2023

Let's Talk About C++ Abstraction Layers

Inbal Levi

C++ now

Let’s Talk About C++ Abstraction Layers

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Who Am I

- Lead C++ Developer at MPGC Services Ltd
- Active member of ISO C++ work group (WG21):
  - Israeli NB Chair
  - Ranges SG Chair
- C++ International Conferences
  - Core C++ 2023 Organizer
  - C++Now 2023 Program Chair
- I love language & software design, I also love cataloguing

What This Talk Is About

I. What are Abstraction Layers?

II. Abstraction Layers model for C++

III. Existing solutions

IV. Future solutions -or- How can we do better?

Part I: What Are Abstraction Layers

Part 0: What Are Abstractions

- Software development is all about communicating logic to the computer
- To achieve that, we need to apply some level of abstraction

Abstraction (computer science)

- **The process of removing or generalizing** physical, spatial, or temporal details or attributes in the study of objects or systems **to focus attention on details of greater importance;** it is similar in nature to the process of generalization;
- the creation of abstract concept-objects by mirroring common features or attributes of various non-abstract objects or systems of study– the result of the process of abstraction.

Part 0: What Are Abstractions

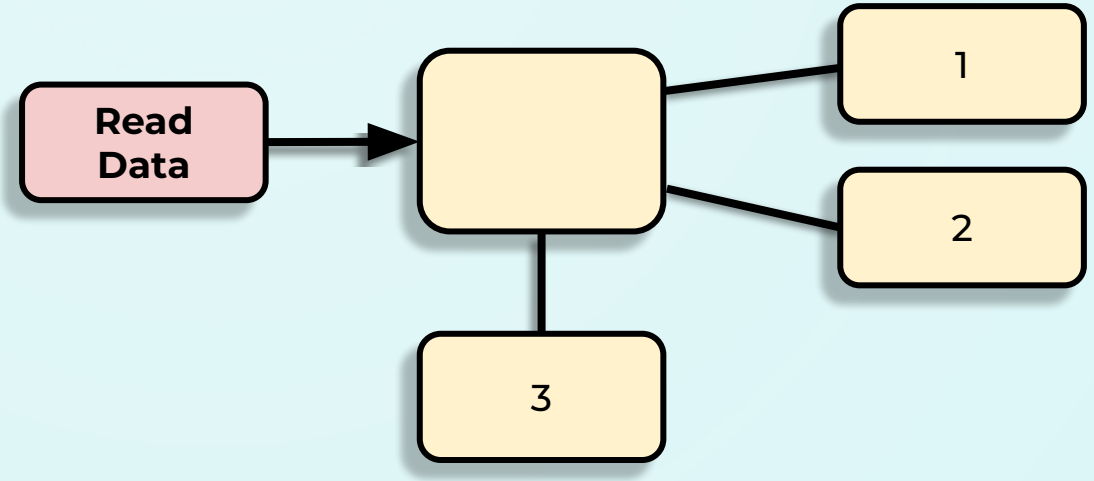
```
int main()
{
    int arr[]={11,22,33};
    int* ptr = arr;
    for (int i=0 ; i<SIZE ; i++)
    {
        printf("Int: %d\n",*(ptr+i));
    }
}
```

```
int main()
{
    auto arr[]={11,22,33};
    auto* ptr = arr;
    for (auto i=0 ; i<SIZE ; i++)
    {
        print("Int: {}\n",*(ptr+i)); // C++23
    }
}
```

Part 0: What Are Abstractions

- Choosing messaging technique to use for the following system?

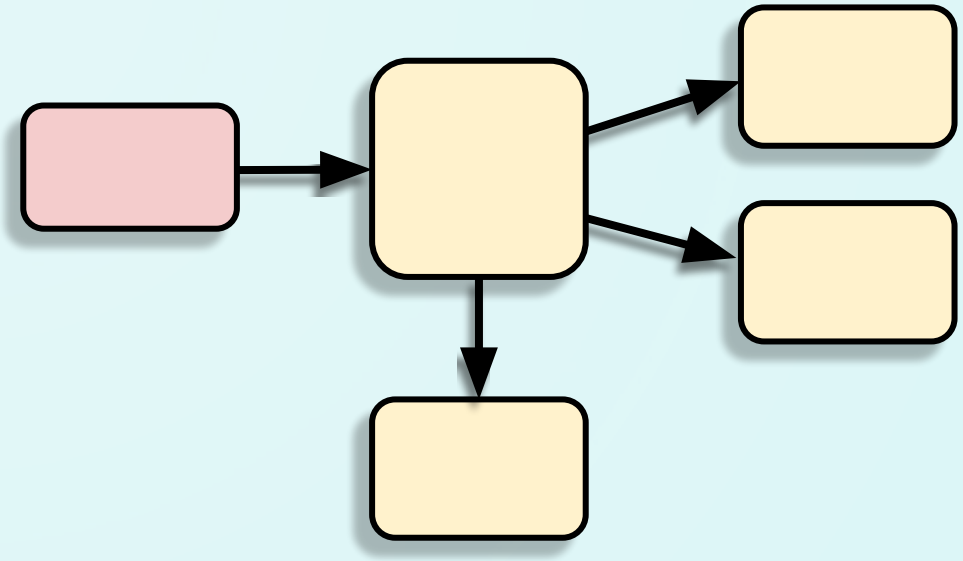
1. Push
2. Pull
3. Message board
4. Something else...?



- We need more information...
  a. Which technology?
  b. Which components?
  c. Which latency requirements?

Part 0: What Are Abstractions

```
int main()
{
    int arr[] = {1, 2, 3};
    int* ptr = arr;
    for (auto i = 0 ; i < SIZE ; i++) {
        printf("Int:\t%d\n", *(ptr + i) );
    }
}
```



Under Abstraction

Over Abstraction

The essence of abstraction is **preserving information that is relevant** in a given context, and **forgetting information** that is irrelevant **in that context**.

