COMP6771
Advanced C++ Programming

Week 5.1
Resource Management

In this lecture

Why?

- performance & <u>control---> responsibility</u>
- *C++ responsibility and leak?*
- automatic *garbage collection to free heap?*
- *While we have ignored heap resources (malloc/free) to date, they are a critical part of many libraries and we need to understand best practices around usage.*

What?

- Resource can be very different
  - Memory allocation, mutex, MPI communicator
  - full control: create, manage and release
- new/delete
- copy and move semantics
- destructors
- lvalues and rvalues

Revision: Objects

- What is an object in C++?
  - An object is a region of memory associated with a type
  - Unlike some other languages (Java), basic types such as int and bool are objects
- For the most part, C++ objects are designed to be intuitive to use
- What special things can we do with objects
  - Create
  - Destroy
  - Copy
  - Move

Long lifetimes

- There are 3 ways you can try and make an object in C++ have a lifetime that outlives the scope it was defined it:
  - Returning it out of a function via copy (can have limitations)
  - Returning it out of a function via references (bad, see slide below)
  - Returning it out of a function as a heap resource (today's lecture)

```
//This function returns a new object,
// not a reference to the object
const Point multiply(const Point& p){
Point point();
//... Do multiplication
return point;
}
```

```
//passing by reference with object
// created on stack
const Point& multiply(const Point& p){
Point point();
//... Do multiplication
return point;
}
```

```
/passing by reference with object
/ created on heap
onst Point& multiply(const Point& p){
oint *point=new Point();
/... Do multiplication
eturn *point;
```

Return what passed into the func

Long lifetime with references

- We need to be very careful when returning references.
- **The object must always outlive the reference.**
- This is undefined behaviour - if you're unlucky, the code might even work!
- **Moral of the story**: Do not return references to variables local to the function returning.
- For objects we create INSIDE a function, we're going to have to create heap memory and return that.

```
auto okay(int& i) -> int& {
  return i;
}

auto okay(int& i) -> int const& {
  return i;
}
```

BAD

```
auto not_okay(int i) -> int& {
  return i;
}

auto not_okay() -> int& {
  auto i = 0;
  return i;
}
```

New and delete

- Objects are either stored on the **stack** or the **heap**
- In general, most times you've been creating objects of a type it has been on the stack
- We can create heap objects via **new** and free them via **delete** just like in C (malloc/free)
  - New and delete call the constructors/destructors of what they are creating

```cpp
1  #include <iostream>
2  #include <vector>
3
4  int main() {
5    int* a = new int{4};
6    std::vector<int>* b = new std::vector<int>{1,2,3};
7    std::cout << *a << "\n";
8    std::cout << (*b)[0] << "\n";
9    delete a;
10   delete b;
11   return 0;
12 }
```

demo501-new.cpp

Q: 5, 7, 9 How many memory?

A: 5. Named (a) Resource = Stack resource, create a int pointer. 8 bytes

Unnamed Resource = heap resource, "new"/ malloc (4 bytes)

New and delete

- Why do we need heap resources**?**
  - Heap object outlives the scope it was created in
  - More useful in contexts where we need more explicit control of ongoing memory size (e.g. vector as a dynamically sized array)
  - Stack has limited space on it for storage, heap is much larger

```cpp
#include <iostream>
#include <vector>

int* newInt(int i) {
  int* a = new int{i};
  return a;
}

int main() {
  int* myInt = newInt();
  std::cout << *a << "\n"; // a was defined in a
                           // no longer exists
  delete a;
  return 0;
}
```

```cpp
//No matter how much we try, it is very difficult
//to free all dynamically allocated memory.
void SomeMethod()
{
  ClassA *a = new ClassA;
  SomeOtherMethod();      // it can throw an except
  delete a;
}
```

demo502-scope.cpp

std::vector<int> - under the hood

Let's speculate about how a vector is implemented. It's going to have to manage some form of heap memory, so maybe it looks like this? Is anything wrong with this?

```
class my_vec {
  // Constructor
  my_vec(int size): data_{new int[size]}, size_{size}, capacity_{size} {}

  // Destructor
  ~my_vec() {};

  int* data_;
  int size_;
  int capacity_;
}
```

```
int main() {
    auto vec = my-vec(5);
}
```

