Modern C++ Programming

18. Advanced Topics II

Federico Busato

Table of Context

Table of Context

Undefined Behavior

Undefined Behavior Overview

Undefined behavior means that the semantic of certain operations is undefined (outside the language/library specification) or illegal, and the compiler presumes that such operations never happen

Motivations behind undefined behavior:

- *Compiler optimizations*, e.g. signed overflow or NULL pointer deferencing
- *Simplify compile checks*

Some undefined behavior cases provide an *implementation-defined behavior* depending on the compiler and platform. In this case, the code is *not portable*

- What Every C Programmer Should Know About Undefined Behavior
- What are all the common undefined behaviours that a C++ programmer should know about?

- `const_cast` applied to a `const` variables

```cpp
const int      var = 3;
const_cast<int>(var) = 4;
... // use var
```

- Memory alignment

```cpp
char* ptr = new char[512];
auto ptr2 = reinterpret_cast<uint64_t*>(ptr + 1);
ptr2[3]; // ptr2 is not aligned to 8 bytes (sizeof(uint64_t))
```

- Memory initialization

```cpp
int var;
// use var
auto var2 = new int;
// use var2
```

- **Memory access-related**
    - NULL pointer deferencing
    - Out-of-bound access

- **Platform specific behavior**
    - Endianness
      ```
      union U {
          unsigned x;
          char     y;
      };
      ```

    - Type definition
      ```
      long x = 1ul << 32u; // different behavior depending on the OS
      ```

    - Intrinsic functions

- **Strict aliasing**

```cpp
float x = 3;
auto  y = reinterpret_cast<unsigned&>(x);
// x, y break the strict aliasing rule
```

- **Lifetime issues**

```cpp
int* f() {
    int tmp[10];
    return tmp;
}
int* ptr = f();
ptr[0];
```

- **Operations unspecified behavior**
  - A legal operation but the C++ standard does not document the results
  - Signed shift `-2 ≪ x` (before C++20), large-than-type shift `3 ≪ 32`, signed overflow, etc.
  - Operation ordering `f(i++, i++)`

- **One Definition Rule violation**
  - Different definitions of `inline` functions in distinct translation units

- **Missing `return` statement**

```cpp
int f(float x) {
    int y = x * 2;
}
```

- **Dangling reference**

```
iint n = 1;
const int& r = std::max(n-1, n+1); // dagling
// GCC 13 experimental -Wdangling-reference (enabled by -Wall)
```

Detecting Undefined Behavior

There are several ways to detect undefined behavior at compile-time and at run-time:

- Using GCC/Clang undefined behavior sanitizer (run-time check)

- Static analysis tools

- Use `constexpr` expressions as undefined behavior is not allowed

```cpp
constexpr int   x1 = 2147483647 + 1;   // compile error
constexpr int   x2 = (1 << 32);        // compile error
constexpr int   x3 = (1 << -1);        // compile error
constexpr int   x4 =  3 / 0;           // compile error
constexpr int   x5 = *((int*) nullptr) // compile error
constexpr int   x6 = 6
constexpr float x7 = reinterpret_cast<float&>(x6); // compile error
```

Exploring Undefined Behavior Using Constexpr

Error Handing

Recoverable Error Handing

Recoverable *Conditions that are not under the control of the program*. They indicates *"exceptional"* run-time conditions. e.g. file not found, bad allocation, wrong user input, etc.

