C++ Course 12 : Concurrency.

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Concurrency in C++

Before C++ 11: No concurrency (Не было многопоточности).
Windows vs Posix (Unix) threads. Boost threads, cross-platform.
C++ 11: Concurrency in the standard library, cross-platform.

1. **async()** + **future** : Task-based approach
2. **thread** : Thread-based approach (lower level)
3. **promise, packaged_task** : Using **future** in a **thread**
4. **mutex, atomic** : Protecting shared data
5. **condition_variable** : A monitor with **wait**/ **notify** syntax.

Terminology : поток = thread ? поток = stream ? Почему не *нитка*?

[C++ Concurrency in Action: Practical Multithreading by Anthony Williams]

Physical thread : Implemented by the CPU
Logical thread : Implemented by the OS

sleep_for, sleep_until and yield

Sleep for a while : Спать некоторое время : (**std::chrono::duration**)

```
this_thread::sleep_for(milliseconds(20));
this_thread::sleep_for(seconds(2));
using namespace std::chrono_literals;
this_thread::sleep_for(100ms);  // 100 milliseconds
```

Sleep until a time point : Спать до момента времени : (**std::chrono::time_point**)

```
this_thread::sleep_until(tp);
```

Sleep a bit :

```
this_thread::yield();
```

Print current thread id :

```
cout << this_thread::get_id() << " : starting !\n";
```

future and async()

future<int> : Value of type **int** which can be obtained later

future<int> : Значение типа **int** , которое может быть получено позже

async() : Run a task synchronously or asynchronously

async() : Запустить задание синхронно или асинхронно

```
future<int> f = async([](int x, int y)->int{
   return x*y;
}, 3, 7);     // Calculate 3*7
...
f.wait();     // Optional
cout << "f.get() = " << f.get() << endl;   // Get the result
```

get() : Wait to the task to finish and return the result

get() : Дождаться окончание задания и вернуть результат

wait() : Wait for the task to finish (not really needed if we use **get()**)

get() can be only called once !

Asynchronous (launch::async) vs deferred (launch::deferred)

Asynchronous launch (in a separate thread) : Параллельно !

```
future<int> f = async(launch::async, []{
        cout << "launch::async !!!" << endl;
});
```

Starts immediately, **f.wait()/f.get()** wait for the task to finish

Deferred launch (in the same thread, no concurrency) : Последовательно !

```
future<int> f = async(launch::deferred, []{
        cout << "launch::deferred !!!" << endl;
});
```

Starts, runs and finishes when **f.wait()/f.get()** is called !

Deferred launch : equivalent to :

```
future<int> f = async(launch::deferred | launch::async, []{ ... });
```

async() decides itself what to do !

What if a future is destroyed before wait()/get() is called ?

```
{
    future<int> f = async(...);
}   // f is destroyed here
```

What does the destructor of **future** do ?

Asynchronous tasks : Асинхронные задания :

Wait for the task to finish (Implicit thread **join**). Дождаться окончания.

Deferred tasks : Отложенные задания :

The task is never started ! Задание никогда не запускается !

This is only for the futures created by **async()** !

Other futures : do nothing at all.

Conclusion : Use **wait()/get()** ! Используйте **wait()/get()** !

Running tasks in parallel

```
// Print a char and sleep a bit (100 times)
auto lamChar = [](char c)->void{
    cout << this_thread::get_id() << " : starting !\n";
    for (int i = 0; i< 100; ++i) {
        cout << c;
        this_thread::sleep_for(milliseconds(1));    // Sleep a bit
    }
};

// Run 2 tasks in parallel
future<void> fA = async(launch::async, lamChar, 'A');
future<void> fB = async(launch::async, lamChar, 'B');
// The last one will never start, no get/wait !
future<void> fC = async(launch::deferred, lamChar, 'C');
```

```
6 : starting !
7 : starting !
BAABBAABABBABABABABAABABABBABABABAABBABABABABAABABABBABAABABBABABAABBABAABABAB
ABABABBABABAABABBABBAABABABABBABABABAABABBABAABABABABBAABBABABABAABABABABBABAB
ABAABABBABABAABABABABABABBAABABBABABAABBABAA
```

wait_for() : a timed wait on a future f

future_status result = f.wait_for(milliseconds(100)); // f == some future

Returns the status *after* waiting :

future_status::deferred : Deferred task, not started yet

future_status::ready : The task has finished

future_status::timeout : The task is running, not finished yet

wait_for() does NOT start deferred tasks !