Destructors

- Called when the object goes out of scope
  - What might this be handy for?
  - Does not occur for reference objects
- Implicitly noexcept
  - What would the consequences be if this were not the case
- Why might destructors be handy?
  - Freeing pointers
  - Closing files
  - Unlocking mutexes (from multithreading)
  - Aborting database transactions

std::vector<int> - Destructors

- What happens when vec_short goes out of scope?
  - Destructors are called on each member.
    - Destructing a pointer type does nothing
- As it stands, this will result in a memory leak. How do we fix?

```cpp
class my_vec {
  // Constructor
  my_vec(int size): data_{new int[size]}, size_{size}, capacity_{size} {}

  // Destructor
  ~my_vec() {};

  int* data_;
  int size_;
  int capacity_;
}
```

```cpp
my_vec::~my_vec() {
  delete[] data_;
}
```

Rule of 5

When writing a class, if we can't default all of our operators (preferred), we should consider the "rule of 5"

- Destructor
- Copy constructor
- Copy assignment
- Move assignment
- Move constructor

The presence or absence of these 5 operations are critical in managing resources

std::vector<int> - under the hood

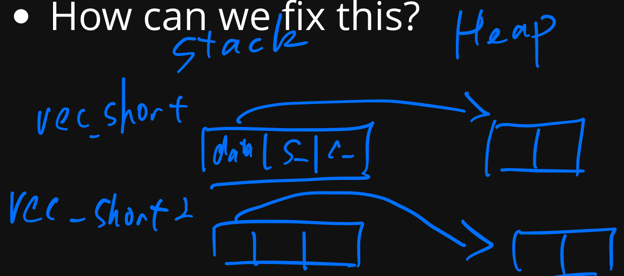
- Though you should always consider it, you should rarely have to write it
  - If all data members have one of these defined, then the class should automatically define this for you
  - But this may not always be what you want
  - C++ follows the principle of "only pay for what you use"
    - Zeroing out the data for an int is extra work
    - Hence, moving an int actually just copies it
    - Same for other basic types

```
class my_vec {
  // Constructor
  my_vec(int size): data_{new int[size]}, size_{size}, capacity_{siz

  // Copy constructor
  my_vec(my_vec const&) = default;
  // Copy assignment
  my_vec& operator=(my_vec const&) = default;

  // Move constructor
  my_vec(my_vec&&) noexcept = default;
  // Move assignment
  my_vec& operator=(my_vec&&) noexcept = default;

  // Destructor
  ~my_vec() = default;

  int* data_;
  int size_;
  int capacity_;
}
```

```
// Call constructor.
auto vec_short = my_vec(2);
auto vec_long = my_vec(9);
// Doesn't do anything
auto& vec_ref = vec_long;
// Calls copy constructor.
auto vec_short2 = vec_short;
// Calls copy assignment.
vec_short2 = vec_long;
// Calls move constructor.
auto vec_long2 = std::move(vec_long);
// Calls move assignment
vec_long2 = std::move(vec_short);
```

std::vector<int> - Copy constructor

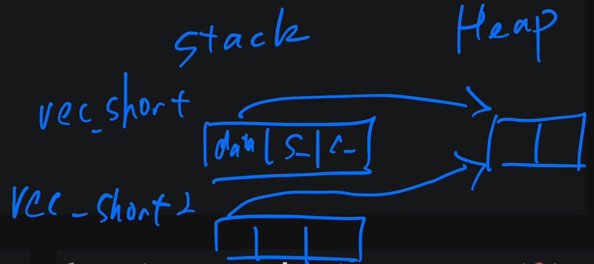
- What does it mean to copy a my_vec?
- What does the default synthesized copy constructor do?
  - It does a memberwise copy
- What are the consequences?
  - Any modification to vec_short will also change vec_short2
  - We will perform a double free
- How can we fix this?



