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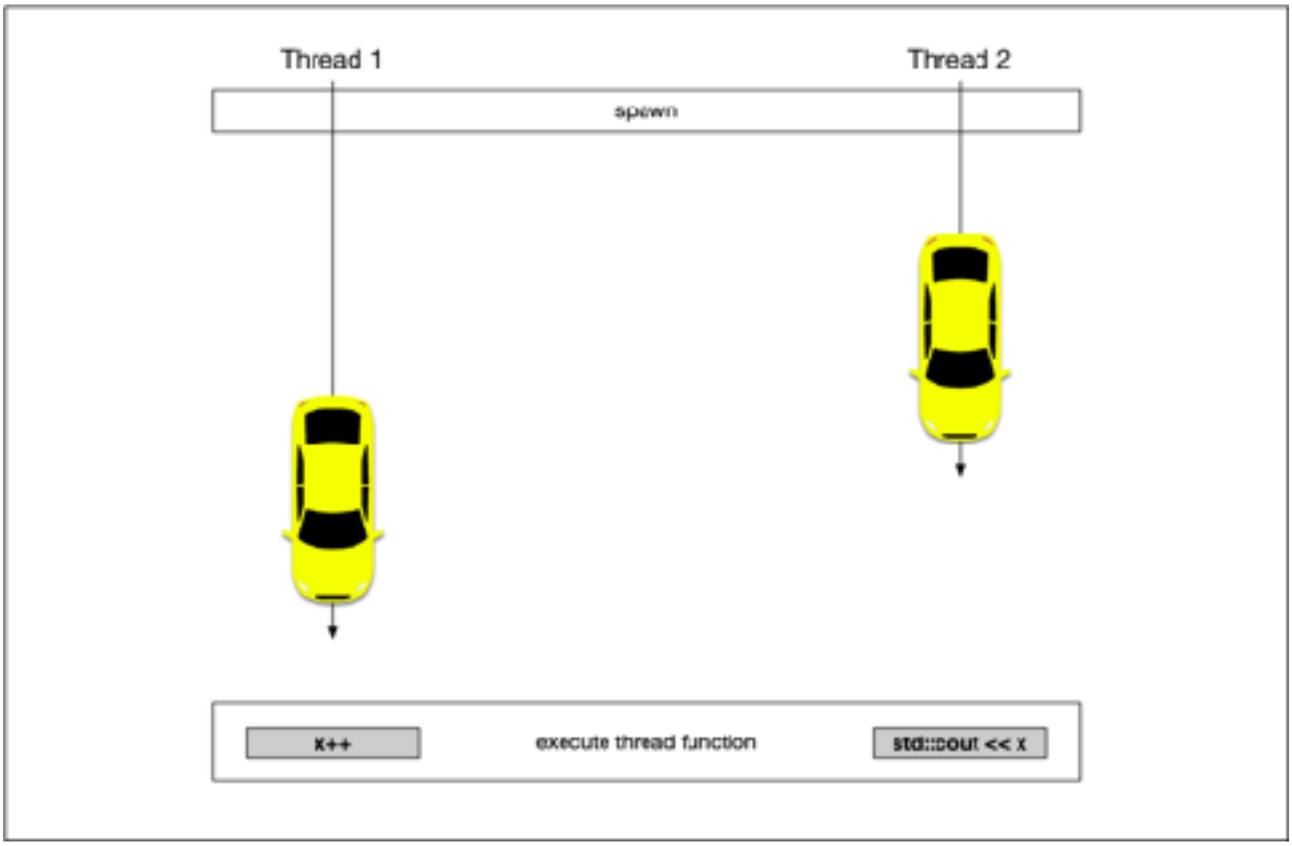
Avoiding Data Races¶

Understanding data races¶

One of the primary sources of error in concurrent programming are data races. They occur, when two concurrent threads are accessing the same memory location while at least one of them is modifying (the other thread might be reading or modifying). In this scenario, the value at the memory location is completely undefined. Depending on the system scheduler, the second thread will be executed at an unknown point in time and thus see different data at the memory location with each execution. Depending on the type of program, the result might be anything from a crash to a security breach when data is read by a thread that was not meant to be read, such as a user password or other sensitive information. Such an error is called a „data race“ because two threads are racing to get access to a memory location first, with the content at the memory location depending on the result of the race.

The following diagram illustrates the principle: One thread wants to increment a variable `x`, whereas the other thread wants to print the same variable. Depending on the timing of the program and thus the order of execution, the printed result might change each time the program is executed.