Use **wait_for(seconds(0))** to check on a task :

```
while (f.wait_for(seconds(0)) == future_status::timeout) {
        cout << "Still waiting ..." << endl;
        this_thread::sleep_for(milliseconds(100));
}
```

Of course we could have used **wait_for(milliseconds(100))** ...

future, async() and exceptions

```
future <int> f = async(launch::async, [](int x, int y)->int{
    if (x<0 || y<0) throw runtime_error("The user is an IDIOT !!!");
    return x*y;     // Suppose we don't like negative numbers ...
}, 7, -3);

cout << "Task started ..." << endl;
this_thread::sleep_for(milliseconds(10));  // Give it some time
cout << "Before get ..." << endl;
cout << "f.get() = " <<  f.get() << endl;
cout << "After get ..." << endl;
```

An exception is thrown inside an **async()** task !

What happens ?

future, async() and exceptions

```
future <int> f = async(launch::async, [](int x, int y)->int{
    if (x<0 || y<0) throw runtime_error("The user is an IDIOT !!!");
    return x*y;     // Suppose we don't like negative numbers ...
}, 7, -3);

cout << "Task started ..." << endl;
this_thread::sleep_for(milliseconds(10)); // Give it some time
cout << "Before get ..." << endl;
cout << "f.get() = " << f.get() << endl;    // Thrown by get()!!!
cout << "After get ..." << endl;
```

An exception is thrown inside an **async()** task !

It's caught and remembered in the **future** !

get() rethrows the exception.

Threads

std::thread is a handle to a software thread.

```
thread t([]{
    cout << " A thread !" << endl;
});  // Start a thread
...   // Thread runs in parallel
t.join();    // Wait to finish
```

You must **join()** or **detach()** every software thread!
join() : Wait for the thread to finish
detach() : Detach software thread from the **std::thread** object

Otherwise the **std::thread** destructor stops the program!

std::thread does not return any results.
Uncaught exception in a thread terminates the program.

Run 4 threads in parallel

```
// Print a char and sleep a bit (100 times)
auto lamChar = [](char c)->void{
    cout << this_thread::get_id() << " : starting !\n";
    for (int i = 0; i< 100; ++i) {
        cout << c;
        this_thread::sleep_for(milliseconds(1));    // Sleep a bit
    }
};
// Run 4 threads in parallel
thread tA(lamChar, 'A');    // Join tA, tB, t0, but not tC !
thread tB(lamChar, 'B');
thread tC(lamChar, 'C');
thread t0([]{cout << "IDIOT\n";} );
tC.detach();  // Detach this one from the std::thread handle
cout << "Threads  started ..." << endl;
this_thread::sleep_for(milliseconds(10));
cout << "About to join threads ..." << endl;
tA.join();
tB.join();
t0.join();
```

Run 4 threads in parallel

```
12 : starting !
14 : starting !
A13 : starting !
CThreads  started ...
BIDIOT
About to join threads ...CAB
BCACBACBABACBACABCACBABCACBBACBACACBABCACBACBCBABCABACBACBACBCAABCCBAABCCBACAB
ACBBACABCACBACBABCABCBACABCCBACBACBACABCABABCACBACBACBACBCBABACBCABACBACCABBCA
CBACABCBAACBABCCABABCACBABCACBACBCBABACBACBACBACBACCBABACBACBCABCABCACABACBACB
ACBACBACBBCACABABCACBABCBCABCACBACABCABCBACBABACABCABCACBABC
```

Passing argument by reference : std::ref()

thread and **async** use an **std::bind**-like syntax to pass arguments.
To pass arguments by reference, you must wrap them in **std::ref** !

