3) = "
227         << all_positive(1, -2, 3) << std::endl;
228     std::cout << "    any_negative(1,2,3) = "
229         << any_negative(1, 2, 3) << std::endl;
230     std::cout << "    any_negative(1,-2,3) = "
231         << any_negative(1, -2, 3) << std::endl;
232
233     std::cout << "\nPrint with fold: ";
234     print_all_fold(1, "hello", 3.14, "world");
235
236     std::cout << "\n FOLD EXPRESSIONS:" << std::endl;
237     std::cout << " • Simpler than explicit recursion" << std::endl;
238     std::cout << " • Still compile-time only" << std::endl;
239     std::cout << " • More readable code" << std::endl;
240     std::cout << " • Zero runtime cost" << std::endl;
241 }
242
243 // =====
244 // SECTION 5: PRACTICAL USE CASE - TYPE-SAFE PRINTF
245 // =====
246
247 // Validate format string at compile-time
248 template<typename... Args>
249 void safe_printf(const char* format, Args... args) {
250     // Count format specifiers
251     int format_count = 0;
252     for (const char* p = format; *p; ++p) {
253         if (*p == '%' && *(p+1) != '%') {
254             ++format_count;
255         }

```

```
256     }
257
258     int arg_count = sizeof...(args);
259
260     if (format_count != arg_count) {
261         std::cout << "ERROR: Format string has " << format_count
262             << " specifiers but " << arg_count << " arguments!" << std::endl;
263         return;
264     }
265
266     printf(format, args...);
267 }
268
269 void demonstrate_safe_printf() {
270     std::cout << "\n==== 5. TYPE-SAFE PRINTF ===" << std::endl;
271
272     std::cout << "\n Correct usage:" << std::endl;
273     safe_printf("Integer: %d, String: %s, Float: %.2f\n", 42, "hello", 3.14);
274
275     std::cout << "\n Incorrect usage (caught at runtime):" << std::endl;
276     safe_printf("Two specifiers: %d %s\n", 42); // Missing argument!
277
278     std::cout << "\n BETTER APPROACH:" << std::endl;
279     std::cout << "    Use C++20 std::format for complete type safety!" << std::endl;
280     std::cout << "    Or compile-time format string validation" << std::endl;
281 }
282
283 // =====
284 // SECTION 6: COMPILE-TIME ARRAY INITIALIZATION
285 // =====
286
287 // Create array with compile-time computed values
288 template<typename... Args>
289 constexpr auto make_array(Args... args) {
290     return std::array<std::common_type_t<Args...>, sizeof...(Args)>{args...};
291 }
292
293 // Fibonacci at compile-time
294 constexpr int fib(int n) {
295     return (n <= 1) ? n : fib(n-1) + fib(n-2);
296 }
297
298 // Generate array of first N fibonacci numbers
299 template<size_t... Is>
300 constexpr auto fib_array_impl(std::index_sequence<Is...>) {
301     return std::array<int, sizeof...(Is)>{fib(Is)...};
302 }
303
304 template<size_t N>
305 constexpr auto fib_array() {
306     return fib_array_impl(std::make_index_sequence<N>{});
307 }
```

```
308
309 void demonstrate_compile_time_array() {
310     std::cout << "\n==== 6. COMPILE-TIME ARRAY INITIALIZATION ===" << std::endl
311     ;
312
313     // Array created at compile-time!
314     constexpr auto arr = make_array(10, 20, 30, 40, 50);
315     std::cout << "\nArray: ";
316     for (auto val : arr) {
317         std::cout << val << " ";
318     }
319     std::cout << std::endl;
320
321     // Fibonacci array computed at compile-time!
322     constexpr auto fibs = fib_array<10>();
323     std::cout << "\nFirst 10 Fibonacci numbers (compile-time): ";
324     for (auto val : fibs) {
325         std::cout << val << " ";
326     }
327     std::cout << std::endl;
328
329     std::cout << "\n PERFORMANCE:" << std::endl;
330     std::cout << " • Arrays are in .rodata section (read-only)" << std::endl
331     ;
332     std::cout << " • No initialization code at runtime" << std::endl;
333     std::cout << " • Values embedded in binary" << std::endl;
334 }
335
336 // =====
337 // SECTION 7: EMBEDDED SYSTEMS - REGISTER CONFIGURATION
338 // =====
339
340 // Compile-time register bit field computation
341 template<uint32_t... Bits>
342 struct RegisterBits {
343     static constexpr uint32_t value = ((1u << Bits) | ...);
344 };
345
346 // Compile-time register configuration
347 enum class GPIO_Pin : uint8_t {
348     Pin0 = 0, Pin1 = 1, Pin2 = 2, Pin3 = 3,
349     Pin4 = 4, Pin5 = 5, Pin6 = 6, Pin7 = 7
350 };
351
352 template<GPIO_Pin... Pins>
353 struct GPIO_Config {
354     static constexpr uint8_t mask = ((1u << static_cast<uint8_t>(Pins)) | ...
355     ;
356
357     static void set_output() {
358         // This would write to actual hardware register
359         std::cout << "    Setting pins 0x" << std::hex
360             << static_cast<int>(mask) << std::dec
361             << " as output" << std::endl;
362 }
```

```

359     }
360 };
361
362 // Compile-time validation of peripheral configuration
363 template<uint32_t ClockFreq, uint32_t DesiredBaud>
364 struct UART_Divider {
365     static constexpr uint32_t divider = ClockFreq / (16 * DesiredBaud);
366     static constexpr uint32_t actual_baud = ClockFreq / (16 * divider);
367     static constexpr uint32_t error_percent =
368         (actual_baud > DesiredBaud)
369             ? ((actual_baud - DesiredBaud) * 100 / DesiredBaud)
370             : ((DesiredBaud - actual_baud) * 100 / DesiredBaud);
371
372     static_assert(divider > 0 && divider < 65536,
373                 "UART divider out of range!");
374     static_assert(error_percent < 3,
375                 "Baud rate error exceeds 3%!");
376 };
377
378 void demonstrate_embedded_usage() {
379     std::cout << "\n==== 7. EMBEDDED SYSTEMS APPLICATIONS ===" << std::endl;
380
381     std::cout << "\n Register bit configuration (compile-time):" << std::endl
382         ;
383     constexpr uint32_t bits = RegisterBits<0, 2, 4, 7>::value;
384     std::cout << "    Bits 0,2,4,7 = 0x" << std::hex << bits << std::dec
385         << " (0b" << std::bitset<8>(bits) << ")" << std::endl;
386
387     std::cout << "\n GPIO configuration (compile-time):" << std::endl;
388     using MyGPIO = GPIO_Config<GPIO_Pin::Pin0, GPIO_Pin::Pin3, GPIO_Pin::Pin7
389         >;
390     std::cout << "    GPIO mask: 0x" << std::hex
391         << static_cast<int>(MyGPIO::mask) << std::dec << std::endl;
392     MyGPIO::set_output();
393
394     std::cout << "\n UART configuration (compile-time validated):" << std::
395         endl;
396     using UART = UART_Divider<16000000, 9600>;
397     std::cout << "    Clock: 16MHz, Baud: 9600" << std::endl;
398     std::cout << "    Divider: " << UART::divider
399         << " (computed at compile-time)" << std::endl;
400
401     std::cout << "\n EMBEDDED BENEFITS:" << std::endl;
402     std::cout << "    Configuration errors caught at compile-time" << std::
403         endl;
404     std::cout << "    Zero runtime overhead" << std::endl;
405     std::cout << "    No magic numbers - everything is named" << std::endl;
406     std::cout << "    Hardware constraints validated at compile-time" << std
407         ::endl;
408 }
409
410 // =====
411 // SECTION 8: TUPLE OPERATIONS - COMPILE-TIME RECURSION
412 // =====

```

```
408 // Print tuple recursively at compile-time
409 template<size_t Index = 0, typename... Types>
410 void print_tuple(const std::tuple<Types...>& t) {
411     if constexpr (Index < sizeof...(Types)) {
412         std::cout << std::get<Index>(t);
413         if constexpr (Index + 1 < sizeof...(Types)) {
414             std::cout << ", ";
415         }
416         print_tuple<Index + 1>(t);
417     }
418 }
419
420
421 // Sum all tuple elements (if numeric)
422 template<size_t Index = 0, typename... Types>
423 auto sum_tuple(const std::tuple<Types...>& t) {
424     if constexpr (Index < sizeof...(Types)) {
425         if constexpr (Index + 1 < sizeof...(Types)) {
426             return std::get<Index>(t) + sum_tuple<Index + 1>(t);
427         } else {
428             return std::get<Index>(t);
429         }
430     } else {
431         return 0;
432     }
433 }
434
435 void demonstrate_tuple_operations() {
436     std::cout << "\n== 8. TUPLE OPERATIONS WITH RECURSION ==" << std::endl;
437
438     auto mixed_tuple = std::make_tuple(1, "hello", 3.14, 'X');
439     std::cout << "\nTuple: ";
440     print_tuple(mixed_tuple);
441     std::cout << std::endl;
442
443     auto numeric_tuple = std::make_tuple(10, 20, 30, 40, 50);
444     std::cout << "\nNumeric tuple: ";
445     print_tuple(numeric_tuple);
446     std::cout << std::endl;
447
448     auto total = sum_tuple(numeric_tuple);
449     std::cout << "Sum: " << total << std::endl;
450
451     std::cout << "\n if constexpr:" << std::endl;
452     std::cout << " • Compile-time conditional" << std::endl;
453     std::cout << " • Dead branches eliminated by compiler" << std::endl;
454     std::cout << " • Perfect for template recursion termination" << std::endl;
455 }
456
457 // =====
458 // SECTION 9: WHEN TO USE COMPILE-TIME RECURSION
459 // =====
```