The common ways for handling recoverable errors are:

Exceptions Robust but slower and requires more resources
Error values Fast but difficult to handle in complex programs

---

- Modern C++ best practices for exceptions and error handling
- Back to Basics: Exceptions - CppCon2020
- ISO C++ FAQ: Exceptions and Error Handling
- Zero-overhead deterministic exceptions: Throwing values
- C++ exceptions are becoming more and more problematic

C++ Exceptions - Advantages

C++ Exceptions provide a well-defined mechanism to detect errors passing the information up the call stack

- **Exceptions cannot be ignored**. Unhandled exceptions stop program execution (call `std::terminate()`)

- **Intermediate functions are not forced to handle them**. They don't have to coordinate with other layers and, for this reason, they provide good composability

- Throwing an exception **acts like a return statement** destroying all objects in the current scope

- An exception enables a **clean separation** between the code that detects the error and the code that handles the error

- Exceptions work well with object-oriented semantic (constructor)

C++ Exceptions - Disadvantages

- **Code readability**: Using exception can involve more code than the functionality itself

- **Code comprehension**: Exception control flow is invisible and it is not explicit in the function signature

- **Performance:** Extreme performance overhead in the failure case (violate the zero-overhead principle)

- **Dynamic behavior**: `throw` requires dynamic allocation and `catch` requires RTTI. It is not suited for real-time, safety-critical, or embedded systems

- **Code bloat**: Exceptions could increase executable size by 5-15% (or more*)

---

*Binary size and exceptions

Cost of returning error up ten stack frames on x64
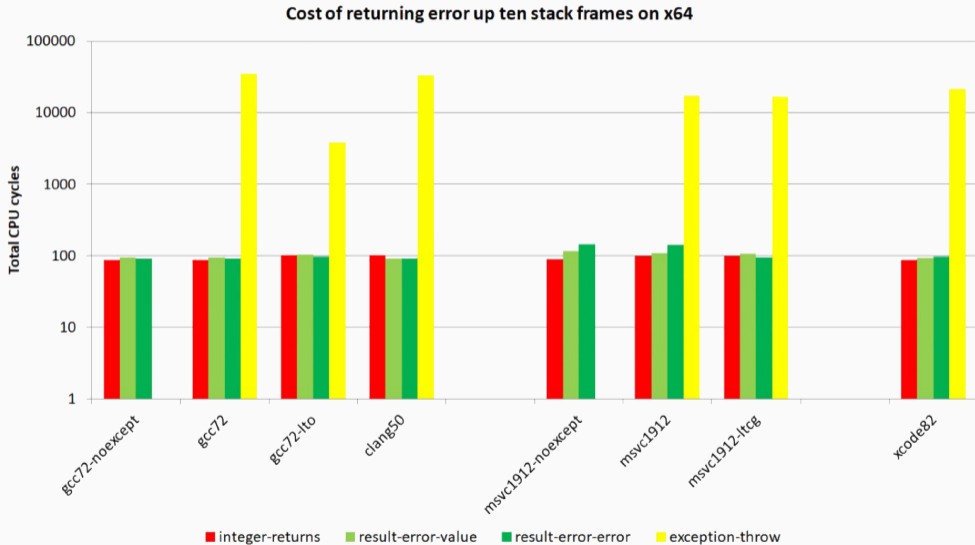
C++ Exception Basics

C++ provides three keywords for exception handling:

throw Throws an exception

try Code block containing potential throwing expressions

catch Code block for handling the exception

```cpp
void f() { throw 3; }

int main() {
    try {
        f();
    } catch (int x) {
        cout << x; // print "3"
    }
}
```

std **Exceptions**

`throw` can throw everything such as integers, pointers, objects, etc. The standard way consists in using the std library exceptions `<stdexcept>`

```cpp
#include <stdexcept>

void f(bool b) {
    if (b)
        throw std::runtime_error("runtime error");
    throw std::logic_error("logic error");
}
int main() {
    try {
        f(false);
    } catch (const std::runtime_error& e) {
        cout << e.what();
    } catch (const std::exception& e) {
        cout << e.what();  // print: "logic error"
    }
}
```

Exception Capture

NOTE: C++, differently from other programming languages, does not require explicit dynamic allocation with the keyword `new` for throwing an exception. The compiler implicitly generates the appropriate code to construct and clean up the exception object. Dynamically allocated objects require a `delete` call

The right way to capture an exception is by `const`-reference. Capturing by-value is also possible but, it involves useless copy for non-trivial exception objects