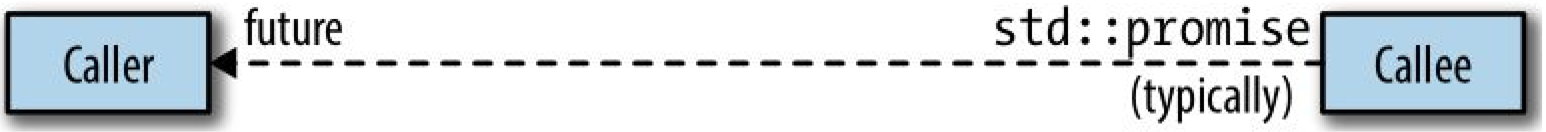
```
void doSomething(int par, int & data) {...}
...
int i, j;
thread t(doSomething, 13, ref(i));
future<void> f = async(doSomething, 14, ref(j));
```

Alternative: use a lambda wrapper:

```
thread t([&i](){
        doSomething(13, i);
});
future<void> f = async([&j](){
        doSomething(14, j);
});  // DANGER ! With detach() variables i, j can run out of scope !!!
```

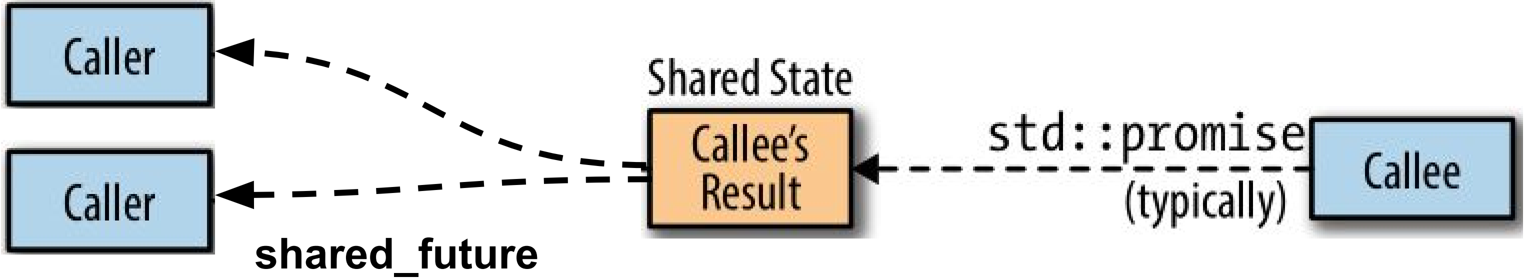
Promise and future

std::promise provides a result (or exception) to **std::future**



The result (or exception) is kept in *shared state* until you call **get()**

shared_future is a version which can be copied, and you can call **get()** many times



Using promise and future with threads (without async)

1. Create a **promise** + **future** pair
2. Pass **promise** and/or **future** by reference to threads
3. Store the result/exception into **promise** in one thread : **set_value(), set_exception()**
4. And call **get()** on the **future** in the other one

```
promise<int> p;  // Create a promise/future pair
future<int> f = p.get_future();

// Now we start the thread, capturing promise by ref
thread t([&p](int x, int y)->void{
    // We use set_value() on promise instead of return !!!
    p.set_value(x*y);
}, 3, 7);

// Now we run get() on the future as usual
cout << "f.get() = " << f.get() << endl;
t.join();  // Don't forget to join, before or after get()
```

Storing exceptions into std::promise : set_exception()

Exceptions in C++ can be of *any type*, not only **std::exception** !
There is a standard wrapper : **std::exception_ptr**.
There are 2 options (**p** = some **promise**) :

1. Create an **exception_ptr** directly by **make_exception_ptr()** :

```
p.set_exception(make_exception_ptr(runtime_error("The user is an IDIOT !!!")));
```

2. Use **current_exception()** within a **catch** clause:

```
try {
        ...
} catch(...) {
        p.set_exception(current_exception());
}
```