```
461 void explain_when_to_use() {
462     std::cout << "\n" << std::string(70, '=') << std::endl;
463     std::cout << "WHEN TO USE COMPILE-TIME RECURSION:\n";
464     std::cout << std::string(70, '=') << std::endl;
465
466     std::cout << "\n USE FOR:" << std::endl;
467     std::cout << "\n1. TYPE COMPUTATIONS:" << std::endl;
468     std::cout << " • Finding largest type in parameter pack" << std::endl;
469     std::cout << " • Type trait combinations" << std::endl;
470     std::cout << " • Template metaprogramming" << std::endl;
471
472     std::cout << "\n2. COMPILE-TIME CONSTANTS:" << std::endl;
473     std::cout << " • Mathematical computations (Fibonacci, factorial)" <<
474         std::endl;
474     std::cout << " • Configuration values" << std::endl;
475     std::cout << " • Lookup tables" << std::endl;
476
477     std::cout << "\n3. HETEROGENEOUS COLLECTIONS:" << std::endl;
478     std::cout << " • Tuple operations" << std::endl;
479     std::cout << " • Variant handling" << std::endl;
480     std::cout << " • Type-safe function wrappers" << std::endl;
481
482     std::cout << "\n4. EMBEDDED SYSTEMS:" << std::endl;
483     std::cout << " • Hardware register configuration" << std::endl;
484     std::cout << " • Peripheral setup validation" << std::endl;
485     std::cout << " • Zero-overhead abstractions" << std::endl;
486     std::cout << " • Compile-time constraint checking" << std::endl;
487
488     std::cout << "\n5. CODE GENERATION:" << std::endl;
489     std::cout << " • Unrolling loops at compile-time" << std::endl;
490     std::cout << " • Generating specialized functions" << std::endl;
491     std::cout << " • Avoiding runtime dispatch" << std::endl;
492
493     std::cout << "\n DON'T USE FOR:" << std::endl;
494     std::cout << "\n1. RUNTIME DATA:" << std::endl;
495     std::cout << " • User input processing" << std::endl;
496     std::cout << " • Dynamic collections" << std::endl;
497     std::cout << " • Data-dependent logic" << std::endl;
498
499     std::cout << "\n2. EXCESSIVE RECURSION:" << std::endl;
500     std::cout << " • Deep recursion slows compilation" << std::endl;
501     std::cout << " • Can cause compiler errors (recursion limits)" << std::
502         endl;
502     std::cout << " • Use fold expressions when possible" << std::endl;
503
504     std::cout << "\n3. SIMPLE CASES:" << std::endl;
505     std::cout << " • Use standard library when available" << std::endl;
506     std::cout << " • Don't reinvent the wheel" << std::endl;
507
508     std::cout << "\n MODERN C++ ALTERNATIVES:" << std::endl;
509     std::cout << " • C++17: Fold expressions (replace simple recursion)" <<
510         std::endl;
510     std::cout << " • C++17: if constexpr (cleaner recursion)" << std::endl;
511     std::cout << " • C++20: Concepts (constrain templates)" << std::endl;
```

```

512     std::cout << " • C++20: consteval (force compile-time evaluation)" <<
513         std::endl;
514 }
515 // =====
516 // SECTION 10: PERFORMANCE COMPARISON
517 // =====
518
519 // Runtime version
520 int sum_runtime(int* values, size_t count) {
521     int total = 0;
522     for (size_t i = 0; i < count; ++i) {
523         total += values[i];
524     }
525     return total;
526 }
527
528 void demonstrate_performance_comparison() {
529     std::cout << "\n" << std::string(70, '=') << std::endl;
530     std::cout << "PERFORMANCE: COMPILE-TIME VS RUNTIME:\n";
531     std::cout << std::string(70, '=') << std::endl;
532
533     std::cout << "\n COMPILE-TIME (variadic template):" << std::endl;
534     constexpr int compile_time_sum = sum(1, 2, 3, 4, 5);
535     std::cout << "    Result: " << compile_time_sum << std::endl;
536     std::cout << "    Binary: MOV EAX, 15 (single instruction!)" << std::endl;
537     std::cout << "    Cost: 0 CPU cycles at runtime" << std::endl;
538     std::cout << "    Size: ~4 bytes (just the constant)" << std::endl;
539
540     std::cout << "\n RUNTIME (loop):" << std::endl;
541     int values[] = {1, 2, 3, 4, 5};
542     int runtime_sum = sum_runtime(values, 5);
543     std::cout << "    Result: " << runtime_sum << std::endl;
544     std::cout << "    Binary: ~20+ instructions (loop, increment, add)" << std
545         ::endl;
546     std::cout << "    Cost: ~10+ CPU cycles" << std::endl;
547     std::cout << "    Size: ~40+ bytes (loop code)" << std::endl;
548
549     std::cout << "\n SPEEDUP: Infinite (0 vs ~10 cycles)" << std::endl;
550     std::cout << "    SIZE: 10x smaller (4 vs 40+ bytes)" << std::endl;
551
552     std::cout << "\n WHEN COMPILE-TIME WINS:" << std::endl;
553     std::cout << " • Values known at compile-time" << std::endl;
554     std::cout << " • Constant configuration" << std::endl;
555     std::cout << " • Type computations" << std::endl;
556     std::cout << " • Safety-critical embedded systems" << std::endl;
557 }
558 // =====
559 // SECTION 11: DRAWBACKS AND PITFALLS
560 // =====
561
562 // Pitfall 1: Deep recursion causes slow compilation
563 template<int N>

```

```
564 struct Fibonacci {
565     static constexpr int value = Fibonacci<N-1>::value + Fibonacci<N-2>::value
566     ;
567 };
568 template<> struct Fibonacci<0> { static constexpr int value = 0; };
569 template<> struct Fibonacci<1> { static constexpr int value = 1; };
570
571 // Pitfall 2: Exponential template instantiations
572 template<typename... Args>
573 struct InstantiationExplosion {
574     // Each call creates multiple instantiations
575     using type = std::tuple<Args..., Args...>; // Doubles the types!
576 };
577
578 // Pitfall 3: Cryptic error messages
579 template<typename... Args>
580 constexpr auto bad_function(Args... args) {
581     // This will produce a HORRIBLE error message if types don't support
582     // operator+
583     return (args + ...);
584 }
585
586 // Pitfall 4: Code bloat - each instantiation generates code
587 template<typename T>
588 T generic_sort(T value) {
589     // Even though this does nothing different, compiler generates
590     // separate code for EACH type instantiation
591     std::cout << "Sorting single value: " << value << std::endl;
592     return value;
593 }
594
595 // Pitfall 5: Hidden recursion limits
596 template<int N>
597 struct DeepRecursion {
598     static constexpr int value = DeepRecursion<N-1>::value + 1;
599 };
600 template<> struct DeepRecursion<0> { static constexpr int value = 0; };
601
602 void demonstrate_drawbacks_and_pitfalls() {
603     std::cout << "\n" << std::string(70, '=') << std::endl;
604     std::cout << "DRAWBACKS AND POTENTIAL PITFALLS:\n";
605     std::cout << std::string(70, '=') << std::endl;
606
607     std::cout << "\n PITFALL 1: SLOW COMPILATION" << std::endl;
608     std::cout << "    Problem: Deep template recursion is SLOW to compile" <<
609     std::endl;
610     std::cout << "    Example: Fibonacci<40>::value takes FOREVER to compile!" <<
611     std::endl;
612
613     // Safe to compute small values
614     constexpr int fib10 = Fibonacci<10>::value;
615     std::cout << "    Fibonacci<10> = " << fib10 << " (tolerable)" << std::endl
616     ;
```

```
613 // Fibonacci<40> would take minutes to compile!
614 // constexpr int fib40 = Fibonacci<40>::value; // DON'T DO THIS!
615
616
617 std::cout << "\n      Solution:" << std::endl;
618 std::cout << " •      Use constexpr functions instead of template
619   recursion" << std::endl;
620 std::cout << " •      constexpr int fib(int n) { return (n<=1) ? n : fib(n
621     -1)+fib(n-2); }" << std::endl;
622 std::cout << " •      Much faster compilation, same runtime performance"
623   << std::endl;
624
625 std::cout << "\n PITFALL 2: CRYPTIC ERROR MESSAGES" << std::endl;
626 std::cout << "      Problem: Template errors are EXTREMELY hard to read" <<
627   std::endl;
628 std::cout << "      Example error (trying to add strings with +):" << std::
629   endl;
630 std::cout << "      error: invalid operands to binary expression" << std::
631   endl;
632 std::cout << "      ('std::string' and 'std::string')" << std::endl;
633 std::cout << "      in instantiation of function template specialization"
634   << std::endl;
635 std::cout << "      'bad_function<std::string, std::string>' requested
636   here" << std::endl;
637 std::cout << "      ... 50 more lines of template instantiation backtrace
638   ..." << std::endl;
639
640 std::cout << "\n      Solution:" << std::endl;
641 std::cout << " •      Use C++20 concepts to constrain templates EARLY" <<
642   std::endl;
643 std::cout << " •      Add static_assert with clear messages" << std::endl;
644 std::cout << " •      Use std::enable_if with meaningful names" << std::
645   endl;
646
647 std::cout << "\n PITFALL 3: CODE BLOAT" << std::endl;
648 std::cout << "      Problem: Each template instantiation generates SEPARATE
649   code" << std::endl;
650
651 // Each call generates separate function in binary
652 generic_sort(10);
653 generic_sort(20.5);
654 generic_sort(std::string("hello"));
655
656 std::cout << "\n      Impact on binary size:" << std::endl;
657 std::cout << " •      generic_sort<int>      : ~50 bytes" << std::endl;
658 std::cout << " •      generic_sort<double>    : ~50 bytes" << std::endl;
659 std::cout << " •      generic_sort<string>   : ~80 bytes" << std::endl;
660 std::cout << " •      Total                  : ~180 bytes for same logic!"
661   << std::endl;
662
663 std::cout << "\n      Solution:" << std::endl;
664 std::cout << " •      Use type erasure for runtime polymorphism" << std::
665   endl;
666 std::cout << " •      Extract common code into non-template functions" <<
```

```

        std::endl;
653  std::cout << " •      Use extern template to prevent duplicate
           instantiations" << std::endl;

654
655  std::cout << "\n PITFALL 4: COMPILER RECURSION LIMITS" << std::endl;
656  std::cout << "    Problem: Compilers have hard limits on template depth" <<
           std::endl;
657  std::cout << "    Typical limit: 256-1024 instantiation depth" << std::endl
           ;
658
659 // This works (small depth)
660 constexpr int depth_100 = DeepRecursion<100>::value;
661 std::cout << "    DeepRecursion<100> = " << depth_100 << " (works)" << std
           ::endl;
662
663 // DeepRecursion<2000> would hit the limit!
664 // constexpr int depth_2000 = DeepRecursion<2000>::value; // ERROR!
665
666 std::cout << "\n    Error you'd see:" << std::endl;
667 std::cout << "    fatal error: recursive template instantiation exceeded
           " << std::endl;
668 std::cout << "    maximum depth of 1024" << std::endl;
669
670 std::cout << "\n    Solution:" << std::endl;
671 std::cout << " •      Use constexpr functions instead" << std::endl;
672 std::cout << " •      Use fold expressions (no recursion)" << std::endl;
673 std::cout << " •      Increase limit: -ftemplate-depth=2000 (not
           recommended!)" << std::endl;
674
675 std::cout << "\n PITFALL 5: DEBUGGING NIGHTMARE" << std::endl;
676 std::cout << "    Problem: Can't step through template code" << std::endl;
677 std::cout << " •      Debugger shows instantiated code, not template" << std
           ::endl;
678 std::cout << " •      Type names are mangled and unreadable" << std::endl;
679 std::cout << " •      Call stack filled with template instantiation frames"
           << std::endl;
680
681 std::cout << "\n    Solution:" << std::endl;
682 std::cout << " •      Use std::cout for compile-time debugging" << std::
           endl;
683 std::cout << " •      Use static_assert to validate assumptions" << std::
           endl;
684 std::cout << " •      Test with simple types first" << std::endl;
685 std::cout << " •      Use __PRETTY_FUNCTION__ to see instantiated types"
           << std::endl;
686
687 std::cout << "\n PITFALL 6: EXCESSIVE MEMORY DURING COMPILATION" << std::
           endl;
688 std::cout << "    Problem: Complex templates use LOTS of compiler memory"
           << std::endl;
689 std::cout << "    Impact:" << std::endl;
690 std::cout << " •      Simple project: ~500MB compiler memory" << std::endl
           ;
691 std::cout << " •      Heavy template use: 4GB+ compiler memory" << std::

```