`catch(...)` can be used to capture any thrown exception

```cpp
int main() {
    try {
        throw "runtime error"; // throw const char*
    } catch (...) {
        cout << "exception";   // print "exception"
    }
}
```

Exception Propagation

Exceptions are automatically propagated along the call stack. The user can also control how they are propagated

```cpp
int main() {
    try {
        ...
    } catch (const std::runtime_error& e) {
        throw e; // propagate a copy of the exception
    } catch (const std::exception& e) {
        throw;   // propagate the exception
    }
}
```

Defining Custom Exceptions

```cpp
#include <exception> // to not confuse with <stdexcept>

struct MyException : public std::exception {
    const char* what() const noexcept override { // could be also "constexpr"
        return "C++ Exception";
    }
};

int main() {
    try {
        throw MyException();
    } catch (const std::exception& e) {
        cout << e.what(); // print "C++ Exception"
    }
}
```

noexcept Keyword

C++03 allows listing the exceptions that a function might directly or indirectly throw, e.g. `void f() throw(int, const char*) {`

C++11 deprecates `throw` and introduces the `noexcept` keyword

```cpp
void f1();                // may throw
void f2() noexcept;       // does not throw
void f3() noexcept(true); // does not throw
void f4() noexcept(false); // may throw
template<bool X>
void f5() noexcept(X);    // may throw if X is false
```

If a `noexcept` function throw an exception, the runtime calls `std::terminate()`

`noexcept` should be used when throwing an exception is impossible or unacceptable. It is also useful when the function contains code outside user control, e.g. `std` functions/objects

Function-try-block

Exception handlers can be defined around the body of a function

```cpp
void f() try {
    ... // do something
} catch (const std::runtime_error& e) {
    cout << e.what();
} catch (...) { // other exception
    ...
}
```

The `new` operator automatically throws an exception (`std::bad_alloc`) if it cannot allocate the memory

`delete` never throws an exception (unrecoverable error)

```cpp
int main() {
    int* ptr = nullptr;
    try {
        ptr = new int[1000];
    }
    catch (const std::bad_alloc& e) {
        cout << "bad allocation: " << e.what();
    }
    delete[] ptr;
}
```

C++ also provides an overload of the `new` operator with non-throwing memory allocation

```cpp
#include <new> // std::nothrow

int main() {
    int* ptr = new (std::nothrow) int[1000];
    if (ptr == nullptr)
        cout << "bad allocation";
}
```

Throwing exceptions in *constructors* is fine while it is not allowed in *destructors*

```cpp
struct A {
    A()  { new int[10]; }
    ~A() { throw -2;     }
};
int main() {
    try {
       A a; // could throw "bad_alloc"
            // "a" is out-of-scope -> throw 2
    } catch (...) {
            // two exceptions at the same time
    }
}
```

Destructors should be marked noexcept

```cpp
struct A {
    int* ptr1, *ptr2;

    A() {
        ptr1 = new int[10];
        ptr2 = new int[10]; // if bad_alloc here, ptr1 is lost
    }
};
```

```cpp
struct A {
    std::unique_ptr<int> ptr1, ptr2;

    A() {
        ptr1 = std::make_unique<int[]>(10);
        ptr2 = std::make_unique<int[]>(10); // if bad_alloc here,
    }                                        // ptr1 is deallocated
};
```

- **Global state**, e.g. `errno`
  - Easily forget to check for failures
  - Error propagation using `if` statements and early `return` is manual
  - No compiler optimizations due to global state

- **Simple error code**, e.g. `int`, `enum`, etc.
  - Easily forget to check for failures (workaround `[[nodiscard]]`)
  - Error propagation using `if` statements and early `return` is manual
  - Potential error propagation through different contexts and losing initial error information
  - Constructor errors cannot be handled

- `std::error_code`, standardized error code
    - Easily forget to check for failures (workaround `[[nodiscard]]`)
    - Error propagation using `if` statements and early `return` is manual
    - Code bloating for adding new enumerators (see `Your own error code`)
    - Constructor errors cannot be handled