In this example, one safe way of passing data to a thread would be to carefully synchronize the two threads using either `join()` or the promise-future concept that can guarantee the availability of a result. Data races are always to be avoided. Even if nothing bad seems to happen, they are a bug and should always be treated as such. Another possible solution for the above example would be to make a copy of

```
#include <iostream>
#include <thread>
#include <future>

class Vehicle
{
public:
   //default constructor
   Vehicle() : _id(0)
   {
      std::cout << "Vehicle #" << _id << " Default constructor
called" << std::endl;
   }
```

```
    //initializing constructor
    Vehicle(int id) : _id(id)
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor
called" << std::endl;
    }

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }

private:
    int _id;
};

int main()
{
    // create instances of class Vehicle
    Vehicle v0; // default constructor
    Vehicle v1(1); // initializing constructor

    // read and write name in different threads (which one of the
above creates a data race?)
    std::future<void> ftr = std::async([](Vehicle v) {

std::this_thread::sleep_for(std::chrono::milliseconds(500)); //
simulate work
        v.setID(2);
    }, v0);

    v0.setID(3);

    ftr.wait();
    std::cout << "Vehicle #" << v0.getID() << std::endl;

    return 0;
}
```

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Passing data to a thread by value¶

In the following example, an instance of the proprietary class `Vehicle` is created and passed to a thread by value, thus making a copy of it.

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

class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0)
    {
        std::cout << "Vehicle #" << _id << " Default constructor called" << std::endl;
    }

    //initializing constructor
    Vehicle(int id) : _id(id)
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor called" << std::endl;
    }

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }

private:
    int _id;
};

int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1); // initializing constructor

    // launch a thread that modifies the Vehicle id
    std::future<void> ftr = std::async([](Vehicle v) {
        std::this_thread::sleep_for(std::chrono::milliseconds(500)); // simulate work
        v.setID(2);
    },v0);

    v0.setID(3);

    ftr.wait();
    std::cout << "Vehicle #" << v0.getID() << std::endl;

    return 0;
}
```

Note that the class Vehicle has a default constructor and an initializing constructor. In the main function, when the instances `v0` and `v1` are created, each constructor is called respectively. Note that `v0` is passed by value to a Lambda, which serves as the thread function for `std::async`. Within the Lambda, the id of the Vehicle object is changed from the default (which is 0) to a new value 2. Note that the thread execution is paused for 500 milliseconds to guarantee that the change is performed well after the main thread has proceeded with its execution.
In the `main` thread, immediately after starting up the worker thread, the id of `v0` is changed to 3. Then, after waiting for the completion of the thread, the vehicle id is printed to the console. In this program, the output will always be the following:

```
Vehicle #0 Default constructor called
Vehicle #1 Initializing constructor called
Vehicle #3
```

Passing data to a thread in this way is a clean and safe method as there

```
#include <iostream>
#include <thread>
#include <future>

class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0), _name(new std::string("Default Name"))
    {
        std::cout << "Vehicle #" << _id << " Default constructor called"
<< std::endl;
    }

    //initializing constructor
    Vehicle(int id, std::string name) : _id(id), _name(new
std::string(name))
    {
```

```
        std::cout << "Vehicle #" << _id << " Initializing constructor
called" << std::endl;
    }

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }
    void setName(std::string name) { *_name = name; }
    std::string getName() { return *_name; }

private:
    int _id;
    std::string *_name;
};

int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1, "Vehicle 1"); // initializing constructor

    // launch a thread that modifies the Vehicle name
    std::future<void> ftr = std::async([](Vehicle v) {
        std::this_thread::sleep_for(std::chrono::milliseconds(500)); //
simulate work
        v.setName("Vehicle 2");
    },v0);

    v0.setName("Vehicle 3");

    ftr.wait();
    std::cout << v0.getName() << std::endl;

    return 0;
}
```

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When passing a complex data structure however, there are sometimes pointer variables hidden within, that point to a (potentially) shared data buffer - which might cause a data race even though the programmer believes that the copied data will effectively preempt this. The next example illustrates this case by adding a new member variable to the `Vehicle` class, which is a pointer to a string object, as well as the corresponding getter and setter functions.