```
        endl;
692     std::cout << " •      Can cause out-of-memory errors in CI/CD" << std::
       endl;

693
694     std::cout << "\n      Solution:" << std::endl;
695     std::cout << " •      Split template-heavy code across files" << std::endl
       ;
696     std::cout << " •      Use forward declarations" << std::endl;
697     std::cout << " •      Use precompiled headers for common instantiations"
       << std::endl;
698     std::cout << " •      Consider compilation time in design decisions" <<
       std::endl;
699 }
700
701 // =====
702 // SECTION 12: REAL-WORLD EXAMPLES OF THINGS GOING WRONG
703 // =====
704
705 // Example 1: Accidental O(2^N) compilation complexity
706 template<int N, typename... Args>
707 struct BadMetaFunction {
708     // Each level DOUBLES the work - exponential explosion!
709     using result = typename BadMetaFunction<N-1, Args..., Args...>::result;
710 };
711
712 template<typename... Args>
713 struct BadMetaFunction<0, Args...> {
714     using result = std::tuple<Args...>;
715 };
716
717 // Example 2: Forgetting base case - infinite recursion
718 // template<typename T, typename... Rest>
719 // struct ForgetBaseCase {
720 //     static constexpr int value = 1 + ForgetBaseCase<Rest...>::value;
721 //     // OOPS! No base case for empty pack!
722 // };
723
724 // Example 3: Ambiguous overload resolution
725 template<typename T>
726 void overload_problem(T value) {
727     std::cout << "Generic version" << std::endl;
728 }
729
730 template<typename T, typename... Args>
731 void overload_problem(T first, Args... rest) {
732     std::cout << "Variadic version" << std::endl;
733 }
734
735 // overload_problem(42); // Ambiguous! Which one to call?
736
737 // Example 4: Type deduction failure
738 template<typename... Args>
739 auto broken_deduction(Args... args) {
740     // This fails if args is empty!
```

```
741 // auto first = args...; // ERROR: can't expand to nothing
742 return 0;
743 }

744

745 void demonstrate_real_world_failures() {
746     std::cout << "\n" << std::string(70, '=') << std::endl;
747     std::cout << "REAL-WORLD EXAMPLES OF FAILURES:\n";
748     std::cout << std::string(70, '=') << std::endl;

749

750     std::cout << "\n FAILURE 1: EXPONENTIAL COMPILE TIME" << std::endl;
751     std::cout << "    Code: BadMetaFunction<N, Types...>" << std::endl;
752     std::cout << "    Problem: Each recursion DOUBLES the type list" << std::endl;
753     std::cout << "    Complexity: O(2^N) template instantiations!" << std::endl;
754     std::cout << "    Result:" << std::endl;
755     std::cout << " •      N=5: 32 instantiations (0.1s)" << std::endl;
756     std::cout << " •      N=10: 1024 instantiations (5s)" << std::endl;
757     std::cout << " •      N=15: 32768 instantiations (MINUTES!)" << std::endl;
758     std::cout << " •      N=20: Out of memory / compiler crash" << std::endl;

759

760     std::cout << "\n FAILURE 2: MISSING BASE CASE" << std::endl;
761     std::cout << "    Error message:" << std::endl;
762     std::cout << "    fatal error: template instantiation depth exceeds
763         maximum" << std::endl;
764     std::cout << "    note: use -ftemplate-depth= to increase the maximum"
765         << std::endl;
766     std::cout << "    Root cause: Forgot to specialize for empty parameter pack
767         " << std::endl;
768     std::cout << "    Fix: Always provide template<> specialization" << std::endl;

769

770     std::cout << "\n FAILURE 3: AMBIGUOUS OVERLOADS" << std::endl;
771     std::cout << "    Problem: overload_problem(42)" << std::endl;
772     std::cout << "    Both match:" << std::endl;
773     std::cout << " •      void overload_problem(T)           // T=int" << std::endl;
774     std::cout << " •      void overload_problem(T, Args...) // T=int, Args=<>
775         " << std::endl;
776     std::cout << "    Solution: Use SFINAE or concepts to disambiguate" << std::endl;

777

778     std::cout << "\n FAILURE 4: EMPTY PARAMETER PACK" << std::endl;
779     std::cout << "    Problem: broken_deduction() called with no arguments" <<
780         std::endl;
781     std::cout << "    Can't expand empty pack in certain contexts" << std::endl;
782     std::cout << "    Solution: Always check sizeof...(Args) or provide base
783         case" << std::endl;

784

785     std::cout << "\n FAILURE 5: TYPE DEDUCTION CONFUSION" << std::endl;
786     std::cout << "    Problem: auto deduction with parameter packs" << std::endl;
787     std::cout << "    Example:" << std::endl;
```

```

782     std::cout << "      template<typename... Args>" << std::endl;
783     std::cout << "      auto func(Args... args) {" << std::endl;
784     std::cout << "          return args; // Which one? ERROR!" << std::endl;
785     std::cout << "      }" << std::endl;
786     std::cout << "      Solution: Be explicit about which argument to return" <<
787         std::endl;
788 }
789
790 // =====
791 // SECTION 13: BEST PRACTICES TO AVOID PITFALLS
792 // =====
793 void explain_best_practices() {
794     std::cout << "\n" << std::string(70, '=') << std::endl;
795     std::cout << "BEST PRACTICES TO AVOID PITFALLS:\n";
796     std::cout << std::string(70, '=') << std::endl;
797
798     std::cout << "\n DO:" << std::endl;
799
800     std::cout << "\n1. USE FOLD EXPRESSIONS (C++17+):" << std::endl;
801     std::cout << "      BAD: Explicit recursion for sum" << std::endl;
802     std::cout << "          template<typename T>" << std::endl;
803     std::cout << "          T sum(T t) { return t; }" << std::endl;
804     std::cout << "          template<typename T, typename... Args>" << std::endl;
805     std::cout << "          T sum(T t, Args... args) { return t + sum(args...); }"
806         << std::endl;
807     std::cout << "\n      GOOD: Fold expression" << std::endl;
808     std::cout << "          template<typename... Args>" << std::endl;
809     std::cout << "          auto sum(Args... args) { return (args + ...); }" <<
810         std::endl;
811
812     std::cout << "\n2. USE CONSTEXPR FUNCTIONS OVER TEMPLATE RECURSION:" <<
813         std::endl;
814     std::cout << "      BAD: template<int N> struct Fib { ... };" << std::endl;
815     std::cout << "          ;"
816     std::cout << "      GOOD: constexpr int fib(int n) { ... }" << std::endl;
817     std::cout << "      Benefits: Faster compilation, clearer code, easier to
818         debug" << std::endl;
819
820     std::cout << "\n3. USE CONCEPTS TO CONSTRAIN EARLY (C++20):" << std::endl;
821     std::cout << "      BAD: template<typename T> void func(T t) { t + t; }"
822         << std::endl;
823     std::cout << "      GOOD: template<std::integral T> void func(T t) { t + t;
824         }" << std::endl;
825     std::cout << "      Benefits: Clear error messages, compile-time validation"
826         << std::endl;
827
828     std::cout << "\n4. ALWAYS PROVIDE BASE CASE:" << std::endl;
829     std::cout << "      BAD: Only recursive case" << std::endl;
830     std::cout << "      GOOD: template<> struct Base { }; + recursive case"
831         << std::endl;
832     std::cout << "      Benefits: Avoid infinite recursion errors" << std::endl;
833
834     std::cout << "\n5. USE static_assert WITH CLEAR MESSAGES:" << std::endl;

```

```

826     std::cout << "      GOOD: static_assert(sizeof...(Args) > 0, \"Need at"
827         "least one argument\");" << std::endl;
828     std::cout << "      Benefits: Catch errors early with helpful messages" <<
829         std::endl;
830
831     std::cout << "\n6. TEST WITH SIMPLE TYPES FIRST:" << std::endl;
832     std::cout << " • Start with int, double before complex types" << std::
833         endl;
834     std::cout << " • Verify logic works before adding complexity" << std::
835         endl;
836     std::cout << " • Use small parameter counts during development" << std::
837         endl;
838
839     std::cout << "\n7. MEASURE COMPILATION TIME:" << std::endl;
840     std::cout << " • Use -ftime-report (GCC/Clang)" << std::endl;
841     std::cout << " • Track build times in CI/CD" << std::endl;
842     std::cout << " • Set reasonable limits (e.g., <10s per file)" << std::
843         endl;
844
845     std::cout << "\n8. DOCUMENT CONSTRAINTS:" << std::endl;
846     std::cout << " • Specify required type traits" << std::endl;
847     std::cout << " • Document recursion depth limits" << std::endl;
848     std::cout << " • Provide usage examples" << std::endl;
849
850
851     std::cout << "\n DON'T:" << std::endl;
852     std::cout << "1. DON'T use template recursion for deep computations" <<
853         std::endl;
854     std::cout << "2. DON'T instantiate with many types unless necessary" <<
855         std::endl;
856     std::cout << "3. DON'T ignore compilation time during development" << std
857         ::endl;
858     std::cout << "4. DON'T use variadic templates for runtime data" << std::
859         endl;
860     std::cout << "5. DON'T nest template recursion deeply" << std::endl;
861
862
863     std::cout << "\n GOLDEN RULE:" << std::endl;
864     std::cout << " If it takes more than 1 second to compile," << std::endl;
865     std::cout << " you're probably doing it wrong!" << std::endl;
866 }

867 // =====
868 // MAIN FUNCTION
869 // =====

870 int main() {
871     std::cout << "\n";
872     std::cout << "                                     \n";
873     std::cout << "      VARIADIC TEMPLATES & COMPILE-TIME RECURSION
874                                     \n";
875     std::cout << "                                     \n";
876     std::cout << "      Zero runtime cost • Type safety • Perfect for embedded
877                                     \n";
878     std::cout << "                                     \n";

```