- **Supporting libraries**, e.g. `Boost Outcome`, `STX`, etc.
    - Require external dependencies
    - Constructor errors cannot be handled in a direct way
    - Extra logic for managing return values

C++ Idioms

Rule of Zero

The **Rule of Zero** is a rule of thumb for C++

> Utilize the *value semantics* of existing types to <u>avoid</u> having to implement *custom* copy and move operations

Note: many classes (such as **std** classes) manage resources themselves and should not implement copy/move constructor and assignment operator

```cpp
class X {
public:
    X(...); // constructor
            // NO need to define copy/move semantic
private:
    std::vector<int>    v; // instead raw allocation
    std::unique_ptr<int> p; // instead raw allocation
};                          // see smart pointer
```

Rule of Three

The **Rule of Three** is a rule of thumb for C++(03)

> If your class needs <u>any</u> of
>
> - a copy constructor `X(const X&)`
>
> - an assignment operator `X& operator=(const X&)`
>
> - or a destructor `~X()`
>
> defined explicitly, then it is likely to need <u>all</u> three of them

Some resources <u>cannot</u> or <u>should not</u> be copied. In this case, they should be declared as deleted
```
X(const X&) = delete
X& operator=(const X&) = delete
```

Rule of Five

The **Rule of Five** is a rule of thumb for C++11

> If your class needs any of
>
> - a copy constructor `X(const X&)`
>
> - a move constructor `X(X&&)`
>
> - an assignment operator `X& operator=(const X&)`
>
> - an assignment operator `X& operator=(X&&)`
>
> - or a destructor `~X()`
>
> defined explicitly, then it is likely to need all five of them

Singleton

Singleton is a software design pattern that restricts the instantiation of a class to one and only one object (a common application is for logging)

```cpp
class Singleton {
public:
    static Singleton& get_instance() {  // note "static"
        static Singleton instance { ..init.. } ;
        return instance;   // destroyed at the end of the program
    }                      // initiliazed at first use

    Singleton(const& Singleton)        = delete;
    void operator=(const& Singleton) = delete;

    void f() {}
private:
    T _data;

    Singleton( ..args.. ) { ... }  // used in the initialization
}
```

PIMPL - Compilation Firewalls

Pointer to IMPLementation (PIMPL) idiom allows decoupling the interface from the implementation in a clear way

header.hpp

```cpp
class A {
public:
    A();
    ~A();
    void f();
private:
    class Impl;  // forward declaration
    Impl* ptr;   // opaque pointer
};
```

NOTE: The class does not expose internal data members or methods

PIMPL - Implementation

source.cpp (Impl actual implementation)

```cpp
class A::Impl { // could be a class with a complex logic
public:
    void internal_f() {
        ..do something..
    }
private:
    int   _data1;
    float _data2;
};

A::A()    : ptr{new Impl()} {}
A::~A()    { delete ptr; }
void A::f() { ptr->internal_f(); }
```

PIMPL - Advantages, Disadvantages

Advantages:

- ABI stability
- Hide private data members and methods
- Reduce compile type and dependencies

Disadvantages:

- Manual resource management
  - `Impl* ptr` can be replaced by `unique_ptr<impl> ptr` in C++11
- Performance: pointer indirection + dynamic memory
  - dynamic memory could be avoided by using a reserved space in the interface e.g.
    `uint8_t data[1024]`

PIMPL - Implementation Alternatives

What parts of the class should go into the `Impl` object?

- *Put all private and protected members into `Impl`*:
  Error prone. Inheritance is hard for opaque objects

- *Put all private members (but not functions) into `Impl`*:
  Good. Do we need to expose all functions?