– John V. Guttag
(former head of EE and CS at MIT)

Part I: What Are Abstraction Layers

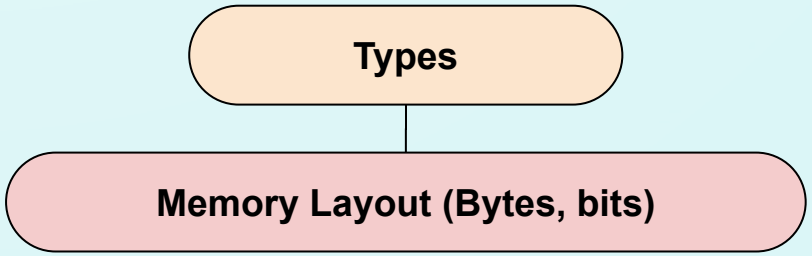
```
int main()
{
    char arr[] = {'a', 'b'};
    char* ptr = arr;
    for (auto i = 0 ; i < SIZE ; i++)
    {
        printf("Char:\t%c, pointer location: %X\n", arr[i], ptr);
        ptr++;
    }
}
```

```
Char: a, pointer location: 78744098
Char: b, pointer location: 78744099

Int:  1, pointer location: C0ED03E0
Int:  2, pointer location: C0ED03E4
```

1

4



Part I: What Are Abstraction Layers

```
int main()
{
    int i = 0;
    // std::cout << &i;                  // 0x7ffc8584085c
    *(int*)0x7ffc8584085c = 1;           // UB (when don't store the value)
    return i;
}
```

- The example is about:
  - The duality of int and memory address
  - The invalidity of the address
  - The UB created by using the address

- P2434: Nondeterministic pointer provenance

Part I: What Are Abstraction Layers

- We don't care about this, we're modern C++ developers... right?
- Wrong.
  - N2222: Further Pointer Issues (2018)
  - N2311: Exploring C Semantics and Pointer Provenance (2018)
  - N2443: Lifetime-End Pointer Zap (2019)
  - P2318: A Provenance-aware Memory Object Model for C (2021)
  - P1726: Pointer lifetime-end zap and provenance, too (2021)
  - P2434: Nondeterministic pointer provenance (2022)

Part II: Abstraction Layers Model for C++

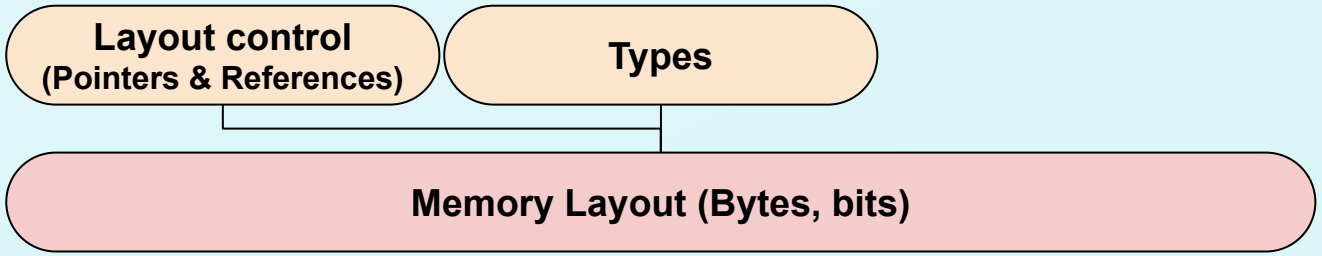
Part II: Abstraction Layers Model for C++

- We will analyze C++ language and library, building a “layers” model
- We want to identify the borders between layers
- We want to recognize the “dangerous” parts, where bugs occur

Part II: Abstraction Layers Model for C++

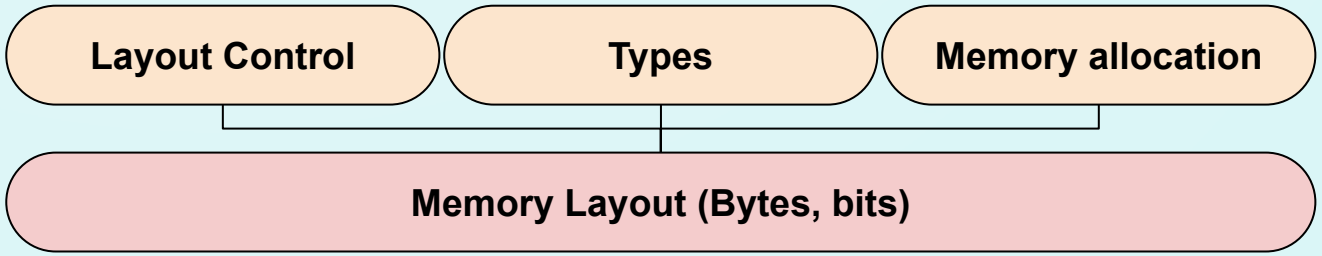
- The example is about three topics:
  - The invalidity of the address
  - The duality of int and memory address
  - The UB created by using the address

```
int main()
{
    int i = 0;
    std::cout << &i;
    *(int*)0x7ffc8584085c = 1;
    return i;
}
```



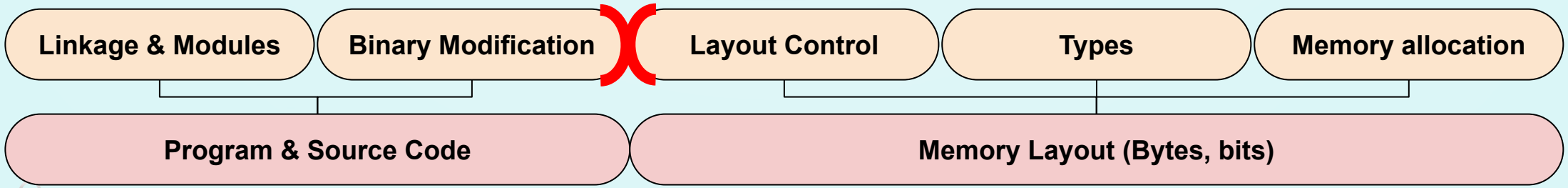
Part II: Abstraction Layers Model for C++

- Types
  - bool, char, <stdfloat>, etc.
  - casts, <charconv>
  - cv qualifiers
  - <limits>
- Layout Control:
  - Pointers, References
  - alignas, alignof - query and set alignment of primitives and structs
- Memory Allocation
  - delete, new
  - <memory_resource>
  - <scoped_allocator>