Good.

```
class my_vec {
  // Constructor
  my_vec(int size):
    data_{new int[size]},
    size_{size},
    capacity_{size} {}

  // Copy constructor
  my_vec(my_vec const&) = default;
  // Copy assignment
  my_vec& operator=(my_vec const&) = default;

  // Move constructor
  my_vec(my_vec&&) noexcept = default;
  // Move assignment
  my_vec& operator=(my_vec&&) noexcept = default;

  // Destructor
  ~my_vec() = default;

  int* data_;
  int size_;
  int capacity_;
}
```

BAD




```
my_vec::my_vec(my_vec const& orig): data_{new int[orig.size_]},
                                    size_{orig.size_},
                                    capacity_{orig.size_} {
  std::copy(orig.data_, orig.data_ + orig.size_, data_);
}
```

default ones.

```
auto vec_short = my_vec(2);
auto vec_short2 = vec_short;
```

std::vector<int> - Copy assignment

- Assignment is the same as construction, except that there is already a constructed object in your destination
- You need to clean up the destination first
- The copy-and-swap idiom makes this trivial

```
my_vec& my_vec::operator=(my_vec const& orig) {
  my_vec(orig).swap(*this); return *this;
}

void my_vec::swap(my_vec& other) {
  std::swap(data_, other.data_);
  std::swap(size_, other.size_);
  std::swap(capacity_, other.capacity_);
}

// Alternate implementation, may not be as performant.
my_vec& my_vec::operator=(my_vec const& orig) {
  my_vec copy = orig;
  std::swap(copy, *this);
  return *this;
}
```

deleted

```
auto vec_short = my_vec(2);
auto vec_long = my_vec(9);
vec_long = vec_short;
```

swap

this

~~copy~~

out of scope deleted.

copy constructor

orig

```
class my_vec {
  // Constructor
  my_vec(int size):
    data_{new int[size]},
    size_{size},
    capacity_{size} {}

  // Copy constructor
  my_vec(my_vec const&) = default;
  // Copy assignment
  my_vec& operator=(my_vec const&) = default;

  // Move constructor
  my_vec(my_vec&&) noexcept = default;
  // Move assignment
  my_vec& operator=(my_vec&&) noexcept = default;

  // Destructor
  ~my_vec() = default;

  int* data_;
  int size_;
  int capacity_;
}
```

lvalue vs rvalue

Left side always lvalue.

name of address.

- **lvalue**: An expression that is an object reference
  - E.G. Variable name, subscript reference
  - Always has a defined address in memory
- **rvalue**: Expression that is not an lvalue
  - E.G. Object literals, return results of functions
  - Generally has no storage associated with it

```
int main() {
  int i = 5; // 5 is rvalue, i is lvalue
  int j = i; // j is lvalue, i is lvalue
  int k = 4 + i; // 4 + i produces rvalue
                 // then stored in lvalue k
}
```

lvalue references

```
void f(my_vec& x);
```

- There are multiple types of references
  - Lvalue references look like T&
  - Lvalue references to const look like T const&
- Once the lvalue reference goes out of scope, it may still be needed

rvalue references

```
void f(my_vec&& x);
```

- Rvalue references look like T&&
- An rvalue reference formal parameter means that the value was disposable from the caller of the function
  - If outer modified value, who would notice / care?
    - The caller (main) has promised that it won't be used anymore
  - If inner modified value, who would notice / care?
    - The caller (outer) has never made such a promise.
    - An rvalue reference parameter is an lvalue inside the function

```
void inner(std::string&& value) {
  value[0] = 'H';
  std::cout << value << '\n';
}

void outer(std::string&& value) {
  inner(value); // This fails? Why?
  std::cout << value << '\n';
}

int main() {
  outer("hello"); // This works fine.
  auto s = std::string("hello");
  inner(s); // This fails because s is an lvalue
}
```

std::move

```
// Looks something like this.
T&& move(T& value) {
  return static_cast<T&&>(value);
}
```