- *Put everything into `Impl`, and write the public class itself as only the public interface, each implemented as a simple forwarding function*:
  Good

The **Curiously Recurring Template Pattern (CRTP)** is an idiom in which a class `X` derives from a class template instantiation using `X` itself as template argument

A common application is *static polymorphism*

```cpp
template <class T>
struct Base {
    void my_method() {
        static_cast<T*>(this)->my_method_impl();
    }
};

class Derived : public Base<Derived> {
// void my_method() is inherited
    void my_method_impl() { ... } // private method
};
```

```cpp
#include <iostream>
template <typename T>
struct Writer {
    void write(const char* str) {
        static_cast<const T*>(this)->write_impl(str);
    }
};
class CerrWriter : public Writer<CerrWriter> {
    void write_impl(const char* str) {  std::cerr << str;  }
};
class CoutWriter : public Writer<CoutWriter> {
    void write_impl(const char* str) {  std::cout << str;  }
};
CoutWriter x;
CerrWriter y;
x.write("abc");
y.write("abc");
```

```cpp
template <typename T>
void f(Writer<T>& writer) {
    writer.write("abc);
}

CoutWriter x;
CerrWriter y;
f(x);
f(y);
```

Virtual functions cannot have template arguments, but they can be emulated by
using the following pattern

```cpp
class Base {
public:
    template<typename T>
    void method(T t) {
        v_method(t);    // call the actual implementation
    }
protected:
    virtual void v_method(int t)    = 0; // v_method is valid only
    virtual void v_method(double t) = 0; // for "int" and "double"
};
```

Actual implementations for derived class `A` and `B`

```cpp
class AImpl : public Base {
protected:
    template<typename T>
    void t_method(T t) { // template "method()" implementation for A
        std::cout << "A " << t << std::endl;
    }
};

class BImpl : public Base {
protected:
    template<typename T>
    void t_method(T t) { // template "method()" implementation for B
        std::cout << "B " << t << std::endl;
    }
};
```

```cpp
template<class Impl>
class DerivedWrapper : public Impl {
private:
    void v_method(int t) override {
        Impl::t_method(t);
    }
    void v_method(double t) override {
        Impl::t_method(t);
    } // call the base method
};


using A = DerivedWrapper<AImpl>;
using B = DerivedWrapper<BImpl>;
```

```cpp
int main(int argc, char* argv[]) {
    A a;
    B b;
    Base* base = nullptr;

    base = &a;
    base->method(1);   // print "A 1"
    base->method(2.0); // print "A 2.0"

    base = &b;
    base->method(1);   // print "B 1"
    base->method(2.0); // print "B 2.0"
}
```

method() calls v_method() (pure virtual method of Base)

v_method() calls t_method() (actual implementation)

Smart pointers

Smart Pointers

Smart pointer is a pointer-like type with some additional functionality, e.g. *automatic memory deallocation* (when the pointer is no longer in use, the memory it points to is deallocated), reference counting, etc.

C++11 provides three smart pointer types:

- **std::unique_ptr**
- **std::shared_ptr**
- **std::weak_ptr**

Smart pointers prevent most situations of memory leaks by making the memory deallocation automatic

Smart Pointers Benefits

- If a smart pointer goes *out-of-scope*, the appropriate method to release resources is called automatically. The memory is not left dangling

- Smart pointers will automatically be set to `nullptr` if not initialized or when memory has been released

- `std::shared_ptr` provides automatic reference count

- If a special `delete` function needs to be called, it will be specified in the pointer type and declaration, and will automatically be called on delete

`std::unique_ptr` is used to manage any dynamically allocated object that is <u>not</u> <u>shared</u> by multiple objects

```cpp
#include <iostream>
#include <memory>
struct A {
    A()  { std::cout << "Constructor\n"; } // called when A()
    ~A() { std::cout << "Destructor\n";  } // called when u_ptr1,
};                                         // u_ptr2 are out-of-scope
int main() {
    auto              raw_ptr = new A();
    std::unique_ptr<A> u_ptr1(new A());
    std::unique_ptr<A> u_ptr2(raw_ptr);
// std::unique_ptr<A> u_ptr3(raw_ptr); // no compile error, but wrong!! (not unique)

// u_ptr1 = raw_ptr;                 // compile error (not unique)
// u_ptr1 = u_ptr2;                  // compile error (not unique)
    u_ptr1 = std::move(u_ptr2); // delete u_ptr1;
}                               // u_ptr1 = u_ptr2;
                                // u_ptr2 = nullptr
```