```
867 demonstrate_basic_recursion();
868 demonstrate_compile_time_computation();
869 demonstrate_type_manipulation();
870 demonstrate_fold_expressions();
871 demonstrate_safe_printf();
872 demonstrate_compile_time_array();
873 demonstrate_embedded_usage();
874 demonstrate_tuple_operations();
875 explain_when_to_use();
876 demonstrate_performance_comparison();
877 demonstrate_drawbacks_and_pitfalls();
878 demonstrate_real_world_failures();
879 explain_best_practices();

880 std::cout << "\n" << std::string(70, '=')
881 << std::endl;
882 std::cout << "SUMMARY:\n";
883 std::cout << std::string(70, '=')
884 << std::endl;

885 std::cout << "\n KEY TAKEAWAYS:" << std::endl;
886 std::cout << "\n1. COMPILE-TIME RECURSION:" << std::endl;
887 std::cout << " • All computation happens during compilation" << std::endl;
888 std::cout << " • Zero runtime cost" << std::endl;
889 std::cout << " • Results embedded in binary as constants" << std::endl;

890 std::cout << "\n2. VARIADIC TEMPLATES:" << std::endl;
891 std::cout << " • Handle any number of arguments" << std::endl;
892 std::cout << " • Type-safe heterogeneous processing" << std::endl;
893 std::cout << " • Perfect for metaprogramming" << std::endl;

894 std::cout << "\n3. EMBEDDED SYSTEMS:" << std::endl;
895 std::cout << " • Validate hardware configurations at compile-time" <<
896 std::endl;
897 std::cout << " • Zero-overhead abstractions" << std::endl;
898 std::cout << " • Catch errors before deployment" << std::endl;
899 std::cout << " • Minimal binary size impact" << std::endl;

900 std::cout << "\n4. MODERN FEATURES:" << std::endl;
901 std::cout << " • Use fold expressions (C++17) when possible" << std::endl;
902 std::cout << " • Use if constexpr for cleaner recursion" << std::endl;
903 std::cout << " • Use constexpr/constexpr for clarity" << std::endl;
904 std::cout << " • Combine with concepts for constraints" << std::endl;

905 std::cout << "\n CRITICAL PITFALLS TO AVOID:" << std::endl;
906 std::cout << "\n1. COMPILATION TIME:" << std::endl;
907 std::cout << " • Template recursion can be VERY slow" << std::endl;
908 std::cout << " • Prefer constexpr functions over template recursion" <<
909 std::endl;
910 std::cout << " • Use fold expressions to eliminate recursion" << std::endl;

911 std::cout << "\n2. CODE BLOAT:" << std::endl;
```

```
916     std::cout << " • Each instantiation = separate code in binary" << std::endl;
917     std::cout << " • Can increase binary size significantly" << std::endl;
918     std::cout << " • Extract common code to non-template functions" << std::endl;
919
920     std::cout << "\n3. ERROR MESSAGES:" << std::endl;
921     std::cout << " • Template errors are cryptic and verbose" << std::endl;
922     std::cout << " • Use concepts (C++20) for better errors" << std::endl;
923     std::cout << " • Add static_assert with clear messages" << std::endl;
924
925     std::cout << "\n4. RECURSION LIMITS:" << std::endl;
926     std::cout << " • Compilers limit template depth (256-1024)" << std::endl;
927     std::cout << " • Don't increase limits - redesign instead!" << std::endl;
928     std::cout << " • Always provide proper base cases" << std::endl;
929
930     std::cout << "\n Compile-Time = Type Safety + Zero Cost!\n" << std::endl;
931     std::cout << " But use responsibly - compilation time matters!\n" << std::endl;
932
933     return 0;
934 }
```

75 Source Code: VirtualFunctionsInTemplates.cpp

File: src/VirtualFunctionsInTemplates.cpp

Repository: [View on GitHub](#)

```
1  /*
2   * VIRTUAL FUNCTIONS IN TEMPLATES: THE CODE BLOAT PROBLEM
3   *
4   * This file demonstrates WHY you should AVOID virtual functions in class
5   * templates
6   * and shows the severe code bloat that results from naive templatization.
7   *
8   * KEY PRINCIPLE: Virtual functions in templates are instantiated EVERY TIME,
9   * even if never called, causing exponential code bloat.
10  *
11  * References:
12  * - C++ Core Guidelines T.80: Do not naively templatize a class hierarchy
13  * - C++ Core Guidelines T.5: Combine generic and OO techniques judiciously
14  * - C++ Core Guidelines T.84: Use a non-template core implementation
15  */
16 #include <iostream>
17 #include <vector>
18 #include <string>
19 #include <memory>
20 #include <algorithm>
21 //
22 //=====
23 // SECTION 1: THE PROBLEM - WHY VIRTUAL FUNCTIONS CAUSE BLOAT
24 //=====
25
26 namespace the_problem {
27
28 /*
29  * THE CORE ISSUE:
30  *
31  * In a class template:
32  * - NON-VIRTUAL functions: Only instantiated if explicitly called (lazy)
33  * - VIRTUAL functions: ALWAYS instantiated when class is instantiated (eager)
34  *
35  * WHY?
36  * Virtual functions MUST be in the vtable, and the vtable is constructed
37  * at compile-time during template instantiation. Therefore, ALL virtual
38  * functions must be compiled, even if your code never calls them.
39  *
40  * This is the root cause of code bloat in template hierarchies.
41  */
42
43 template<typename T>
44 class DemoInstantiation {
```

```
45 | public:
46 |     // VIRTUAL: Compiled when class is instantiated
47 |     virtual void always_compiled() {
48 |         std::cout << "Virtual: always compiled for " << typeid(T).name() << "\n";
49 |     }
50 |
51 |     virtual void never_called_but_still_compiled() {
52 |         std::cout << "Virtual: wasting space for " << typeid(T).name() << "\n";
53 |         ;
54 |     }
55 |
56 |     virtual ~DemoInstantiation() = default;
57 |
58 |     // NON-VIRTUAL: Only compiled if actually called
59 |     void only_if_used() {
60 |         std::cout << "Non-virtual: only compiled if called for " << typeid(T).name()
61 |             () << "\n";
62 |     }
63 |
64 |     void also_only_if_used() {
65 |         std::cout << "Non-virtual: lazy instantiation for " << typeid(T).name()
66 |             () << "\n";
67 |     }
68 |
69 | };
70 |
71 | void demonstrate() {
72 |     std::cout << "\n" << std::string(70, '=') << "\n";
73 |     std::cout << "THE PROBLEM: Virtual Functions Cause Template Bloat\n";
74 |     std::cout << std::string(70, '=') << "\n\n";
75 |
76 |     std::cout << "Creating DemoInstantiation<int>:\n\n";
77 |     DemoInstantiation<int> demo;
78 |
79 |     std::cout << "What gets compiled?\n";
80 |     std::cout << "    always_compiled() - YES (virtual, in vtable)\n";
81 |     std::cout << "    never_called_but_still_compiled() - YES (virtual, in
82 |                 vtable)\n";
83 |     std::cout << "    only_if_used() - NO (not called yet)\n";
84 |     std::cout << "    also_only_if_used() - NO (not called yet)\n\n";
85 |
86 |     demo.always_compiled();
87 |
88 |     std::cout << "\n THE BLOAT:\n";
89 |     std::cout << " • never_called_but_still_compiled() is compiled\n";
90 |     std::cout << " • It's in the binary taking up space\n";
91 |     std::cout << " • But we never call it!\n";
92 |     std::cout << " • This is WASTED CODE\n\n";
93 |
94 |     std::cout << "Now imagine:\n";
95 |     std::cout << " • 10 virtual functions\n";
96 |     std::cout << " • 10 template instantiations\n";
97 |     std::cout << " • = 100 compiled functions\n";
98 |     std::cout << " • If you only use 2-3 per type = 70-80 wasted functions!\n";
```

```
        n";
94 }
95
96 } // namespace the_problem
97
98 // =====
99 // SECTION 2: THE BAD EXAMPLE - C++ Core Guidelines T.80
100 // =====
101
102 namespace bad_example_t80 {
103
104 /*
105 *   BAD DESIGN: Template with virtual functions
106 *
107 * This is the EXACT example from C++ Core Guidelines T.80 showing
108 * what NOT to do when designing template hierarchies.
109 */
110
111 template<typename T>
112 struct Container {           // an interface
113     virtual T* get(int i) = 0;
114     virtual T* first() = 0;
115     virtual T* next() = 0;
116     virtual void sort() = 0;
117     virtual ~Container() = default;
118 };
119
120 template<typename T>
121 class Vector : public Container<T> {
122 private:
123     std::vector<T> data_;
124     typename std::vector<T>::iterator current_;
125
126 public:
127     Vector() : current_(data_.begin()) {}
128
129     T* get(int i) override {
130         return (i >= 0 && i < static_cast<int>(data_.size())) ? &data_[i] :
131             nullptr;
132     }
133
134     T* first() override {
135         current_ = data_.begin();
136         return current_ != data_.end() ? &(*current_) : nullptr;
137     }
138
139     T* next() override {
140         if (current_ != data_.end()) ++current_;
141         return current_ != data_.end() ? &(*current_) : nullptr;
142     }
143 }
```

```
142
143     void sort() override {
144         std::sort(data_.begin(), data_.end());
145     }
146
147     void add(const T& item) { data_.push_back(item); }
148 };
149
150 void demonstrate() {
151     std::cout << "\n" << std::string(70, '=') << "\n";
152     std::cout << "BAD EXAMPLE: C++ Core Guidelines T.80\n";
153     std::cout << std::string(70, '=') << "\n\n";
154
155     std::cout << "Code:\n";
156     std::cout << "    template<typename T>\n";
157     std::cout << "    struct Container {\n";
158     std::cout << "        virtual T* get(int i);\n";
159     std::cout << "        virtual T* first();\n";
160     std::cout << "        virtual T* next();\n";
161     std::cout << "        virtual void sort();\n";
162     std::cout << "    };\n\n";
163
164     std::cout << "Creating two instantiations:\n";
165     std::cout << "    Vector<int> vi;\n";
166     std::cout << "    Vector<string> vs;\n\n";
167
168     Vector<int> vi;
169     Vector<std::string> vs;
170
171     std::cout << "    WHAT GETS COMPILED:\n\n";
172
173     std::cout << "Vector<int>:\n";
174     std::cout << "    •    get(int) - compiled\n";
175     std::cout << "    •    first() - compiled\n";
176     std::cout << "    •    next() - compiled\n";
177     std::cout << "    •    sort() - compiled\n";
178     std::cout << "    Even if you only use get()!\n\n";
179
180     std::cout << "Vector<string>:\n";
181     std::cout << "    •    get(int) - compiled AGAIN\n";
182     std::cout << "    •    first() - compiled AGAIN\n";
183     std::cout << "    •    next() - compiled AGAIN\n";
184     std::cout << "    •    sort() - compiled AGAIN\n";
185     std::cout << "    Complete duplication!\n\n";
186
187     std::cout << "    CODE BLOAT CALCULATION:\n";
188     std::cout << "    •    2 types × 4 virtual functions = 8 functions\n";
189     std::cout << "    •    10 types × 10 virtual functions = 100 functions\n";
190     std::cout << "    •    Average function: 50-100 bytes\n";
191     std::cout << "    •    100 functions × 75 bytes = 7.5 KB of bloat\n";
192     std::cout << "    •    In large projects: MEGABYTES of wasted code\n\n";
193
194     std::cout << "    WHY THIS IS BAD:\n";
195     std::cout << "    1. Binary size increases unnecessarily\n";
```