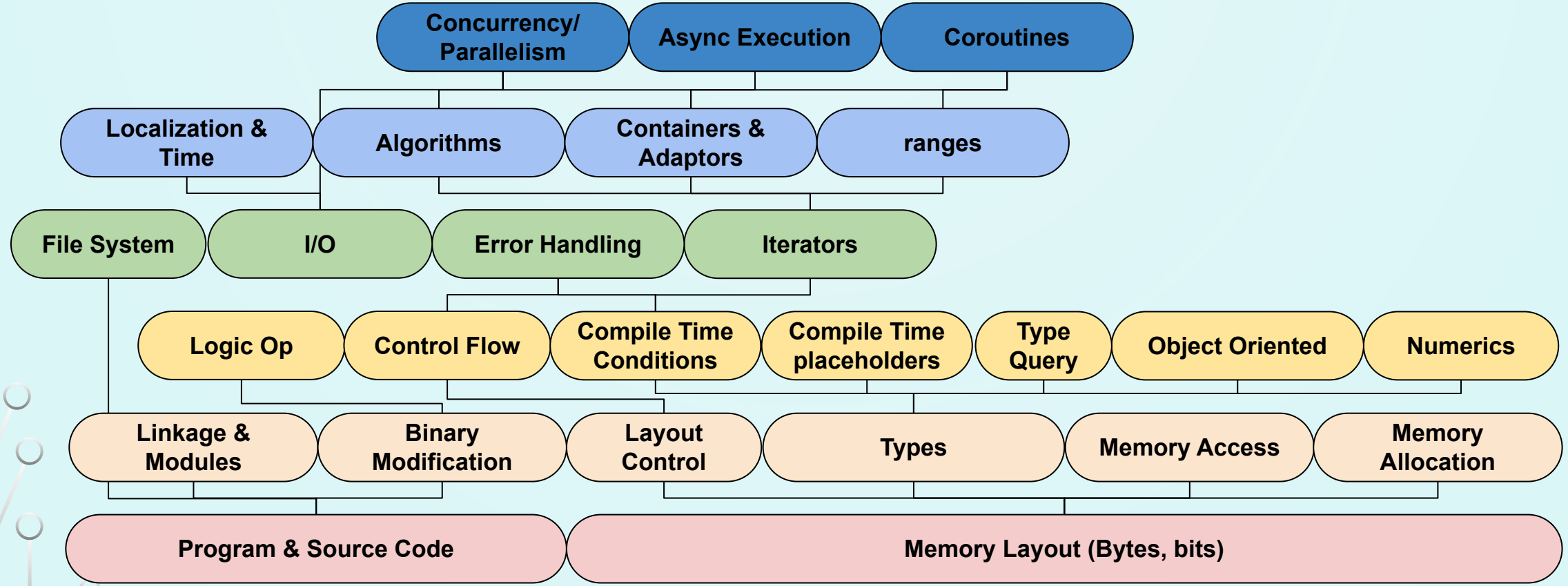


Part II: Abstraction Layers Model for C++

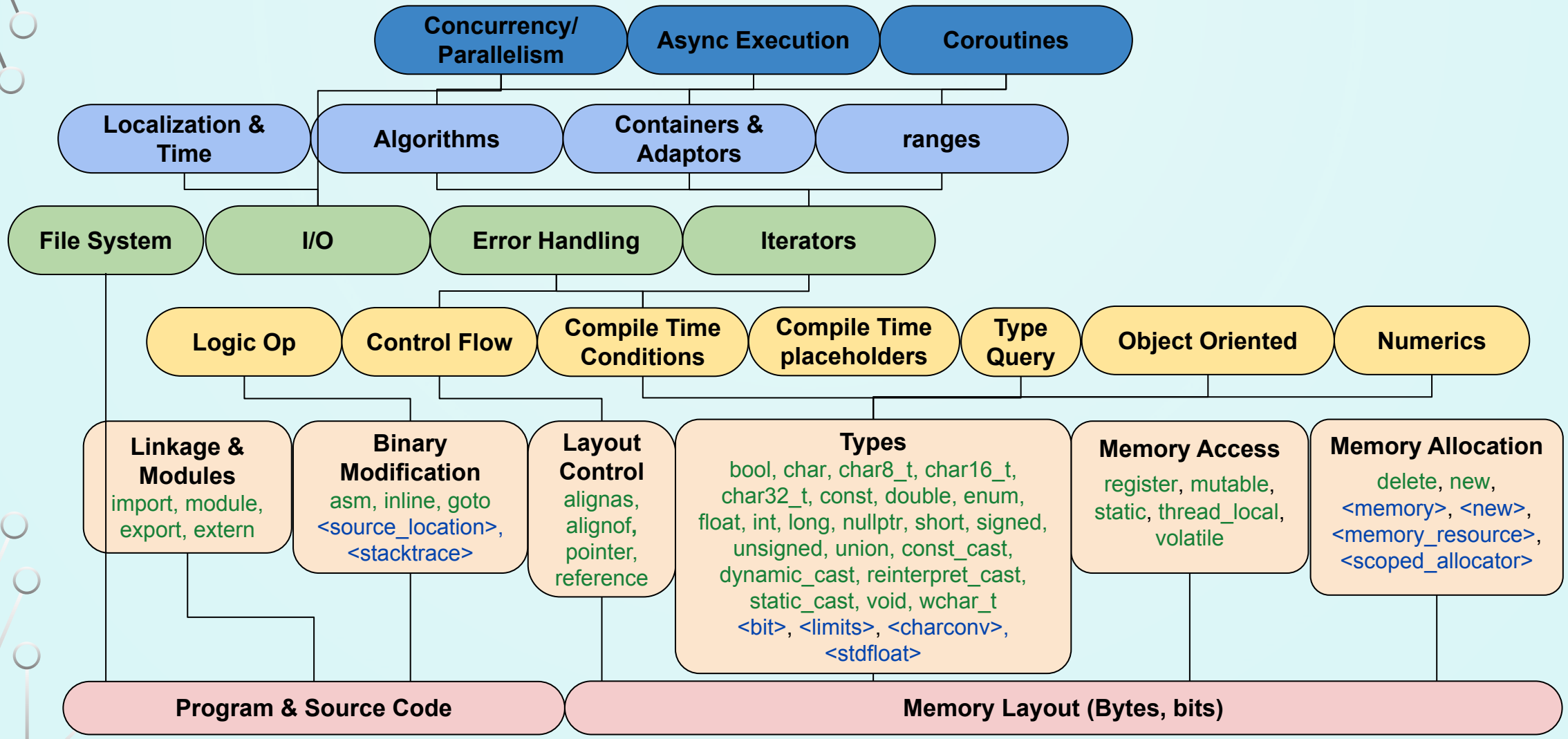
- Binary Level Queries & Modification
  - asm - inline assembly block
  - inline
  - goto
  - <source_location>
- Linkage & Modules
  - extern
  - export, import, module