```
#include <iostream>
#include <thread>
#include <future>

class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0), _name(new std::string("Default Name"))
    {
        std::cout << "Vehicle #" << _id << " Default constructor called" << std::endl;
    }

    //initializing constructor
    Vehicle(int id, std::string name) : _id(id), _name(new std::string(name))
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor called" << std::endl;
    }

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }
    void setName(std::string name) { *_name = name; }
    std::string getName() { return *_name; }

private:
    int _id;
    std::string *_name;
};

int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1, "Vehicle 1"); // initializing constructor

    // launch a thread that modifies the Vehicle name
    std::future<void> ftr = std::async([](Vehicle v) {
        std::this_thread::sleep_for(std::chrono::milliseconds(500)); // simulate work
        v.setName("Vehicle 2");
    },v0);

    v0.setName("Vehicle 3");

    ftr.wait();
    std::cout << v0.getName() << std::endl;

    return 0;
}
```

The output of the program looks like this:

```
Vehicle #0 Default constructor called
Vehicle #1 Initializing constructor called
Vehicle 2
```

The basic program structure is mostly identical to the previous example with the object `v0` being copied by value when passed to

the thread function. This time however, even though a copy has been made, the original object `v0` is modified, when the thread function sets the new name. This happens because the member `_name` is a pointer to a string and after copying, even though the pointer variable has been duplicated, it still points to the same location as its value (i.e. the memory location) has not changed. Note that when the delay is removed in the thread function, the console output varies between "Vehicle 2" and "Vehicle 3", depending on the system scheduler. Such an error might go unnoticed for a long time. It could show itself well after a program has been shipped to the client - which is what makes this error type so treacherous.
Classes from the standard template library usually implement a deep copy behavior by default (such as `std::vector`). When dealing with proprietary data types, this is not guaranteed. The only safe way to tell whether a data structure can be safely passed is by looking at its implementation: Does it contain only atomic data types or are there pointers somewhere? If this is the case, does the data structure implement the copy constructor (and the assignment operator) correctly? Also, if the data structure under scrutiny contains sub-objects, their respective implementation has to be analyzed as well to ensure that deep copies are made everywhere. Unfortunately, one of the primary concepts of object-oriented programming - information hiding - often prevents us from looking at the implementation details of a class - we can only see the interface,

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Overwriting the copy constructor¶

The problem with passing a proprietary class is that the standard copy constructor makes a 1:1 copy of all data members, including pointers to objects. This behavior is also referred to as "shallow copy". In the above example we would have liked (and maybe expected) a "deep copy" of the object though, i.e. a copy of the data to which the pointer refers. A solution to this problem is to create a proprietary copy constructor in the class `Vehicle`. The following piece of code overwrites the default copy constructor and can be modified to make a customized copy of the data members.

```
// copy constructor
Vehicle(Vehicle const &src)
{
    //...
    std::cout << "Vehicle #" << _id << " copy constructor called" << std::endl;
};
```

Expanding on the code example from above, please implement the code required for a deep copy so that the program always prints "Vehicle 3" to the console, regardless of the delay within the thread function.

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Passing data using move semantics¶

Even though a customized copy constructor can help us to avoid data races, it is also time (and memory) consuming. In the following, we will use move semantics to implement a more effective way of safely passing data to a thread.
A move constructor enables the resources owned by an rvalue object to be moved into an lvalue without physically copying it. Rvalue references support the implementation of move semantics, which enables the programmer to write code that transfers resources (such as dynamically allocated memory) from one object to another.
To make use of move semantics, we need to provide a move constructor (and optionally a move assignment operator). Copy and assignment operations whose sources are rvalues automatically take advantage of move semantics. Unlike the default copy constructor however, the compiler does not provide a default move constructor.

To define a move constructor for a C++ class, the following steps are required:

1. Define an empty constructor method that takes an rvalue reference to the class type as its parameter

```
// move constructor
Vehicle(Vehicle && src)
{
    //...
    std::cout << "Vehicle #" << _id << " move constructor called" << std::endl;
};
```

2. In the move constructor, assign the class data members from the source object to the object that is being constructed

```
_id = src.getID();
_name = new std::string(src.getName());
```

3. Assign the data members of the source object to default values.