Using packaged_task in a thread

packaged_task is a template similar to **function**, which stores result and exceptions in a **future**

```
auto lam = [](int x, int y)->int{
    if (x<0 || y<0)
        throw runtime_error("The user is an IDIOT !!!");
    else
        return x*y;
};
packaged_task<int(int, int)> pt3(lam), pt4(lam);   // Create 2 tasks
```

packaged_task can be launched in a **thread**, get result with **get()** :

```
future<int> f3 = pt3.get_future();       // Create future from packaged_task
thread t3(move(pt3), 3, 7);              // Must move !
f3.join();                               // Join thread before or after get()
cout << "f3.get() = " << f3.get() << endl;

future<int> f4 = pt4.get_future();       // Same with pt4
thread t4(move(pt4), 3, -7);             // Wrong input !
f4.join();
cout << "f4.get() = " << f4.get() << endl;  // Exception is thrown here !
```

Data shared between threads : Data Race !

```
vector<string> data;
thread t1([& data](){ ... });
thread t2([& data](){ ... });
```

If both **t1** and **t2** only *read* data, everything is OK !

If *either* **t1** or **t2** *write* data : DATA RACE = BAD !

C++ standard: the behavior is UNDEFINED !

Глупые люди скажут:

...А я пробовал все работало...

...А что там может случиться...

...У меня не класс, а примитивный тип...

...А я видел пример в интернете...

...А я делал по простому...

...А я думал что...

...Это все фигня на самом деле все работает...

Data shared between threads : Data Race !

```
vector<string> data;
thread t1([& data](){ ... });
thread t2([& data](){ ... });
```

If both **t1** and **t2** only *read* data, everything is OK !

If *either* **t1** or **t2** *write* data : DATA RACE = BAD !

C++ standard: the behavior is UNDEFINED !

A good programmer will say:

No fooling around !

I want my code reliable !

I'll protect my data with **atomic** or **mutex** !

Data race demo :

```
int result = 0;
auto lam = [& result]{
    for (int i=0; i < 10000; ++i)
        ++result;
};
vector <thread> v;
for (int i=0; i < 100; ++i)
    v.emplace_back(lam);
for (auto & t : v)
    t.join();
cout << "result = " << result << endl;
```

What is the result ???

Data race demo :

```
int result = 0;
auto lam = [& result]{
    for (int i=0; i < 10000; ++i)
        ++result;
};
vector <thread> v;
for (int i=0; i < 100; ++i)
    v.emplace_back(lam);
for (auto & t : v)
    t.join();
cout << "result = " << result << endl;
```

The result should be 1'000'000 (one million), but ...

Actually it can be anywhere between 900'000 and one million !

And this was Debug build, can be worse with optimization !

Are standard types thread safe?

Most C++ types are NOT thread safe, including primitives !
Atomics, mutexes *are* thread-safe.

Especially strings and containers are dangerous !

I/O streams (such as **cout**) are *partly* thread-safe:
They don't get broken by writing, but the results can mix up.
Thread 1:
cout << "a = " << 17 << endl;
Thread 2:
cout << "b = " << 20 << endl;
Can give (for example):
a=b=1720

With 2 newlines in the end.

atomic variables

atomic<T> is an atomic wrapper of type **T**.

T must be trivially copyable, so **int** is OK, **string** or **vector** are not!

Example:

```
atomic<int> a1(17);   // Ctor
atomic<int> a2;
a2.store(18);         // Set a value
a2 = 18;              // The same
++a1;
a2 += 3;
int i = a1.load();    // Get a value
int i = a1;           // The same
a2 = a1;              // Error ! Atomics cannot be copied !
```

Atomics cannot be copied nor moved !