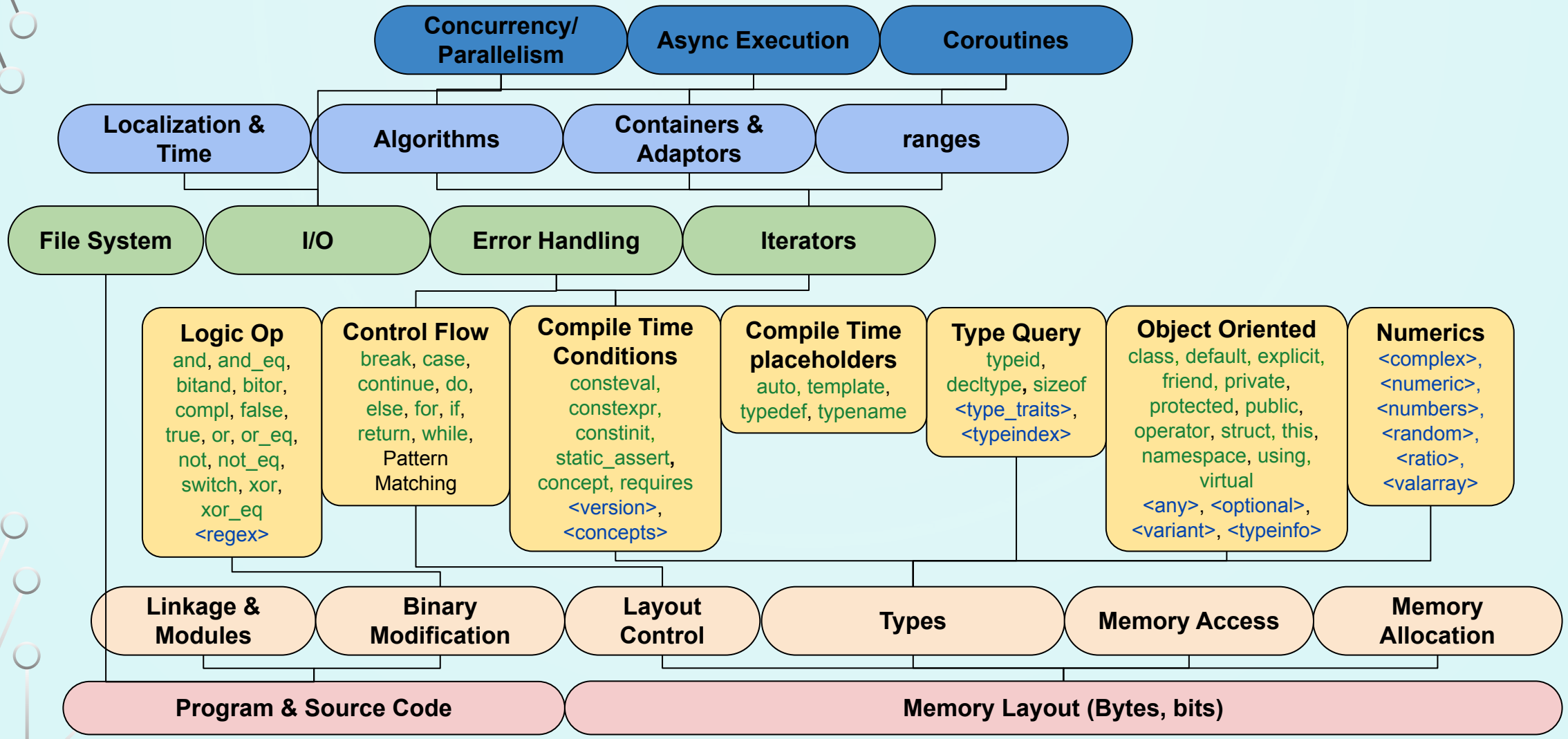
Part II: Abstraction Layers Model for C++



Part II: Abstraction Layers Model for C++



Part II: Abstraction Layers Model for C++



Part II: Keywords by Layers

A. Memory Access:
- register (2)
- mutable (1)
- static (B)
- thread_local (C++11) (B)
- volatile (1)

B. Memory Allocation:
- delete (1)
- new

C. Memory Layout Control (Bytes, bits):
- alignas (C++11)
- alignof (C++11)

D. Binary Level Modifications:
- asm
- inline (1)
- goto

E. Logic operators:
- and
- and_eq
- bitand
- bitor
- compl
- false
- true
- or
- or_eq
- not
- not_eq
- switch
- xor
- xor_eq

1. Types:
- bool
- char
- char8_t (C++20)
- char16_t (C++11)
- char32_t (C++11)
- const (A)
- double
- enum
- float
- int
- long
- nullptr (C++11)
- short
- signed (C)
- unsigned (C)
- union
- const_cast
- dynamic_cast (b)
- reinterpret_cast (A)
- static_cast (A)
- void
- wchar_t

2. Error Handling:
- catch
- try
- throw
- noexcept (C++11)

a. Object Oriented:
- class (1)
- default (1)
- explicit
- friend
- private
- protected
- public
- operator
- struct (1)
- this (4)
- namespace
- using (1)
- virtual

b. Type Query:
- typeid
- decltype (C++11) (1, d)
- sizeof (1)

c. Compile Time Conditions
- Compile Time Hints:
  - consteval (C++20)
  - constexpr (C++11)
  - constinit (C++20)
  - static_assert (C++11)
- concepts:
  - concept (C++20)
  - requires (C++20)

d. Compile Time Placeholders:
- auto (1)
- template
- typedef
- typename

a) Control Flow:
- break
- case
- continue
- do
- else
- for
- if
- return
- while
- (Pattern Matching)

b) Linkage Control & Modules:
- import
- module
- export (1) (3)
- extern (1)

c) Coroutines:
- co_await (C++20)
- co_return (C++20)
- co_yield (C++20)

d) Experimental (non-layer):
- atomic_cancel (TM TS)
- atomic_commit (TM TS)
- atomic_noexcept (TM TS)
- reflexpr (reflection TS)
- synchronized (TM TS)