```
196     std::cout << "    2. Longer compilation times\n";
197     std::cout << "    3. More pressure on instruction cache\n";
198     std::cout << "    4. Harder to maintain\n";
199     std::cout << "    5. Embedded systems: wastes precious flash memory\n";
200 }
201
202 } // namespace bad_example_t80
203
204 /**
205 =====
206 // SECTION 3: WHY IT HAPPENS - THE VTABLE REQUIREMENT
207 // =====
208
209 namespace why_it_happens {
210
211 void demonstrate() {
212     std::cout << "\n" << std::string(70, '=') << "\n";
213     std::cout << "WHY VIRTUAL FUNCTIONS MUST BE INSTANTIATED\n";
214     std::cout << std::string(70, '=') << "\n\n";
215
216     std::cout << "    THE MECHANISM:\n\n";
217
218     std::cout << "1. VTABLE CONSTRUCTION:\n";
219     std::cout << "    • Each class with virtual functions has a vtable\n";
220     std::cout << "    • vtable is built at COMPILE-TIME\n";
221     std::cout << "    • vtable contains pointers to ALL virtual functions\n";
222     std::cout << "    • Therefore, all virtual functions MUST exist\n\n";
223
224     std::cout << "2. TEMPLATE INSTANTIATION:\n";
225     std::cout << "    • Template<int> creates a new class type\n";
226     std::cout << "    • This class needs its own vtable\n";
227     std::cout << "    • Compiler must compile ALL virtual functions\n";
228     std::cout << "    • Even those never called\n\n";
229
230     std::cout << "3. COMPARISON:\n\n";
231
232     std::cout << "    Non-virtual function:\n";
233     std::cout << "        Compiler sees call site\n";
234     std::cout << "        \"Oh, this function is used, compile it\"\n";
235     std::cout << "        No call = no compilation (lazy)\n\n";
236
237     std::cout << "    Virtual function:\n";
238     std::cout << "        Compiler instantiates class\n";
239     std::cout << "        \"Must build vtable for this class\"\n";
240     std::cout << "        \"Need ALL virtual function addresses\"\n";
241     std::cout << "        ALL compiled regardless of use (eager)\n\n";
242
243     std::cout << "    STANDARD LIBRARY MISTAKE:\n";
244     std::cout << "    • std::locale facets (std::ctype<T>) made this mistake\n";
245         ;
246     std::cout << "    • ~15 virtual functions per facet\n";
```

```
245     std::cout << " • Most programs use 2-3 of them\n";
246     std::cout << " • But all 15 are instantiated\n";
247     std::cout << " • Acknowledged in C++ Core Guidelines as historical error
248         \n";
249 }
250 } // namespace why_it_happens
251 //
252 =====
253 // SOLUTION 1: NON-TEMPLATE BASE CLASS (TYPE ERASURE)
254 //
255 =====
256
257 namespace solution_type_erasure {
258 /*
259 * GOOD: Move virtual interface to non-template base
260 *
261 * Virtual functions compiled ONCE, not per template instantiation.
262 * This is the T.84 guideline: "Use a non-template core implementation"
263 */
264
265 // Non-template base - compiled ONCE
266 class ContainerBase {
267 public:
268     virtual ~ContainerBase() = default;
269     virtual void* get_impl(int i) = 0;
270     virtual void* first_impl() = 0;
271     virtual void* next_impl() = 0;
272     virtual void sort_impl() = 0;
273 };
274
275 // Template provides type safety
276 template<typename T>
277 class Vector : public ContainerBase {
278 private:
279     std::vector<T> data_;
280     typename std::vector<T>::iterator current_;
281
282 public:
283     Vector() : current_(data_.begin()) {}
284
285     void* get_impl(int i) override {
286         return (i >= 0 && i < static_cast<int>(data_.size())) ? &data_[i] :
287             nullptr;
288     }
289
290     void* first_impl() override {
291         current_ = data_.begin();
292         return current_ != data_.end() ? static_cast<void*>(&(*current_)) :
293             nullptr;
294 }
```

```
292     }
293
294     void* next_implementation() override {
295         if (current_ != data_.end()) ++current_;
296         return current_ != data_.end() ? static_cast<void*>(&(*current_)) :
297             nullptr;
298     }
299
300     void sort_implementation() override {
301         std::sort(data_.begin(), data_.end());
302     }
303
304     // Type-safe wrappers
305     T* get(int i) { return static_cast<T*>(get_implementation(i)); }
306     T* first() { return static_cast<T*>(first_implementation()); }
307     T* next() { return static_cast<T*>(next_implementation()); }
308     void sort() { sort_implementation(); }
309     void add(const T& item) { data_.push_back(item); }
310 };
311
312 void demonstrate() {
313     std::cout << "\n" << std::string(70, '=') << "\n";
314     std::cout << "SOLUTION 1: Non-Template Base (Type Erasure)\n";
315     std::cout << std::string(70, '=') << "\n\n";
316
317     Vector<int> vi;
318     Vector<std::string> vs;
319
320     std::cout << " FIXED DESIGN:\n\n";
321
322     std::cout << "ContainerBase (non-template):\n";
323     std::cout << " • Virtual functions compiled ONCE\n";
324     std::cout << " • get_implementation(), first_implementation(), next_implementation(), sort_implementation()\n";
325     std::cout << " • Shared across ALL instantiations\n\n";
326
327     std::cout << "Vector<T> (template):\n";
328     std::cout << " • Overrides virtual functions (minimal code)\n";
329     std::cout << " • Type-specific logic only\n";
330     std::cout << " • Type-safe wrapper functions\n\n";
331
332     std::cout << " BLOAT REDUCTION:\n";
333     std::cout << " • 10 types × 4 virtuals = 4 base + 10 overrides\n";
334     std::cout << " • vs Bad design: 40 separate functions\n";
335     std::cout << " • Reduction: 50-80% less code\n\n";
336
337     std::cout << " TRADE-OFFS:\n";
338     std::cout << " • Massive code size reduction\n";
339     std::cout << " • Runtime polymorphism preserved\n";
340     std::cout << " • Slight runtime overhead (void* casts)\n";
341     std::cout << " • Loss of type information in base\n";
342 }
343 } // namespace solution_type_erasure
```

```
345 // =====
346 // SOLUTION 2: CRTP - NO VIRTUAL FUNCTIONS
347 // =====
348
349 namespace solution_crtp {
350
351 /*
352 * BETTER: CRTP for compile-time polymorphism
353 *
354 * No vtable = No forced instantiation = No bloat
355 * Zero runtime overhead
356 */
357
358 template<typename Derived>
359 class ContainerCRTP {
360 public:
361     auto* get(int i) { return derived()->get_impl(i); }
362     auto* first() { return derived()->first_impl(); }
363     auto* next() { return derived()->next_impl(); }
364     void sort() { derived()->sort_impl(); }
365
366 private:
367     Derived* derived() { return static_cast<Derived*>(this); }
368 };
369
370 template<typename T>
371 class Vector : public ContainerCRTP<Vector<T>> {
372 private:
373     std::vector<T> data_;
374     typename std::vector<T>::iterator current_;
375
376 public:
377     Vector() : current_(data_.begin()) {}
378
379     T* get_impl(int i) {
380         return (i >= 0 && i < static_cast<int>(data_.size())) ? &data_[i] :
381             nullptr;
382     }
383
384     T* first_impl() {
385         current_ = data_.begin();
386         return current_ != data_.end() ? &(*current_) : nullptr;
387     }
388
389     T* next_impl() {
390         if (current_ != data_.end()) ++current_;
391         return current_ != data_.end() ? &(*current_) : nullptr;
392     }
393
394     void sort_impl() {
```

```
394     std::sort(data_.begin(), data_.end());
395 }
396
397 void add(const T& item) { data_.push_back(item); }
398 };
399
400 void demonstrate() {
401     std::cout << "\n" << std::string(70, '=') << "\n";
402     std::cout << "SOLUTION 2: CRTP (Static Polymorphism)\n";
403     std::cout << std::string(70, '=') << "\n\n";
404
405     Vector<int> vi;
406     vi.add(5); vi.add(3); vi.add(9);
407
408     std::cout << " NO VIRTUAL FUNCTIONS:\n\n";
409
410     std::cout << "Benefits:\n";
411     std::cout << " • No vtable\n";
412     std::cout << " • No vptr (8 bytes saved per object)\n";
413     std::cout << " • Functions ONLY compiled if called\n";
414     std::cout << " • Can be fully inlined\n";
415     std::cout << " • Zero runtime overhead\n\n";
416
417     vi.sort();
418
419     std::cout << "What got compiled:\n";
420     std::cout << " sort_impl<int> - used\n";
421     std::cout << " add - used\n";
422     std::cout << " get_impl - NOT compiled (not used)\n";
423     std::cout << " first_impl - NOT compiled (not used)\n";
424     std::cout << " next_impl - NOT compiled (not used)\n\n";
425
426     std::cout << " BLOAT ELIMINATION:\n";
427     std::cout << " • Only used functions compiled\n";
428     std::cout << " • Lazy instantiation = minimal code\n";
429     std::cout << " • Perfect for performance-critical code\n\n";
430
431     std::cout << " TRADE-OFFS:\n";
432     std::cout << " Zero code bloat\n";
433     std::cout << " Zero runtime overhead\n";
434     std::cout << " No runtime polymorphism\n";
435     std::cout << " Cannot use heterogeneous containers\n";
436 }
437
438 } // namespace solution_crtp
439
440 /**
441 // =====
442 // SOLUTION 3: C++20 CONCEPTS
443 // =====
```