- A library function that converts an lvalue to an rvalue so that a "move constructor" (similar to copy constructor) can use it.
  - This says "I don't care about this anymore"
  - All this does is allow the compiler to use rvalue reference overloads

```
void inner(std::string&& value) {
  value[0] = 'H';
  std::cout << value << '\n';
}

void outer(std::string&& value) {
  inner(std::move(value));
  // Value is now in a valid but unspecified state.
  // Although this isn't a compiler error, this is bad code.
  // Don't access variables that were moved from, except to reconstruct them.
  std::cout << value << '\n';
}

int main() {
  f1("hello"); // This works fine.
  auto s = std::string("hello");
  f2(s); // This fails because i is an lvalue.
}
```

Moving objects

- Always declare your moves as noexcept
  - Failing to do so can make your code slower
  - Consider: push_back in a vector
- Unless otherwise specified, objects that have been moved from are in a valid but unspecified state
- Moving is an optimisation on copying
  - The only difference is that when moving, the moved-from object is mutable
  - Not all types can take advantage of this
    - If moving an int, mutating the moved-from int is extra work
    - If moving a vector, mutating the moved-from vector potentially saves a lot of work
- Moved from objects must be placed in a valid state
  - Moved-from containers **usually** contain the default-constructed value
  - Moved-from types that are cheap to copy are **usually** unmodified
  - Although this is the only requirement, individual types may add their own constraints
- Compiler-generated move constructor / assignment performs memberwise moves

std::vector<int> - Move constructor

Very similar to copy constructor, except we can use std::exchange instead.

```
my_vec::my_vec(my_vec&& orig) noexcept
  : data_{std::exchange(orig.data_, nullptr)}
  , size_{std::exchange(orig.size_, 0)}
  , capacity_{std::exchange(orig.capacity_, 0)} {}
```

data_ = orig.data_
orig.data_ = nullptr

```
class my_vec {
  // Constructor
  my_vec(int size)
  : data_{new int[size]}
  , size_{size}
  , capacity_{size} {}

  // Copy constructor
  my_vec(my_vec const&) = default;
  // Copy assignment
  my_vec& operator=(my_vec const&) = default;

  // Move constructor
  my_vec(my_vec&&) noexcept = default;
  // Move assignment
  my_vec& operator=(my_vec&&) noexcept = default;

  // Destructor
  ~my_vec() = default;

  int* data_;
  int size_;
  int capacity_;
}
```

```
auto vec_short = my_vec(2);
auto vec_short2 = std::move(vec_short);
```

std::vector<int> - Move assignment

Like the move constructor, but the destination is already constructed

```
my_vec& my_vec::operator=(my_vec&& orig) noexcept {
  // The easiest way to write a move assignment is generally to do
  // memberwise swaps, then clean up the orig object.
  // Doing so may mean some redundant code, but it means you don't
  // need to deal with mixed state between objects.
  std::swap(data_, orig.data_);
  std::swap(size_, orig.size_);
  std::swap(capacity_, orig.capacity_);

  // The following line may or may not be nessecary, depending on
  // if you decide to add additional constraints to your moved-from
object.
  delete[] orig.data_
  orig.data_ = nullptr;
  orig.size_ = 0;
  orig.capacity = 0;

  return *this;
}
```

```
class my_vec {
  // Constructor
  my_vec(int size): data_{new int[size]}, size_{size}, ca

  // Copy constructor
  my_vec(my_vec const&) = default;
  // Copy assignment
  my_vec& operator=(my_vec const&) = default;

  // Move constructor
  my_vec(my_vec&&) noexcept = default;
  // Move assignment
  my_vec& operator=(my_vec&&) noexcept = default;

  // Destructor
  ~my_vec() = default;

  int* data_;
  int size_;
  int capacity_;
}
```

```
auto vec_short = my_vec(2);
auto vec_long = my_vec(9);
vec_long = std::move(vec_short);
```