`std::unique_ptr` methods

- `get()` returns the underlying pointer

- `operator*` `operator->` dereferences pointer to the managed object

- `operator[]` provides indexed access to the stored array (if it supports random access iterator)

- `release()` returns a pointer to the managed object and releases the ownership

- `reset(ptr)` replaces the managed object with ptr

Utility method: `std::make_unique<T>()` creates a unique pointer to a class `T` that manages a new object

```cpp
#include <iostream>
#include <memory>
struct A {
    int value;
};
int main() {
    std::unique_ptr<A> u_ptr1(new A());
    u_ptr1->value;      // dereferencing
    (*u_ptr1).value;    // dereferencing

    auto u_ptr2 = std::make_unique<A>();  // create a new unique pointer

    u_ptr1.reset(new A());          // reset
    auto raw_ptr = u_ptr1.release(); // release
    delete[] raw_ptr;

    std::unique_ptr<A[]> u_ptr3(new A[10]);
    auto& obj = u_ptr3[3];          // access
}
```

Implement a custom deleter

```cpp
#include <iostream>
#include <memory>
struct A {
    int value;
};
int main() {
    auto DeleteLambda = [](A* x) {
        std::cout << "delete" << std::endl;
        delete x;
    };

    std::unique_ptr<A, decltype(DeleteLambda)>
        x(new A(), DeleteLambda);
} // print "delete"
```

`std::shared_ptr` is the pointer type to be used for memory that can be owned by multiple resources at one time

`std::shared_ptr` maintains a reference count of pointer objects. Data managed by `std::shared_ptr` is only freed when there are no remaining objects pointing to the data

```cpp
#include <iostream>
#include <memory>
struct A {
    int value;
};
int main() {
    std::shared_ptr<A> sh_ptr1(new A());
    std::shared_ptr<A> sh_ptr2(sh_ptr1);
    std::shared_ptr<A> sh_ptr3(new A());
    sh_ptr3 = nullptr; // allowed, the underlying pointer is deallocated
                       //   sh_ptr3 : zero references
    sh_ptr2 = sh_ptr1; // allowed. sh_ptr1, sh_ptr2: two references
    sh_ptr2 = std::move(sh_ptr1); // allowed // sh_ptr1: zero references
}                                            // sh_ptr2: one references
```

`std::shared_ptr` methods

- `get()` returns the underlying pointer

- `operator*` `operator->` dereferences pointer to the managed object

- `use_count()` returns the number of objects referring to the same managed object

- `reset(ptr)` replaces the managed object with ptr

Utility method: `std::make_shared()` creates a shared pointer that manages a new object

```cpp
#include <iostream>
#include <memory>
struct A {
    int value;
};
int main() {
    std::shared_ptr<A> sh_ptr1(new A());
    auto sh_ptr2 = std::make_shared<A>();  // std::make_shared
    std::cout << sh_ptr1.use_count();  // print 1

    sh_ptr1 = sh_ptr2;                 // copy
//  std::shared_ptr<A> sh_ptr2(sh_ptr1); // copy (constructor)
    std::cout << sh_ptr1.use_count();  // print 2
    std::cout << sh_ptr2.use_count();  // print 2

    auto raw_ptr = sh_ptr1.get();      // get
    sh_ptr1.reset(new A());            // reset
    (*sh_ptr1).value = 3;              // dereferencing
    sh_ptr1->value = 2;                // dereferencing
}
```