```
444 namespace solution_concepts {
445
446 #if __cplusplus >= 202002L
447
448 template<typename T>
449 concept Container = requires(T c, int i) {
450     { c.get(i) };
451     { c.first() };
452     { c.next() };
453     { c.sort() } -> std::same_as<void>;
454 };
455
456 template<typename T>
457 class Vector {
458 private:
459     std::vector<T> data_;
460     typename std::vector<T>::iterator current_;
461
462 public:
463     Vector() : current_(data_.begin()) {}
464
465     T* get(int i) {
466         return (i >= 0 && i < static_cast<int>(data_.size())) ? &data_[i] :
467             nullptr;
468     }
469
470     T* first() {
471         current_ = data_.begin();
472         return current_ != data_.end() ? &(*current_) : nullptr;
473     }
474
475     T* next() {
476         if (current_ != data_.end()) ++current_;
477         return current_ != data_.end() ? &(*current_) : nullptr;
478     }
479
480     void sort() { std::sort(data_.begin(), data_.end()); }
481     void add(const T& item) { data_.push_back(item); }
482 };
483
484 template<Container C>
485 void process(C& cont) {
486     cont.sort();
487 }
488
489 #endif
490
491 void demonstrate() {
492     std::cout << "\n" << std::string(70, '=') << "\n";
493     std::cout << "SOLUTION 3: C++20 Concepts\n";
494     std::cout << std::string(70, '=') << "\n\n";
495
496 #if __cplusplus >= 202002L
497     Vector<int> vi;
```

```
497     vi.add(5);
498     process(vi);
499
500     std::cout << " NO INHERITANCE, NO VIRTUAL:\n\n";
501
502     std::cout << "Concepts provide:\n";
503     std::cout << " • Compile-time interface checking\n";
504     std::cout << " • Duck typing with type safety\n";
505     std::cout << " • No base class needed\n";
506     std::cout << " • Better error messages\n";
507     std::cout << " • Zero runtime overhead\n\n";
508
509     std::cout << " BLOAT ELIMINATION:\n";
510     std::cout << " • No virtual functions at all\n";
511     std::cout << " • Only used functions instantiated\n";
512     std::cout << " • Cleanest solution\n";
513 #else
514     std::cout << " C++20 concepts not available.\n";
515     std::cout << " Compile with -std=c++20 to see this solution.\n";
516 #endif
517 }
518
519 } // namespace solution_concepts
520
521 //
522 =====
523 // GUIDELINES AND RECOMMENDATIONS
524 // =====
525
526 namespace guidelines {
527
528 void demonstrate() {
529     std::cout << "\n" << std::string(70, '=') << "\n";
530     std::cout << "GUIDELINES: AVOID VIRTUAL FUNCTIONS IN TEMPLATES\n";
531     std::cout << std::string(70, '=') << "\n\n";
532
533     std::cout << " AVOID THIS:\n\n";
534     std::cout << " template<typename T>\n";
535     std::cout << " class Container {\n";
536     std::cout << "     virtual void operation(); // BAD!\n";
537     std::cout << " };\n\n";
538
539     std::cout << " PROBLEMS:\n";
540     std::cout << " 1. CODE BLOAT: All virtuals instantiated every time\n";
541     std::cout << " 2. COMPILATION: Slower, more memory\n";
542     std::cout << " 3. BINARY SIZE: Can add megabytes in large projects\n";
543     std::cout << " 4. PERFORMANCE: More pressure on I-cache\n";
544     std::cout << " 5. MAINTENANCE: Harder to track what's compiled\n\n";
545
546     std::cout << " WHEN IT'S A PROBLEM:\n";
547     std::cout << " • Many virtual functions (5+)\n";
```

```
547     std::cout << " • Many template instantiations (10+)\n";
548     std::cout << " • Large codebase\n";
549     std::cout << " • Embedded systems (limited flash)\n";
550     std::cout << " • Header-only libraries\n\n";
551
552     std::cout << " SOLUTIONS (IN ORDER OF PREFERENCE):\n\n";
553
554     std::cout << "1. C++20 CONCEPTS (best)\n";
555     std::cout << " • No inheritance, no virtual\n";
556     std::cout << " • Compile-time duck typing\n";
557     std::cout << " • Zero overhead\n\n";
558
559     std::cout << "2. CRTP (for static polymorphism)\n";
560     std::cout << " • No virtual functions\n";
561     std::cout << " • Lazy instantiation\n";
562     std::cout << " • Zero runtime overhead\n\n";
563
564     std::cout << "3. NON-TEMPLATE BASE (for runtime polymorphism)\n";
565     std::cout << " • Virtual compiled once\n";
566     std::cout << " • Massive bloat reduction\n";
567     std::cout << " • Runtime flexibility preserved\n\n";
568
569     std::cout << " WHEN VIRTUAL IN TEMPLATES IS OK:\n";
570     std::cout << " • Very few virtual functions (1-2)\n";
571     std::cout << " • Few instantiations (2-3 types)\n";
572     std::cout << " • Virtual functions actually needed\n";
573     std::cout << " • Code clarity more important than size\n\n";
574
575     std::cout << " RELATED GUIDELINES:\n";
576     std::cout << " • T.5: Combine generic and OO judiciously\n";
577     std::cout << " • T.80: Do not naively templatize a hierarchy\n";
578     std::cout << " • T.83: Do not declare member function template virtual\n";
579     std::cout << " • T.84: Use a non-template core implementation\n";
580 }
581
582 } // namespace guidelines
583
584 // =====
585 // MAIN
586 //
587 // =====
588
589 int main() {
590     std::cout << "\n";
591     std::cout << "                                     \n";
592     std::cout << "      VIRTUAL FUNCTIONS IN TEMPLATES: THE CODE BLOAT\n";
593     std::cout << "      PROBLEM          \n";
594     std::cout << "                                     \n";
595     std::cout << "                                     \n";
596     ;
597 }
```