Using **load()** and **store()** is a good practice

atomic<int> example :

```
atomic<int> result(0);
auto lam = [& result]{
    for (int i=0; i < 10000; ++i)
        ++result;
};
vector <thread> v;
for (int i=0; i < 100; ++i)
    v.emplace_back(lam);
for (auto & t : v)
    t.join();
cout << "result = " << result.load() << endl;
```

The result is exactly 1'000'000 (one million) !

atomic<int> works !

mutex (MUTual EXclusion)

mutex is a simple lock:

```
vector<string> data;
mutex m;
```

In thread 1:

```
m.lock();          // Wait for m to unlock (if locked), then lock
data.push_back(s);
m.unlock();        // Unlock
```

In thread 2:

```
m.lock();          // Wait for m to unlock (if locked), then lock
for (const string & s : data)
    cout << s << endl;
m.unlock();        // Unlock
```

Is everything OK with the code ?

```
set<string> data;
mutex m;
...
m.lock();
if (data.empty())
	throw runtime_error("No data !!!");
else if (data.count("QUIT"))
	return -1;
else
	...   // Do something with the data
m.unlock();
```

Solution lock_guard !

```
set<string> data;
mutex m;
...
{
	lock_guard<mutex> lock(m);	// Lock until '}'
	if (data.empty())
		throw runtime_error("No data !!!");
	else if (data.count("QUIT"))
		return -1;
	else
		...   // Do something with the data
}		// Unlock here
```

When the lock is destroyed, the mutex is unlocked !

Resource acquisition is initialization (RAII) pattern (like **ofstream, unique_ptr**).

Versions which can be moved or copied: **unique_lock<mutex>, shared_lock<mutex>**

mutex example :

```
int result = 0;
mutex m;
auto lam = [& result, & m]{
    for (int i=0; i < 10000; ++i) {
        lock_guard<mutex> lock(m);    // Lock until '}'
        ++result;
    }                                 // Unlock here
};
vector <thread> v;
for (int i=0; i < 100; ++i)
    v.emplace_back(lam);
for (auto & t : v)
    t.join();
cout << "result = " << result << endl;
```

The result is exactly 1'000'000 (one million) !

mutex works !

Thread interaction 1: flag

```
atomic<bool> stop(false);
auto lam = [&stop]{
     int i = 0;
     while (!stop) {
          cout << i++;
          this_thread::sleep_for(milliseconds(50));
     }
};

thread t1(lam), t2(lam);
this_thread::sleep_for(milliseconds(500));
stop = true;                              // Signal stop
t1.join();
t2.join();
```

Prints (for example) : 00112233445566778 8

Thread interaction 2: condition variables

A **condition_variable** implements **wait()** and **notify()** logic:

1. Thread 1 calls **wait(condition)** and waits.
2. Thread 2 calls **notify_one()** or **notify_all()** .
3. Thread 1 wakes up if **condition** is true.

wait() can be used without condition, but it's a BAD practice !

Spurious wakeup : Thread 1 can wake without **notify()** ! C++ standard allows it !

Note : **condition_variable** requires a **mutex**.

Dangerous: **notify()** before **wait()** means waiting forever: FREEZE !

Condition variables: example

```
vector <string> data;
mutex m;                        // mutex protects both cv and data
condition_variable cv;

thread worker([&data, &m, &cv]{
    unique_lock<mutex> lk(m);     // We must use unique_lock
    cv.wait(lk, [&data]{return !data.empty();} ); // Wait for data
    for (const string &s : data)
        cout << s << " ";
    cout << endl;
});   // Here we release the mutex

this_thread::sleep_for(milliseconds(10));  // Don't notify too soon !
m.lock();
data = {"Karin", "Lucia", "Anastasia"};    // Supply the data
m.unlock();
cv.notify_one();
worker.join();
```

Thread interaction 3: promise and future for a 1-shot event

```
promise<void> p;    // promise + future pair
future<void> f = p.get_future();

thread t([&f]{
    f.get();                // Wait for the signal
    cout << "One !\n";
    this_thread::sleep_for(milliseconds(10));
    cout << "Two !\n";
    this_thread::sleep_for(milliseconds(10));
    cout << "Three !\n";
});

for (int i = 0; i < 10; ++i) {
    cout << i << endl;
    if (4 == i)
        p.set_value();               // Send the signal
    this_thread::sleep_for(milliseconds(10));
}

t.join();
```

Thank you for your attention !

title

text