50/64

A `std::weak_ptr` is simply a `std::shared_ptr` that is allowed to dangle (pointer not deallocated)

```cpp
#include <memory>

std::shared_ptr<int> sh_ptr(new int);
std::weak_ptr<int>   w_ptr = sh_ptr;

sh_ptr = nullptr;
cout << w_ptr.expired(); // print 'true'
```

It must be converted to `std::shared_ptr` in order to access the referenced object

`std::weak_ptr` methods

- `use_count()` returns the number of objects referring to the same managed object

- `reset(ptr)` replaces the managed object with `ptr`

- `expired()` checks whether the referenced object was already deleted (`true`, `false`)

- `lock()` creates a `std::shared_ptr` that manages the referenced object

```cpp
#include <memory>

auto sh_ptr1 = std::make_shared<int>();
cout << sh_ptr1.use_count();   // print 1
std::weak_ptr<int> w_ptr = sh_ptr1;
cout << w_ptr.use_count();     // print 1

auto sh_ptr2 = w_ptr.lock();
cout << w_ptr.use_count();     // print 2 (sh_ptr1 + sh_ptr2)

sh_ptr1 = nullptr;
cout << w_ptr.expired();       // print false
sh_ptr2 = nullptr;
cout << w_ptr.expired();       // print true
```

Concurrency

Overview

C++11 introduces the `Concurrency` library to simplify managing OS threads

```cpp
#include <iostream>
#include <thread>

void f() {
    std::cout << "first thread" << std::endl;
}

int main(){
    std::thread th(f);
    th.join();          // stop the main thread until "th" complete
}
```

How to compile:

```
$g++ -std=c++11 main.cpp -pthread
```

Example

```cpp
#include <iostream>
#include <thread>
#include <vector>
void f(int id) {
    std::cout << "thread " << id << std::endl;
}
int main() {
    std::vector<std::thread> thread_vect; // thread vector
    for (int i = 0; i < 10; i++)
        thread_vect.push_back( std::thread(&f, i) );

    for (auto& th : thread_vect)
        th.join();

    thread_vect.clear();
    for (int i = 0; i < 10; i++) { // thread + lambda expression
        thread_vect.push_back(
            std::thread( [](){ std::cout << "thread\n"; } );
    }
}
```

Library methods:

- `std::this_thread::get_id()` returns the thread id

- `std::thread::sleep_for( sleep_duration )`
  Blocks the execution of the current thread for at least the specified `sleep_duration`

- `std::thread::hardware_concurrency()` returns the number of concurrent threads supported by the implementation

Thread object methods:

- `get_id()` returns the thread id

- `join()` waits for a thread to finish its execution

- `detach()` permits the thread to execute independently from the thread handle

```cpp
#include <chrono>    // the following program should (not deterministic)
#include <iostream>  // produces the output:
#include <thread>    //    child thread exit
                     //    main thread exit
int main() {
    using namespace std::chrono_literals;
    std::cout << std::this_thread::get_id();
    std::cout << std::thread::hardware_concurrency(); // e.g. print 6

    auto lambda = []() {
        std::this_thread::sleep_for(1s); // t2
        std::cout << "child thread exit\n";
    };
    std::thread child(lambda);
    child.detach(); // without detach(), child must join() the
                    // main thread (run-time error otherwise)
    std::this_thread::sleep_for(2s);    // t1
    std::cout << "main thread exit\n";
}
// if t1 < t2 the should program prints:
```

Parameters Passing

Parameters passing *by-value* or *by-pointer* to a thread function works in the same way of a standard function. *Pass-by-reference* requires a special wrapper (`std::ref` , `std::cref`) to avoid wrong behaviors

```cpp
#include <iostream>
#include <thread>
void f(int& a, const int& b) {
    a = 7;
    const_cast<int&>(b) = 8;
}
int main() {
    int a = 1, b = 2;
    std::thread th1(f, a, b);                   // wrong!!!
    std::cout << a << ", " << b << std::endl;   // print 1, 2!!

    std::thread th2(f, std::ref(a), std::cref(b)); // correct
    std::cout << a << ", " << b << std::endl;   // print 7, 8!!
    th1.join(); th2.join();
}
```