```
593     std::cout << "          WHY TO AVOID & BETTER ALTERNATIVES\n";
594     std::cout << "                                \n";
595
596     the_problem::demonstrate();
597     bad_example_t80::demonstrate();
598     why_it_happens::demonstrate();
599     solution_type_erasure::demonstrate();
600     solution_crtpp::demonstrate();
601     solution_concepts::demonstrate();
602     guidelines::demonstrate();
603
604     std::cout << "\n" << std::string(70, '=') << "\n";
605     std::cout << "KEY TAKEAWAYS\n";
606     std::cout << std::string(70, '=') << "\n\n";
607
608     std::cout << "  THE PROBLEM:\n";
609     std::cout << "  •  Virtual functions in templates = code bloat\n";
610     std::cout << "  •  ALL virtuals instantiated for EVERY type\n";
611     std::cout << "  •  Even if never called\n";
612     std::cout << "  •  Can add megabytes to binary size\n\n";
613
614     std::cout << "  WHY IT HAPPENS:\n";
615     std::cout << "  •  vtable must be built at compile-time\n";
616     std::cout << "  •  vtable needs ALL virtual function addresses\n";
617     std::cout << "  •  Compiler must compile them all\n";
618     std::cout << "  •  Non-virtual functions use lazy instantiation\n\n";
619
620     std::cout << "  SOLUTIONS:\n";
621     std::cout << "    1. C++20 Concepts - no inheritance needed\n";
622     std::cout << "    2. CRTP - compile-time polymorphism\n";
623     std::cout << "    3. Non-template base - runtime polymorphism\n\n";
624
625     std::cout << "  RECOMMENDATION:\n";
626     std::cout << "    AVOID virtual functions in class templates\n";
627     std::cout << "    unless you have a compelling reason and few
628     instantiations.\n\n";
629
630     std::cout << "                                \n";
631     std::cout << "          Follow C++ Core Guidelines T.80 and T.84
632                                         \n";
633     std::cout << "                                \n\n";
634
635     return 0;
636 }
```

76 Appendix: Comprehensive Index

77 Modern C++ Examples - Comprehensive Index

Last Updated: January 3, 2026

This index maps C++ concepts, keywords, features, design patterns, problems, and standards to specific example files in this repository. Use this as a quick reference to find examples for specific topics.

77.1 Table of Contents

- Interview Preparation
 - C++ Standards Features
 - Design Patterns & Idioms
 - Object-Oriented Programming
 - Memory Management
 - Concurrency & Parallelism
 - Real-Time & Embedded Systems
 - Safety-Critical & Standards
 - STL Containers & Algorithms
 - Template Metaprogramming
 - Error Handling
 - Interoperability
 - Performance & Optimization
 - Common Problems & Solutions
 - Keywords & Language Features
-

77.2 Interview Preparation

77.2.1 Complete C++ Interview Guide

- **File:** [MockInterview.cpp](#)
- **Description:** Comprehensive collection of C++ interview questions with detailed, runnable answers
- **Topics Covered:**
 - **Fundamentals:** Pointers vs references, const correctness, RAII pattern
 - **Memory Management:** Smart pointers (`unique_ptr`, `shared_ptr`, `weak_ptr`), custom deleters, aliasing constructor, `enable_shared_from_this`, memory alignment, custom allocators
 - **OOP & Design Patterns:** Virtual dispatch mechanics, vtable internals, multiple inheritance, CRTP with mixins, PIMPL idiom, compile-time polymorphism
 - **Templates & Metaprogramming:** SFINAE techniques, `enable_if`, detection idiom, variadic templates, fold expressions, compile-time computation, `constexpr/consteval`
 - **Concurrency:** Thread-safe singleton (Meyer's, `call_once`), producer-consumer pattern, condition variables, atomic operations, memory ordering

- **Performance:** Move semantics, copy elision (RVO/NRVO), cache-friendly design, branch prediction optimization
- **Common Interview Questions:**
 - What's the difference between pointers and references?
 - Explain smart pointers and when to use each type
 - How does virtual dispatch work internally?
 - What is SFINAE and how is it used?
 - How do you implement a thread-safe singleton?
 - What's the difference between RVO and move semantics?
 - Explain memory ordering in atomic operations
 - How does CRTP provide compile-time polymorphism?
- **Format:** Each section includes working code examples with detailed explanations and best practices

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77.3 C++ Standards Features

77.3.1 C++11

- **File:** [Cpp11Examples.cpp](#)
- **Topics:** `auto`, `nullptr`, range-based for, lambda expressions, smart pointers, move semantics, `constexpr`, `static_assert`, uniform initialization, `decltype`, `std::array`, `std::thread`, `std::mutex`

77.3.2 C++14

- **File:** [Cpp14Examples.cpp](#)
- **Topics:** Generic lambdas, `auto` return type deduction, binary literals, digit separators, `std::make_unique`, relaxed `constexpr`, variable templates
- **File:** [GenericLambdas.cpp](#)
- **Topics:** Generic lambda expressions with `auto` parameters

77.3.3 C++17

- **File:** [Cpp17Examples.cpp](#)
- **Topics:** Structured bindings, `if constexpr`, fold expressions, `std::optional`, `std::variant`, `std::any`, `std::string_view`, parallel algorithms, `std::filesystem`
- **File:** [Cpp17Concurrency.cpp](#)
- **Topics:** Parallel STL algorithms, execution policies
- **File:** [StructuredBindings.cpp](#)
- **Topics:** Structured bindings syntax and use cases
- **File:** [OptionalExamples.cpp](#)
- **Topics:** `std::optional` usage patterns

77.3.4 C++20

- **File:** [Cpp20Examples.cpp](#)

- **Topics:** Concepts, ranges, coroutines, modules, three-way comparison ($\langle=\rangle$), designated initializers, `std::span`, `consteval`, `constinit`
- **File:** [ConceptsExamples.cpp](#)
- **Topics:** Concepts, constraints, `requires` clauses
- **File:** [RangesExamples.cpp](#)
- **Topics:** Ranges library, views, adaptors, pipelines
- **File:** [CameraModule.cppm](#) / [TemplatedCameraModules.cpp](#)
- **Topics:** C++20 modules

77.3.5 C++23

- **File:** [Cpp23Examples.cpp](#)
- **Topics:** `std::expected`, deducing `this`, `if consteval`, multidimensional subscript operator, `std::print`, `std::stacktrace`

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77.4 Design Patterns & Idioms

77.4.1 CRTP (Curiously Recurring Template Pattern)

- **File:** [CRTPvsVirtualFunctions.cpp](#)
- **Topics:** CRTP vs virtual functions, static polymorphism, performance comparison, vtable overhead

77.4.2 Pimpl (Pointer to Implementation)

- **File:** [PimplIdiom.cpp](#)
- **Topics:** Pimpl idiom, ABI stability, compilation firewall, real-time concerns, cache locality, FastPimpl alternative

77.4.3 NVI (Non-Virtual Interface)

- **File:** [NVIIdiomTemplateMethod.cpp](#)
- **Topics:** Non-virtual interface idiom, template method pattern, Herb Sutter's virtuality guidelines

77.4.4 RAII (Resource Acquisition Is Initialization)

- **File:** [RuleOf3_5_0.cpp](#)
- **Topics:** Rule of 3/5/0, RAII, copy/move semantics, special member functions
- **File:** [ResourceLeaks.cpp](#)
- **Topics:** Preventing resource leaks with RAII

77.4.5 Dependency Injection

- **File:** [DependencyInjection.cpp](#)
- **Topics:** Constructor injection, setter injection, interface injection, composition over inheritance

77.4.6 SOLID Principles

- **File:** [SOLIDPrinciples.cpp](#)
- **Topics:** Single Responsibility, Open/Closed, Liskov Substitution, Interface Segregation, Dependency Inversion

77.4.7 Factory Pattern

- **File:** [CreatingCApiFromCpp.cpp](#)
- **Topics:** Factory functions for C API

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77.5.1 Inheritance

- **File:** [InheritanceTypes.cpp](#)
- **Topics:** Public, private, protected inheritance, IS-A vs implemented-in-terms-of
- **File:** [DiamondProblem.cpp](#)
- **Topics:** Diamond problem, virtual inheritance, composition alternative
- **File:** [FragileBaseClass.cpp](#)
- **Topics:** Fragile base class problem, ABI stability, solutions

77.5.2 Polymorphism

- **File:** [RuntimePolymorphism.cpp](#)
- **Topics:** Virtual functions, pure virtual functions, abstract classes, dynamic polymorphism
- **File:** [VirtualFunctionsInTemplates.cpp](#)
- **Topics:** Why virtual functions in templates cause code bloat, type erasure, CRTP, concepts as alternatives
- **File:** [CRTPvsVirtualFunctions.cpp](#)
- **Topics:** Static vs dynamic polymorphism comparison

77.5.3 Object Slicing

- **File:** [ObjectSlicingCpp20.cpp](#)
- **Topics:** Object slicing problem, C++20 solutions
- **File:** [ObjectSlicingSmartPtr.cpp](#)
- **Topics:** Preventing object slicing with smart pointers

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77.6 Memory Management

77.6.1 Smart Pointers

- **File:** [RuleOf3_5_0.cpp](#)
- **Topics:** `unique_ptr`, `shared_ptr`, `weak_ptr`, ownership semantics

- **File:** ResourceLeaks.cpp
- **Topics:** Smart pointers for preventing leaks
- **File:** ObjectSlicingSmartPtr.cpp
- **Topics:** Smart pointers with polymorphism

77.6.2 Move Semantics

- **File:** MoveSemantics.cpp
- **Topics:** Rvalue references, move constructors, move assignment, perfect forwarding
- **File:** MoveSemanticsPerfectForwarding.cpp
- **Topics:** Move semantics and perfect forwarding patterns
- **File:** PerfectForwardingAndRequires.cpp
- **Topics:** Perfect forwarding with `std::forward`, requires clauses

77.6.3 Memory Pools & Allocators

- **File:** RealTimeProgramming.cpp
- **Topics:** Memory pools, custom allocators, pre-allocation strategies
- **File:** STLContainersNoHeap.cpp
- **Topics:** Custom allocators, stack allocators, pool allocators

77.6.4 Resource Management

- **File:** ResourceLeaks.cpp
- **Topics:** Common resource leak patterns and prevention

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77.7 Concurrency & Parallelism

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- **File:** AsioAndModernCppConcurrency.cpp
- **Topics:** ASIO, thread pools, async operations, `io_context`
- **File:** AsioMultipleContexts.cpp
- **Topics:** Multiple `io_context` patterns, thread distribution
- **File:** ThreadPoolExamples.cpp
- **Topics:** Thread pool implementation patterns

77.7.2 Parallel Algorithms

- **File:** Cpp17Concurrency.cpp
- **Topics:** Parallel STL, execution policies (`std::execution::par`)

77.7.3 Future/Promise/Async

- **File:** FuturePromiseAsync.cpp
- **Topics:** `std::future`, `std::promise`, `std::async`, `std::packaged_task`, ASIO relationship

77.7.4 Stop Tokens

- **File:** [StopTokenExample.cpp](#)
- **Topics:** `std::stop_token`, `std::stop_source`, cooperative cancellation (C++20)

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- **File:** [MultiThreadedMicroservices.cpp](#)
- **Topics:** Multi-threaded microservice architecture

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77.8 Real-Time & Embedded Systems

77.8.1 Real-Time Programming

- **File:** [RealTimeProgramming.cpp](#)
- **Topics:** Deterministic behavior, WCET, Big O notation, memory pre-allocation, `std::bitset`, `std::list::splice()`, real-time patterns

77.8.2 Embedded Systems

- **File:** [EmbeddedSystemsProgramming.cpp](#)
- **Topics:** Best practices for embedded systems, `constexpr`, fixed-size containers
- **File:** [EmbeddedSystemsAvoid.cpp](#)
- **Topics:** What to avoid in embedded systems (exceptions, dynamic allocation, `iostream`)

77.8.3 ARM & Architecture

- **File:** [ARMINstructionSets.cpp](#)
- **Topics:** ARM instruction sets, NEON, SVE, architecture-specific optimization

77.8.4 ROM Placement

- **File:** [ROMability.cpp](#)
- **Topics:** `constexpr`, `consteval`, `constinit`, ROM placement strategies

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77.9 Safety-Critical & Standards

77.9.1 MISRA C++

- **File:** [MISRACppDemo.cpp](#)
- **Topics:** MISRA C++ rules, safety-critical coding guidelines

77.9.2 ISO 26262 (Automotive)

- **File:** [FunctionalSafetyISO26262.cpp](#)
- **Topics:** ISO 26262 functional safety, ASIL levels, automotive safety

77.9.3 STL for Safety-Critical

- **File:** [SafetyCriticalSTLContainers.cpp](#)
- **Topics:** Which STL containers to avoid/use in safety-critical systems, MISRA compliance, AUTOSAR, heap allocation issues

77.9.4 AUTOSAR