Explicitly deleted copies and moves

- We may not want a type to be copyable / moveable
- If so, we can declare fn() = delete

```
class T {
  T(const T&) = delete;
  T(T&&) = delete;
  T& operator=(const T&) = delete;
  T& operator=(T&&) = delete;
};
```

Implicitly deleted copies and moves

- Under certain conditions, the compiler will not generate copies and moves
- The implicitly defined copy constructor calls the copy constructor member-wise
  - If one of its members doesn't have a copy constructor, the compiler can't generate one for you
  - Same applies for copy assignment, move constructor, and move assignment
- Under certain conditions, the compiler will not automatically generate copy / move assignment / constructors
  - eg. If you have manually defined a destructor, the copy constructor isn't generated
- If you define one of the rule of five, you should explictly delete, default, or define all five
  - If the default behaviour isn't sufficient for one of them, it likely isn't sufficient for others
  - Explicitly doing this tells the reader of your code that you have carefully considered this
  - This also means you don't need to remember all of the rules about "if I write X, then is Y generated"

RAII (Resource Acquisition Is Initialization)

In summary, today is really about emphasising RAII

- Resource = heap object
- A concept where we encapsulate resources inside objects
  - Acquire the resource in the constructor
  - Release the resource in the destructor
  - eg. Memory, locks, files
  - resource is always released at a known point in the program, which you can control.
- Every resource should be owned by either:
  - Another resource (eg. smart pointer, data member)
  - Named resource on the stack
  - A nameless temporary variable

Object lifetimes

To create safe object lifetimes in C++, we always attach the lifetime of one object to that of something else

- Named objects:
  - A variable in a function is tied to its scope
  - A data member is tied to the lifetime of the class instance
  - An element in a std::vector is tied to the lifetime of the vector
- Unnamed objects:
  - A heap object should be tied to the lifetime of whatever object created it
  - Examples of bad programming practice
    - An owning raw pointer is tied to nothing
    - A C-style array is tied to nothing
- **Strongly recommend** watching the first 44 minutes of Herb Sutter's cppcon talk "Leak freedom in C++... By Default"

```
class widget {
private:
    gadget g;   // lifetime automatically tied to enclosing object
public:
    void draw();
};

void functionUsingWidget () {
    widget w;   // lifetime automatically tied to enclosing scope
                // constructs w, including the w.g gadget member
    // ...
    w.draw();
    // ...
} // automatic destruction and deallocation for w and w.g
  // automatic exception safety,
  // as if "finally { w.dispose(); w.g.dispose(); }"
```

```
#include <memory>
class widget
{
private:
    std::unique_ptr<int[]> data;
public:
    widget(const int size) { data = std::make_unique<int[]>(size); }
    void do_something() {}
};

void functionUsingWidget() {
    widget w(1000000);  // lifetime automatically tied to enclosing scope
                        // constructs w, including the w.data gadget member
    // ...
    w.do_something();
    // ...
} // automatic destruction and deallocation for w and w.data
```

```
class widget
{
private:
    int* data;
public:
    widget(const int size) { data = new int[size]; } // acquire
    ~widget() { delete[] data; } // release
    void do_something() {}
};

void functionUsingWidget() {
    widget w(1000000);  // lifetime automatically tied to enclosing scope
                        // constructs w, including the w.data member
    w.do_something();

} // automatic destruction and deallocation for w and w.data
```

```
void SomeMethod()
{
  ClassA *a = new ClassA;
  SomeOtherMethod();      // it can throw an exception
  delete a;
}
```

```
void SomeMethod()
{
  std::auto_ptr<ClassA> a(new ClassA); // deprecated, p
  SomeOtherMethod();      // it can throw an exception
}
//Using smart pointers for memory allocation, we may be
 // potential for memory leaks.
```

Feedback