Part II: Library Headers by Layers

A. Memory Access

B. Memory Allocation:
- <memory>
- <new>
- <memory_resource>
- <scoped_allocator>

C. Memory Layout Control

D. Binary Level Modifications:
- <source_location>
- <stacktrace>

E. Logic operators:
- <regex>

F. Algorithms:
- <algorithm>
- <compare>
- <initializer_list> (c.)
- <utility>
- <chrono>
- <functional>

G. Iterators:
- <iterator>

H. Ranges:
- <ranges>

I. Numerics:
- <complex>
- <numeric>
- <numbers>
- <random>
- <ratio>
- <valarray>

J. File System:
- <filesystem>
- <fstream>

1. Types:
- <bit> (C)
- <limits>
- <charconv>
- <stdfloat>

2. Error Handling:
- <expected>
- <exception>
- <stdexcept>
- <system_error>

3. Containers & Adaptors:
- <array>
- <bitset>
- <deque>
- <forward_list>
- <list>
- <map>
- <queue>
- <set>
- <stack>
- <string>
- <unordered_map>
- <unordered_set>
- <tuple>
- <vector>
- <string_view>
-
- <mdspan>
- <flat_set>
- <flat_map>

a. Object Oriented:
- <any>
- <optional>
- <variant>
- <typeinfo> (1)

b. Type Query:
- <type_traits> (c)
- <typeindex>

c. Compile Time Conditions
- Compile Time Hints:
  - <version>
- Concepts:
  - <concepts>

d. Compile Time Placeholders

e. Localization & Time:
- <locale>
- <codecvt>
- <chrono>

f. I/O:
- <format>
- <ios>
- <iosfwd> (forward decl)
- <iomanip>
- <iostream>
- <istream>
- <ostream>
- <print>
- <syncstream>
- <spanstream>
- <streambuf>
- <sstream>
- <strstream>

a) Control Flow

b) Linkage Control & Modules

c) Coroutines:
- <coroutine>
- <generator> (H)

d) Concurrency / parallelism:
- <atomic>
- <barrier>
- <condition_variable>
- <thread>
- <latch>
- <mutex>
- <semaphore>
- <shared_mutex>
- <stop_token>

e) Async
- <future>
- <execution> (F.)

01. C library (non-layer):
- <cassert>
- <clocale>
- <cstdarg>
- <cstring>
- <cctype>
- <cmath>
- <cstddef>
- <ctime>
- <cerrno>
- <csetjmp>
- <cstdio>
- <cwchar>
- <cfloat>
- <csignal>
- <cstdlib>
- <cwctype>
- <climits>

Part II: Abstraction Layers Model for C++

```
int main()
{
    int i = 0;                                  // Types
    // std::cout << &i;          // 0x7ffc8584085c
    *(int*)0x7ffc8584085c = 1;  // UB             // Layout Control
    return i;
}
```

- We can identify different parts of the program with different layers

Part II: Abstraction Layers Model for C++

```
#include <sstream>  // I/O


int main()
{
    auto iss = std::istringstream("0 1 2");
    auto j = 0;
    while (iss >> j)
        std::cout << "j: " << j << '\n';
}
```

```
j: 0
j: 1
j: 2
```

Part II: Abstraction Layers Model for C++

```cpp
#include <sstream>  // I/O
#include <ranges>  // Ranges
int main()
{
    auto iss = std::istringstream("0 1 2");
    for (auto i : rn::istream_view<int>(iss) | rv::take(1))
        std::cout << "j in loop: " << i << '\n';

    auto j = 0;
    iss >> j;                                   // Extraction
    std::cout << "j after loop: " << j << '\n';
}
```

```
j in loop: 0
j after loop: 2          // Observable Bug!
```

Part II: Abstraction Layers Model for C++

- P2406: Add `lazy_counted_iterator` (2023)
- P2799: Closed ranges may be a problem (...) (2023)
- P2846: size_hint: Eagerly reserving memory for non-quite-sized lazy ranges (2023)
- More to follow...

Part II: Abstraction Layers Model for C++

```
int main()
{
    auto iss = std::istringstream("0 1 2");                  // I/O
    for (auto i : rn::istream_view<int>(iss) | rv::take(1)) // Ranges
        std::cout << "In loop: " << i << '\n';
    auto j = 0;
    iss >> j;                                                // I/O
    std::cout << "After loop: " << j << '\n';
}
```

```
In loop: 0
After loop: 2
```

- `ranges::views::take` modifies the layer type of `iss`

Part III: Existing Solutions

Part III: Existing Solutions

- C++ “operates” in especially large number of layers
- Abstraction Layers are the glue areas between features
- These interaction are “dangerous” areas, on which bugs occur
- Our logic should take the transformation under consideration

Part III: Existing Solutions

- **Solution I: Create better code**
  - Create boundaries: Encapsulation, Namespaces, Headers, Modules, etc.
  - Use code guidelines, tools, etc. to enforce those

```
int main()
{
    auto iss = std::istringstream("0 1021 2");

    for (auto i : rn::istream_view<int>(iss) | rv::take(1))
        std::cout << "In loop: " << i << '\n';
    auto j = 0;
    iss >> j;                                          // Error
    std::cout << "After loop: " << j << '\n';
}
```

Part III: Existing Solutions

- **Solution I: Create better code**
  - Create boundaries: Encapsulation, Namespaces, Headers, Modules, etc.
  - Use code guidelines, tools, etc. to enforce those
  - Example of such: CppCon 2021: Up to Code / David Sankel
  - **Upsides:**
    - Existing and familiar idioms, utilities, guidelines, tools 👍
  - **Downsides:**
    - May create unacceptable overhead 👎
    - Enforcing is a challenge, especially in large projects, multiple teams 👎
    - Does not help with cross-boundaries code 👎

Part III: Existing Solutions

- **Solution II: Use a different language for higher level logic**
  - Modern C++ provides a partial solution for shifting between abstractions
  - Following modern idioms will minimize logic errors in our code

  - **Upsides:**
    - Discard previous error-prone code “for free” 👍
  - **Downsides:**
    - Learn (and deploy!) a “new language” with each standard release 👎
    - We didn’t provide a solution for existing code 👎
    - We didn’t provide a solution for Assembly-C-C++ code bases 👎
    - Does not help with cross-boundaries code 👎

Part IV: Future solutions
-or-
How can we do better?