- **File:** [SafetyCriticalSTLContainers.cpp](#)
- **Topics:** AUTOSAR C++14 guidelines, container usage

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77.10 STL Containers & Algorithms

77.10.1 Container Usage

- **File:** [STLContainersNoHeap.cpp](#)
- **Topics:** Using STL containers without heap, custom allocators, `std::array`, `std::span`
- **File:** [SafetyCriticalSTLContainers.cpp](#)
- **Topics:** Container safety analysis, forbidden containers (list, map, set, unordered_*)

77.10.2 std::bitset

- **File:** [RealTimeProgramming.cpp](#)
- **Topics:** `std::bitset` vs `std::vector<bool>`, real-time usage

77.10.3 std::list::splice()

- **File:** [RealTimeProgramming.cpp](#)
- **Topics:** O(1) element movement, splice operations, real-time patterns

77.10.4 Algorithms

- **File:** [BinarySearch.cpp](#)
- **Topics:** Binary search algorithms, STL algorithm usage

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77.11 Template Metaprogramming

77.11.1 Templates & Concepts

- **File:** [ConceptsExamples.cpp](#)
- **Topics:** C++20 concepts, type constraints, `requires` clauses
- **File:** [PerfectForwardingAndRequires.cpp](#)
- **Topics:** Perfect forwarding with concepts

77.11.2 CRTP (Static Polymorphism)

- **File:** [CRTPvsVirtualFunctions.cpp](#)
- **Topics:** Curiously Recurring Template Pattern, compile-time polymorphism

77.11.3 Variadic Templates

- **File:** [VariadicTemplateRecursion.cpp](#)
- **Topics:** Variadic templates, template recursion, parameter packs

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- **File:** [TemplatedCameraInterface.cpp](#)
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77.12 Error Handling

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- **Topics:** Exception handling patterns, custom exceptions
- **File:** [AdvancedExceptionHandling.cpp](#)
- **Topics:** Advanced exception techniques, exception safety guarantees
- **File:** [ExceptionWithSourceLocation.cpp](#)
- **Topics:** `std::source_location` (C++20), exception context
- **File:** [ErrorHandlingStroustrup.cpp](#)
- **Topics:** Bjarne Stroustrup's error handling guidelines

77.12.2 noexcept

- **File:** [NoexceptBestPractices.cpp](#)
- **Topics:** `noexcept` specifier, move operations, best practices

77.12.3 Error Codes & Optional

- **File:** [OptionalExamples.cpp](#)
- **Topics:** `std::optional` for error handling
- **File:** [Cpp23Examples.cpp](#)
- **Topics:** `std::expected` for error handling (C++23)

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77.13.1 C Interop

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- **Topics:** Wrapping C libraries in C++, RAII for C resources
- **File:** [CreatingCApiFromCpp.cpp](#)
- **Topics:** Creating C API from C++ code, `extern "C"`, opaque pointers

77.13.2 Python Binding

- **File:** [Pybind11Example.cpp](#)
- **Topics:** pybind11, exposing C++ to Python, automatic binding generation

77.13.3 Protobuf

- **File:** [ProtobufExample.cpp](#)
- **Topics:** Protocol Buffers, serialization, cross-language data exchange

77.13.4 JSON

- **File:** [NlohmannJsonExample.cpp](#)
- **Topics:** nlohmann/json library, JSON parsing and serialization

77.13.5 REST API

- **File:** [RestApiExample.cpp](#)
- **Topics:** REST API client, HTTP requests, CURL integration

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77.14 Performance & Optimization

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- **File:** [CRTPvsVirtualFunctions.cpp](#)
- **Topics:** CRTP vs virtual functions performance, vtable overhead, benchmarking
- **File:** [PimplIdiom.cpp](#)
- **Topics:** Pimpl performance impact, cache locality, indirection overhead

77.14.2 Cache Locality

- **File:** [PimplIdiom.cpp](#)
- **Topics:** Cache-friendly design, avoiding pointer indirection
- **File:** [RealTimeProgramming.cpp](#)
- **Topics:** Memory layout for real-time systems

77.14.3 Compile-Time Computation

- **File:** [ROMability.cpp](#)
- **Topics:** `constexpr`, `consteval`, compile-time evaluation

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- **File:** [FragileBaseClass.cpp](#)
- **Topics:** Fragile base class problem, ABI breaks, composition over inheritance

77.15.2 Diamond Problem

- **File:** [DiamondProblem.cpp](#)
- **Topics:** Multiple inheritance diamond problem, virtual inheritance solution

77.15.3 Object Slicing

- **File:** [ObjectSlicingCpp20.cpp](#)
- **Topics:** Object slicing, prevention strategies
- **File:** [ObjectSlicingSmartPtr.cpp](#)
- **Topics:** Smart pointers to prevent slicing

77.15.4 Resource Leaks

- **File:** [ResourceLeaks.cpp](#)
- **Topics:** Memory leaks, file handle leaks, RAII solutions

77.15.5 Virtual Functions in Templates

- **File:** [VirtualFunctionsInTemplates.cpp](#)
- **Topics:** Code bloat from virtual functions in templates, C++ Core Guidelines T.80, T.83, T.84

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77.16 Keywords & Language Features

77.16.1 Keywords

77.16.1.1 `auto`

- [Cpp11Examples.cpp](#) - C++11 auto keyword
- [Cpp14Examples.cpp](#) - C++14 auto return type
- [GenericLambdas.cpp](#) - Generic lambdas with auto

77.16.1.2 `constexpr / consteval / constinit`

- [Cpp11Examples.cpp](#) - C++11 constexpr
- [Cpp14Examples.cpp](#) - C++14 relaxed constexpr
- [Cpp20Examples.cpp](#) - C++20 consteval, constinit
- [ROMability.cpp](#) - ROM placement with const* keywords

77.16.1.3 `virtual`

- [RuntimePolymorphism.cpp](#) - Virtual functions basics
- [CRTPvsVirtualFunctions.cpp](#) - Virtual vs CRTP
- [VirtualFunctionsInTemplates.cpp](#) - Virtual in templates problem
- [NVIIdiomTemplateMethod.cpp](#) - Virtual in NVI pattern

77.16.1.4 `noexcept`

- [NoexceptBestPractices.cpp](#) - noexcept best practices
- [MoveSemantics.cpp](#) - noexcept move operations

77.16.1.5 `requires` (Concepts)

- [ConceptsExamples.cpp](#) - Requires clauses
- [PerfectForwardingAndRequires.cpp](#) - Requires with forwarding

77.16.1.6 `final`

- [FragileBaseClass.cpp](#) - Final keyword usage

77.16.1.7 `override`

- [RuntimePolymorphism.cpp](#) - Override specifier

77.16.1.8 `nullptr`

- [Cpp11Examples.cpp](#) - nullptr vs NULL

77.16.1.9 `decltype`

- [Cpp11Examples.cpp](#) - decltype usage
- [PerfectForwardingAndRequires.cpp](#) - decltype with forwarding

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77.17 Event-Driven Programming

77.17.1 Event Systems

- **File:** [EventDrivenProgramming_Lambdas.cpp](#)
- **Topics:** Signals/slots with lambdas, observer pattern
- **File:** [EventDrivenProgramming_Inheritance.cpp](#)
- **Topics:** Event systems with inheritance

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77.18 Lambda Expressions

77.18.1 Lambda Basics

- **File:** [Cpp11Examples.cpp](#)
- **Topics:** Basic lambda syntax (C++11)
- **File:** [GenericLambdas.cpp](#)
- **Topics:** Generic lambdas with auto parameters (C++14)
- **File:** [LambdaCaptures.cpp](#)
- **Topics:** Lambda capture modes, mutable lambdas

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- **File:** [SinglyLinkedList.cpp](#)
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- **File:** [InsertAndDeleteNodes.cpp](#)
- **Topics:** Node insertion and deletion
- **File:** [FindFirstCommonNode.cpp](#)
- **Topics:** Finding common node in linked lists
- **File:** [FindCountOfCommonNodes.cpp](#)
- **Topics:** Counting common nodes
- **File:** [FindMToLastElement.cpp](#)
- **Topics:** Finding m-th to last element

77.19.2 Search & Sort

- **File:** [BinarySearch.cpp](#)
- **Topics:** Binary search implementation
- **File:** [SearchAnagramsDictionary.cpp](#)
- **Topics:** Anagram searching in dictionary

77.19.3 Array Algorithms

- **File:** [FindMaxNoOfConsecutiveOnesFromIntArray.cpp](#)
- **Topics:** Maximum consecutive elements

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77.20 Tuples & Structured Bindings

77.20.1 Tuples

- **File:** [TuplesAndStructuredBindings.cpp](#)
- **Topics:** `std::tuple`, tuple operations, structured bindings

77.20.2 Structured Bindings

- **File:** [StructuredBindings.cpp](#)
- **Topics:** Structured bindings syntax and patterns

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77.21 Configuration & Parsing

77.21.1 Configuration

- **File:** [ConfigLoaderAndChecker.cpp](#)
- **Topics:** Configuration file loading and validation

77.21.2 System Interaction

- **File:** [SystemInteractionAndParsing.cpp](#)
- **Topics:** System calls, command execution, parsing

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77.22 Sensor Fusion & Scientific Computing

77.22.1 Eigen Library

- **File:** [EigenSensorFusion.cpp](#)
- **Topics:** Eigen library, Kalman filter, sensor fusion, matrix operations

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77.23 Quick Reference Tables

77.23.1 By Language Version

C++11	C++14	C++17	C++20	C++23
Cpp11Examples.cpp	Cpp14Examples.cpp	Cpp17Examples.cpp	Cpp20Examples.cpp	Cpp23Examples.cpp
MoveSemantics.cpp	GenericLambdas.cpp	StructuredBindings.cpp	ConceptsExamples.cpp	
LambdaCaptures.cpp		OptionalExamples.cpp	RangesExamples.cpp	
-	-	Cpp17Concurrency.cpp	StopTokenExample.epp	

77.23.2 By Use Case

Use Case	Recommended Files
Learning Modern C++	Start with Cpp11Examples.cpp , then progress through C++14, 17, 20, 23 examples

Use Case	Recommended Files
Real-Time Systems	RealTimeProgramming.cpp , SafetyCriticalSTLContainers.cpp , PimplIdiom.cpp
Embedded Systems	EmbeddedSystemsProgramming.cpp , EmbeddedSystemsAvoid.cpp , STLContainersNoHeap.cpp
Safety-Critical	MISRACppDemo.cpp , FunctionalSafetyISO26262.cpp , SafetyCriticalSTLContainers.cpp
Performance	CRTPvsVirtualFunctions.cpp , PimplIdiom.cpp , RealTimeProgramming.cpp
OOP Design	InheritanceTypes.cpp , DependencyInjection.cpp , SOLIDPrinciples.cpp
Memory Management	RuleOf3_5_0.cpp , MoveSemantics.cpp , ResourceLeaks.cpp
Concurrency	AsioAndModernCppConcurrency.cpp , FuturePromiseAsync.cpp , ThreadPoolExamples.cpp

77.23.3 By Problem You're Trying to Solve

Problem	Solution Files
“My code has memory leaks”	ResourceLeaks.cpp , RuleOf3_5_0.cpp
“Objects are getting sliced”	ObjectSlicingCppClass20.cpp , ObjectSlicingSmartPtr.cpp
“Base class changes break derived classes”	FragileBaseClass.cpp
“Multiple inheritance is causing problems”	DiamondProblem.cpp
“Virtual functions are too slow”	CRTPvsVirtualFunctions.cpp , VirtualFunctionsInTemplates.cpp
“Pimpl hurts performance”	PimplIdiom.cpp
“Need containers without heap”	STLContainersNoHeap.cpp , SafetyCriticalSTLContainers.cpp
“Timing is non-deterministic”	RealTimeProgramming.cpp
“Need C interop”	CppWrappingCLibrary.cpp , CreatingCApiFromCpp.cpp

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77.24 Additional Resources

77.24.1 Documentation Files

- [MarkDownDocuments/](#) - Comprehensive markdown documentation
 - CPP11.md, CPP14.md, CPP17.md, CPP20.md, CPP23.md
 - Cpp20Modules.md, Cpp20ModulesQuickRef.md
 - CppCInterop.md
 - EventDrivenProgramming.md
 - MultiThreadedMicroservices.md

- NlohmannJson.md
- Protobuf.md
- Pybind11.md
- RestApi.md
- SECURITY.md
- TemplatedCameraInterface.md
- VirtualFunctions.md

77.24.2 Build Scripts

- [scripts/](#) - Build and execution scripts
- [build_modules.ps1](#) - PowerShell build script

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77.25 How to Use This Index

1. **Find by Topic:** Search for a keyword (e.g., “lambda”, “virtual”, “real-time”)
 2. **Find by Standard:** Look under C++ Standards Features for version-specific examples
 3. **Find by Problem:** Check “Common Problems & Solutions” section
 4. **Find by Use Case:** See “By Use Case” table for curated file lists
-

77.26 Contributing

When adding new example files: 1. Update this index with appropriate mappings 2. Add to relevant sections 3. Update quick reference tables 4. Add problem-solution mapping if applicable

Repository Structure:

```
1 ModernCppExamples/
2   src/                  # Source files (.cpp, .cppm)
3   MarkDownDocuments/    # Markdown documentation
4   scripts/               # Build scripts
5   proto/                # Protocol buffer definitions
6   CMakeLists.txt         # CMake build configuration
7   INDEX.md              # This file
```

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