The following code produces (in general) a value < 1000:

```cpp
#include <chrono>
#include <iostream>
#include <thread>
#include <vector>
void f(int& value) {
    for (int i = 0; i < 10; i++) {
        value++;
        std::this_thread::sleep_for(std::chrono::milliseconds(10));
    }
}
int main() {
    int value = 0;
    std::vector<std::thread> th_vect;
    for (int i = 0; i < 100; i++)
        th_vect.push_back( std::thread(f, std::ref(value)) );
    for (auto& it : th_vect)
        it.join();
    std::cout << value;
}
```

C++11 provide the `mutex` class as synchronization primitive to protect shared data from being simultaneously accessed by multiple threads

`mutex` methods:

- `lock()` locks the *mutex*, blocks if the *mutex* is not available
- `try_lock()` tries to lock the *mutex*, returns if the *mutex* is not available
- `unlock()` unlocks the *mutex*

More advanced mutex can be found here: en.cppreference.com/w/cpp/thread

C++ includes three mutex wrappers to provide safe copyable/movable objects:

- `lock_guard` (C++11) implements a strictly scope-based mutex ownership wrapper
- `unique_lock` (C++11) implements movable mutex ownership wrapper
- `shared_lock` (C++14) implements movable shared mutex ownership wrapper

```cpp
#include <thread> // iostream, vector, chrono

void f(int& value, std::mutex& m) {
    for (int i = 0; i < 10; i++) {
        m.lock();
        value++;    // other threads must wait
        m.unlock();
        std::this_thread::sleep_for(std::chrono::milliseconds(10));
    }
}
int main() {
    std::mutex m;
    int value = 0;
    std::vector<std::thread> th_vect;
    for (int i = 0; i < 100; i++)
        th_vect.push_back( std::thread(f, std::ref(value), std::ref(m)) );
    for (auto& it : th_vect)
        it.join();
    std::cout << value;
}
```

Atomic

std::atomic (C++11) template class defines an atomic type that are implemented
with lock-free operations (much faster than locks)

```cpp
#include <atomic> // chrono, iostream, thread, vector
void f(std::atomic<int>& value) {
    for (int i = 0; i < 10; i++) {
        value++;
        std::this_thread::sleep_for(std::chrono::milliseconds(10));
    }
}
int main() {
    std::atomic<int> value(0);
    std::vector<std::thread> th_vect;
    for (int i = 0; i < 100; i++)
        th_vect.push_back( std::thread(f, std::ref(value)) );
    for (auto& it : th_vect)
        it.join();
    std::cout << value;    // print 1000
}
```

The `future` library provides facilities to obtain values that are returned and to catch exceptions that are thrown by *asynchronous* tasks

Asynchronous call: `std::future async(function, args...)`
    runs a function asynchronously (potentially in a new thread)
    and returns a `std::future` object that will hold the result

std::future methods:
- `T get()` returns the result
- `wait()` waits for the result to become available

async() can be called with two launch policies for a task executed:
- `std::launch::async` a new thread is launched to execute the task asynchronously
- `std::launch::deferred` the task is executed on the calling thread the first time its result is requested (lazy evaluation)

```cpp
#include <future> // numeric, algorithm, vector, iostream
template <typename RandomIt>
int parallel_sum(RandomIt beg, RandomIt end) {
    auto len = end - beg;
    if (len < 1000)    // base case
        return std::accumulate(beg, end, 0);

    RandomIt mid = beg + len / 2;
    auto handle = std::async(std::launch::async, // right side
                             parallel_sum<RandomIt>, mid, end);
    int sum = parallel_sum(beg, mid);            // left side
    return sum + handle.get();                   // left + right
}
int main() {
    std::vector<int> v(10000, 1); // init all to 1
    std::cout << "The sum is " << parallel_sum(v.begin(), v.end());
}
```