Part IV: How Can We Do Better?

- We need to apply this model on our code
- Apply to language / library syntax creates a new language (or use python 🙃)
- Solution: apply the logic in the **error messages level**
- Applying this model to errors/warnings preserves syntax compatibility,

  but at the same time - moves us to a higher level of analytics

Part IV: How Can We Do Better?

- Static Analysis Tool: Classify tokens according to layers

```
indic_dict = { "std::array<int,..>": "Containers", "sizeof" : "Types" }
token_dict = { "std::cout": "IO", "<<": "IO" }
```

```
1 #include <iostream>
2
3 int main()
4 {
5     std::array<int, SIZE> arr = {0,1,2};
6     std::cout << sizeof(arr);
7 }
```

```
Warning! On line 6, variable `arr` changes abstraction layer from ~Containers to ~Types
```

Part IV: How Can We Do Better?

```
indic_dict = { "int": "Types", "std::istringstream" : "IO", … }
token_dict = { "rn::istream_view": "Ranges", "rv::take": "Ranges", ">>": "IO", … }
```

```
1 int main()
2 {
3     std::istringstream iss("0 1 2");
4     for (int i : rn::istream_view<int>(iss) | rv::take(1))
5         std::cout << "In loop: " << i << '\n';
6     int j = 0;
7     iss >> j;
8     std::cout << "After loop: " << j << '\n';
9 }
```

```
Warning! On line 4, variable `iss` changes abstraction layer from ~IO to ~Ranges
```

```
Warning! On line 7, variable `iss` changes abstraction layer from ~Ranges to ~IO
```

Part IV: How Can We Do Better?

	line_num	lines	tokens	layers	warning
0	1	#include <sstream>	[]	[]	False
1	2	#include <ranges>	[]	[]	False
2	3		[]	[]	False
3	4	int main()	[main()]	[Types]	False
4	5	{	[]	[]	False
5	6	std::istringstream iss ("0 1 2")	[iss]	[IO]	False
6	7	for (int i : rn::istream_view<int>(iss) | r...	[i, rn::istream_view<int>(, iss]	[Types, Ranges, IO]	True
7	8	std::cout << "j in loop: " << i << '\n'	[std::cout, i]	[IO, Types]	True
8	9		[]	[]	False
9	10	int j = 0	[j]	[Types]	False
10	11	iss >> j	[iss, >>, j]	[IO, IO, Types]	True
11	12	std::cout << "j after loop: " << j << '\n'	[std::cout, j]	[IO, Types]	True
12	13	}	[]	[]	False

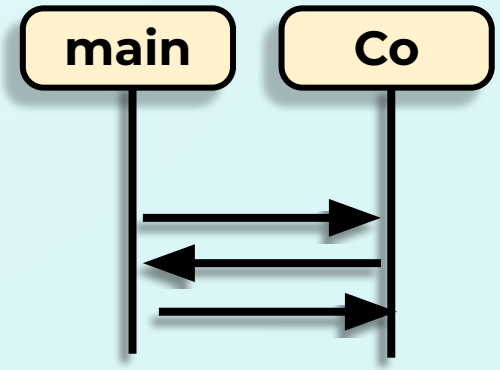
Warnings for: cpp_examples/test2.cpp

Warning! On line 7, variable iss changes abstraction layer from IO to Ranges

Part IV: How Can We Do Better?

- Coroutine is a function which can suspend execution (C++20)

```
Task doWork();    // Coroutine
struct Task {
    struct promise_type {
        HandleWrap get_return_object() { return HandleWrap(this); }
        std::suspend_always initial_suspend() { … }
        struct HandleWrap {
            void resume() { std::cout << "Work\n"; mHandle.resume(); }
        };
    };
};
int main()
{
    auto work_handle = doWork();
    work_handle.resume();
}
```

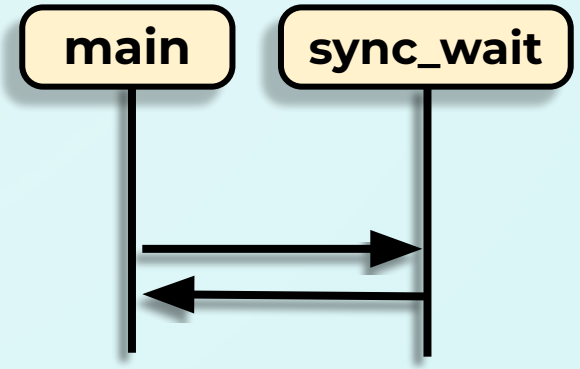


Part IV: How Can We Do Better?

- std::execution is an async execution library, planned to go into C++26

```
scheduler auto sch = thread_pool.scheduler();  // Scheduler
sender auto begin = schedule(sch);
sender auto doWork = then(schedule(sch), [] {
    std::cout << "Work\n";
});

int main()
{
    this_thread::sync_wait(doWork);
}
```



Part IV: How Can We Do Better?

```
indic_dict = { "doWork": "Coroutines", … }
token_dict = { "Task": "Coroutines", "sync_wait": "Async" … }
```

```
Task doWork();    // Coroutine
struct Task {
    struct promise_type {
        HandleWrap get_return_object() { return HandleWrap(this); }
        std::suspend_always initial_suspend() { … }
        void return_void { std::cout << "Work\n"; }
    };
};
```

```
1 int main()
2 {
3   this_thread::sync_wait(doWork());    // Awaitable satisfies requirements for senders
4 }
```

```
Warning! On line 3, variable `doWork` changes abstraction layer from ~Coroutines to ~Async
```

Part IV: How Can We Do Better?

- Templates should be considered with the instantiation type

```
1 #include <functional>
2 #include <string>
3 #include <filesystem>
4 void foo()
5 {
6     std::function<std::filesystem::path()> fp{};
7     std::function<std::string()> fs{};
8     fp = fs; // Works in MSVC, clang, gcc
9     fs = fp; // Works only in GCC and clang
10 }
```

```
Warning! On line 8, variable `fp` changes abstraction layer from ~FileSystem to ~Types
```

* Example by Hana Dusíková

Part IV: How Can We Do Better?