```
src.setID(0);
src.setName("Default Name");
```

When launching the thread, the Vehicle object `v0` can be passed using

#include <iostream>
#include <thread>
#include <future>

```
class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0), _name(new std::string("Default Name"))
    {
        std::cout << "Vehicle #" << _id << " Default constructor
called" << std::endl;
    }

    //initializing constructor
    Vehicle(int id, std::string name) : _id(id), _name(new
std::string(name))
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor
called" << std::endl;
    }

    // copy constructor
    Vehicle(Vehicle const &src)
    {
        //...
        std::cout << "Vehicle #" << _id << " copy constructor
called" << std::endl;
    };

    // move constructor
    Vehicle(Vehicle && src)
    {
        _id = src.getID();
        _name = new std::string(src.getName());

        src.setID(0);
        src.setName("Default Name");

        std::cout << "Vehicle #" << _id << " move constructor
called" << std::endl;
    };
```

```
    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }
    void setName(std::string name) { *_name = name; }
    std::string getName() { return *_name; }

private:
    int _id;
    std::string *_name;
};

int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1, "Vehicle 1"); // initializing constructor

    // launch a thread that modifies the Vehicle name
    std::future<void> ftr = std::async([](Vehicle v) {
        v.setName("Vehicle 2");
    },std::move(v0));

    ftr.wait();
    std::cout << v0.getName() << std::endl;

    return 0;
}
```

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Move semantics and uniqueness¶

As with the above-mentioned copy constructor, passing by value is usually safe - provided that a deep copy is made of all the data structures within the object that is to be passed. With move semantics , we can additionally use the notion of uniqueness to prevent data races by default. In the following example, a `unique_pointer` instead of a raw pointer is used for the string member in the Vehicle class.

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

class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0), _name(new std::string("Default Name"))
    {
        std::cout << "Vehicle #" << _id << " Default constructor called" << std::endl;
    }

    //initializing constructor
    Vehicle(int id, std::string name) : _id(id), _name(new std::string(name))
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor called" << std::endl;
    }

    // move constructor with unique pointer
    Vehicle(Vehicle && src) : _name(std::move(src._name))
    {
        // move id to this and reset id in source
        _id = src.getID();
        src.setID(0);

        std::cout << "Vehicle #" << _id << " move constructor called" << std::endl;
    };

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }
    void setName(std::string name) { *_name = name; }
    std::string getName() { return *_name; }

private:
    int _id;
    std::unique_ptr<std::string> _name;
};


int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1, "Vehicle 1"); // initializing constructor

    // launch a thread that modifies the Vehicle name
    std::future<void> ftr = std::async([](Vehicle v) {
        v.setName("Vehicle 2");
    },std::move(v0));

    ftr.wait();
    std::cout << v0.getName() << std::endl; // this will now cause an exception

    return 0;
}
```

As can be seen, the `std::string` has now been changed to a unique pointer, which means that only a single reference to the memory location it points to is allowed. Accordingly, the move constructor transfers the unique pointer to the worker by using

`std::move` and thus invalidates the pointer in the `main` thread. When calling `v0.getName()`, an exception is thrown, making it clear to the programmer that accessing the data at this point is not permissible - which is the whole point of using a unique pointer here as a data race will now be effectively prevented.
The point of this example has been to illustrate that move semantics on its own is not enough to avoid data races. The key to thread safety is to use move semantics in conjunction with uniqueness. It is the

```
#include <iostream>
#include <thread>
#include <future>
#include <memory>

class Vehicle
{
public:
    //default constructor
    Vehicle() : _id(0), _name(new std::string("Default Name"))
    {
        std::cout << "Vehicle #" << _id << " Default constructor
called" << std::endl;
    }

    //initializing constructor
    Vehicle(int id, std::string name) : _id(id), _name(new
std::string(name))
    {
        std::cout << "Vehicle #" << _id << " Initializing constructor
called" << std::endl;
    }

    // move constructor with unique pointer
    Vehicle(Vehicle && src) : _name(std::move(src._name))
    {
        // move id to this and reset id in source
```

```
        _id = src.getID();
        src.setID(0);

        std::cout << "Vehicle #" << _id << " move constructor
called" << std::endl;
    };

    // setter and getter
    void setID(int id) { _id = id; }
    int getID() { return _id; }
    void setName(std::string name) { *_name = name; }
    std::string getName() { return *_name; }

private:
    int _id;
    std::unique_ptr<std::string> _name;
};


int main()
{
    // create instances of class Vehicle
    Vehicle v0;    // default constructor
    Vehicle v1(1, "Vehicle 1"); // initializing constructor

    // launch a thread that modifies the Vehicle name
    std::future<void> ftr = std::async([](Vehicle v) {
        v.setName("Vehicle 2");
    },std::move(v0));

    ftr.wait();
    std::cout << v0.getName() << std::endl; // this will now cause
an exception

    return 0;
}
```