- False positives are common

```
indic_dict = { "int": "Types", "int&" : "Layout" }
token_dict = { "std::cout": "IO", "<<": "IO" }
```

```
1 #include <iostream>
2
3 int main()
4 {
5     int a = 5;
6     int& ra = a;
7     std::cout << ra;
8 }
```

```
Warning! On line 7, variable `ra` changes abstraction layer from ~Layout to ~IO
```

Part IV: How Can We Do Better?

- April 2023, committee ML: Can we use UTF8 strings with std::format()? (C++20)

```
auto s = u8"Köln";
std::format("Stadt: {}\n", s);  // ERROR
```

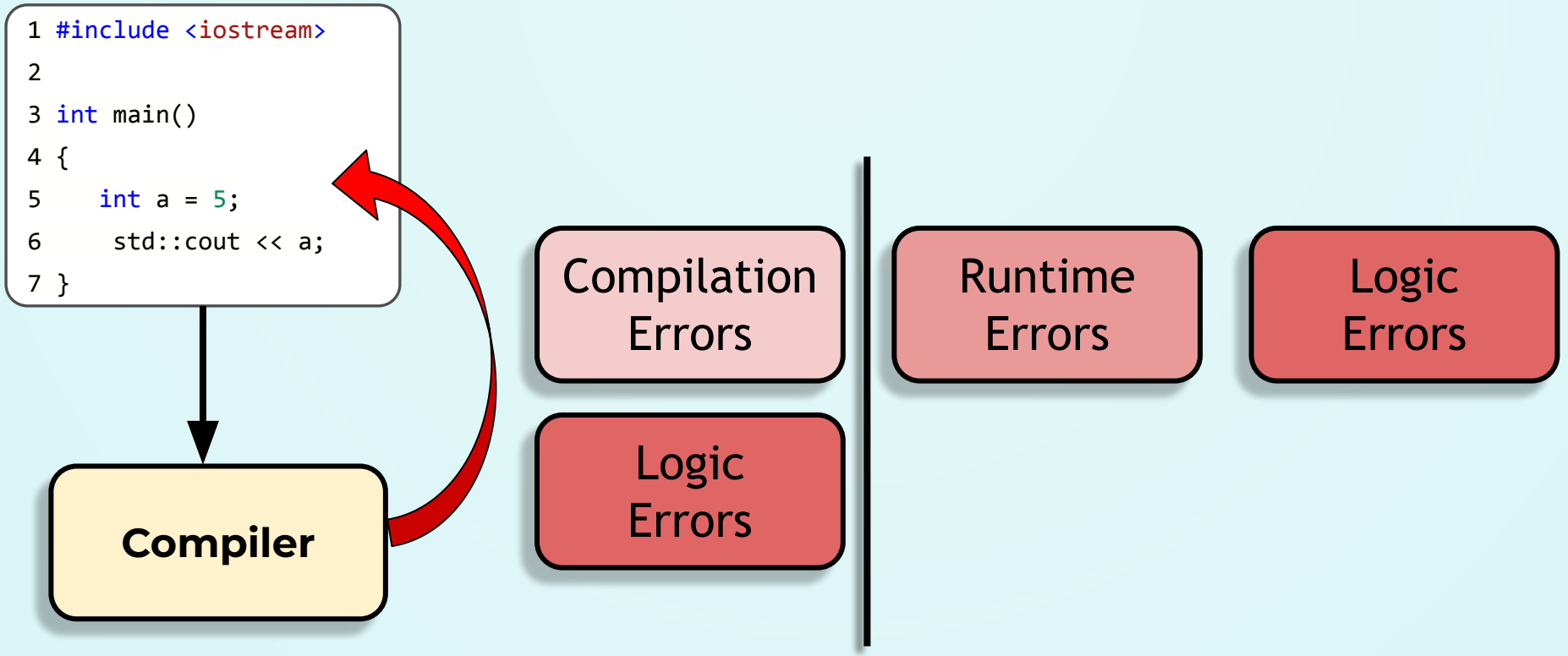
Types ↔ I/O

- P2728R0: Unicode in the Library, Part 1 & Part 2 (Zach Laine) (C++26)

```
int main()
{
    std::string input = get_utf8_input();
    auto const utf16_view = std::uc::as_utf16(input);
    process_input(utf16_view.begin(), utf16.end());    // accepts UTF-16
}
```

  - Formatters added in P2728 allow UTF views will be used in std::format()

Part IV: How Can We Do Better?



Part IV: How Can We Do Better?

- Static Analysis Tool: Classify tokens according to layers

```
-FunctionDecl 0x16fb0d0 <./cpp_examples/test3.cpp:1:1, line:7:1> line:1:5 main 'in
`-CompoundStmt 0x16fb3c8 <line:2:1, line:7:1>
  |-DeclStmt 0x16fb280 <line:3:5, col:14>
  | `-VarDecl 0x16fb1f8 <col:5, col:13> col:9 used i 'int' cinit
  |   `-IntegerLiteral 0x16fb260 <col:13> 'int' 0
  |-BinaryOperator 0x16fb360 <line:5:5, col:29> 'int' lvalue '='
  | |-UnaryOperator 0x16fb328 <col:5, col:12> 'int' lvalue prefix '*' cannot overflow
  | | `-CStyleCastExpr 0x16fb300 <col:6, col:12> 'int *' <IntegralToPointer>
  | |   `-IntegerLiteral 0x16fb298 <col:12> 'long' 140722548508764
  | `-IntegerLiteral 0x16fb340 <col:29> 'int' 1
  `-ReturnStmt 0x16fb3b8 <line:6:5, col:12>
    `-ImplicitCastExpr 0x16fb3a0 <col:12> 'int' <LValueToRValue>
      `-DeclRefExpr 0x16fb380 <col:12> 'int' lvalue Var 0x16fb1f8 'i' 'int'
```

```
1 int main()
2 {
3  int i = 0;
4  *(int*)0x7ffc8584085c = 1;
5  return i;
6 }
```

Warning! On line 4, int literal changes abstraction layer from ~Type to ~Layout

Part IV: How Can We Do Better?

- Add a layer of analytics:
  I. **Compile time**: errors in syntax and software model (e.g. type system)
  II. **Abstractions resolution**: errors in logic and composition
  III. **Runtime**: errors in dynamic data
- Applying abstraction layers to the model exposes logic bugs on earlier stage
- **Do this by adding the abstraction layers classifications into:**
  I. Compilers
  II. Static Analysis Tools
  III. Other tools which generates AST (CastXML, etc.)

Part IV: How Can We Do Better - The Full Solution

- Focus on interfaces with the user, e.g:

Create an “ergonomics” study group

- David Sankel

- But also, we should:
  - Address abstraction layers model **as developers**
  - Address abstraction layers model **as the standards committee**
  - Examine every proposal not only for “local” usability, but also for **integration**

  - **Add Abstraction Layers Error Messages to Our Tools**

Thank you for listening!

Thanks!

Thank you for listening ☺️

Special thanks to:

- Yehezkel Brant
- Corentin Jabot
- NYC++ Meetup group
- Barry Revzin
- Bryce Adelstein Lelbach
- Aditya - layers in IDE
- Vern - user defined layers
- Amir - teachability

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Would love to get your input!

References & More Info

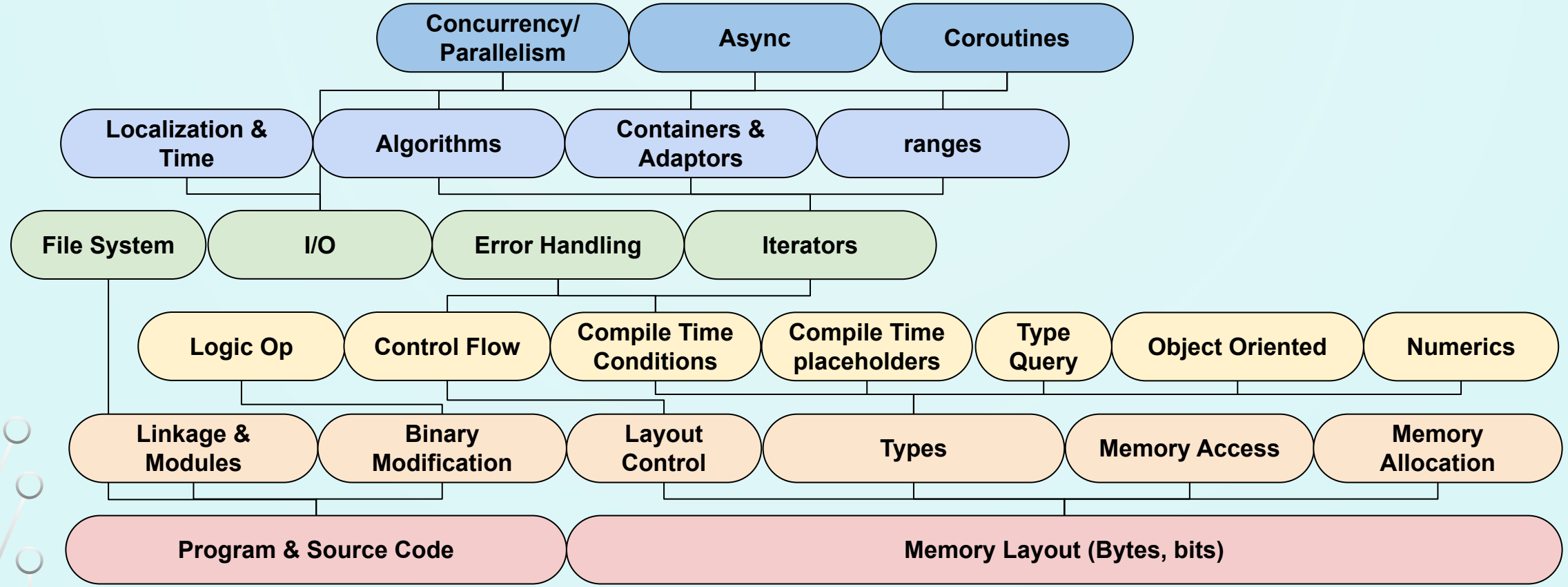
- Papers:
  - P2406R5: Add `lazy_counted_iterator` (Yehezkel Bernat)
  - P2846R0: size_hint: Eagerly reserving memory for non-quite-sized lazy ranges (Corentain Jabot)
  - P2300R7: std::execution (Michał Dominiak, Georgy Evtushenko, Lewis Baker, Lucian Radu Teodorescu, Lee Howes, Kirk Shoop, Michael Garland, Eric Niebler, Bryce Adelstein Lelbach)
  - P2728R0: Unicode in the Library, Part 1 & Part 2 (Zach Laine)
  - P2434: Nondeterministic pointer provenance

- Blogs:
  - What Color Is Your Function / Bob Nystorm
  - C++ Buffer Hardening / Jan Korous

- Talks:
  - CppCon 2021: Up to Code / David Sankel
  - CppNow 2022: Rust Features that I Want in C++ / David Sankel
  - CppNow 2023: Take Five Adventures with Taking Elements from an Input Stream / Barry Revzin

- Books:
  - Abstraction and Specification in Program Development / Barbara Liskov and John Guttag

Part II: Abstraction Layers Model for C++



C++ Keywords

alignas (C++11)
alignof (C++11)
and
and_eq
asm
atomic_cancel (TM TS)
atomic_commit (TM TS)
atomic_noexcept (TM TS)
auto (1)
bitand
bitor
bool
break
case
catch
char
char8_t (C++20)
char16_t (C++11)
char32_t (C++11)
class (1)
compl
concept (C++20)
const
consteval (C++20)
constexpr (C++11)
constinit (C++20)
const_cast
continue
co_await (C++20)
co_return (C++20)
co_yield (C++20)
decltype (C++11)
default (1)
delete (1)
do
double
dynamic_cast
else
enum
explicit
export (1) (3)
extern (1)
false
float
for
friend
goto
if
inline (1)
int
long
mutable (1)
namespace
new
noexcept (C++11)
not
not_eq
nullptr (C++11)
operator
or
or_eq
private
protected
public
reflexpr (reflection TS)
register (2)
reinterpret_cast
requires (C++20)
return
short
signed
sizeof (1)
static
static_assert (C++11)
static_cast
struct (1)
switch
synchronized (TM TS)
template
this (4)
thread_local (C++11)
throw
true
try
typedef
typeid
typename
union
unsigned
using (1)
virtual
void
volatile
wchar_t
while
xor
xor_eq

Library Headers

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