CS100 Lecture 15

Constructors, Destructors, Copy Control

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- Constructors and destructors
- Copy control

Constructors and destructors

Lifetime of an object

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Lifetime of a local non-`static` object:

- Starts on initialization
- Ends when control flow goes out of its **scope**.</div> <div>

```
for (int i = 0; i != n; ++i) {
  do_something(i);
  // Lifetime of `s` begins.
  std::string s = some_string();
  do_something_else(s, i);
/* end of lifetime of `s` */ }
```

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Every time the loop body is executed, `s` undergoes initialization and destruction.

- `std::string` **owns** some resources (memory where the characters are stored).
- `std::string` must *somehow* release that resources (deallocate that memory) at the end of its lifetime.

Lifetime of an object

Lifetime of a global object:

- Starts on initialization (before the first statement of `main`)
- Ends when the program terminates.

Lifetime of a heap-based object:

- Starts on initialization: **A `new` expression will do this, but `malloc` does not!**
- Ends when it is destroyed: **A `delete` expression will do this, but `free` does not!**

$\Rightarrow$ `new` / `delete` expressions are in this week's recitation.

Constructors and Destructors

Take `std::string` as an example:

- Its initialization (done by its constructors) must allocate some memory for its content.
- When it is destroyed, it must *somehow* deallocate that memory.

Constructors and Destructors

Take `std::string` as an example:

- Its initialization (done by its constructors) must allocate some memory for its content.
- When it is destroyed, it must *somehow* deallocate that memory.

-A destructor of a class is the function that is automatically called when an object of that class type is destroyed.

Syntax: `~ClassName() { /* ... */ }`

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```cpp
struct A {
  A() {
    std::cout << 'c';
  }
  ~A() {
    std::cout << 'd';
  }
};
```

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```cpp
for (int i = 0; i != 3; ++i) {
  A a;
  // do something ...
}
```

Output:

```
cdcdcd
```

Destructor

Called **automatically** when the object is destroyed!

- How can we make use of this property?

Destructor

Called **automatically** when the object is destroyed!

- How can we make use of this property?

We often do some **cleanup** in a destructor:

- If the object **owns some resources** (e.g. dynamic memory), destructors can be made use of to avoid leaking!

```cpp
class A {
  SomeResourceHandle resource;

public:
  A(/* ... */) : resource(obtain_resource(/* ... */)) {}
  ~A() {
    release_resource(resource);
  }
};
```

Example: A dynamic array

Suppose we want to implement a "dynamic array":

- It looks like a VLA (variable-length array), but it is heap-based, which is safer.
- It should take good care of the memory it uses.

Expected usage:

```
int n; std::cin >> n;
Dynarray arr(n); // `n` is runtime determined
                 // `arr` should have allocated memory for `n` `int`s now.
for (int i = 0; i != n; ++i) {
  int x; std::cin >> x;
  arr.at(i) = x * x; // subscript, looks as if `arr[i] = x * x`
}
// ...
// `arr` should deallocate its memory itself.
```

Dynarray: members

- It should have a pointer that points to the memory, where elements are stored.
- It should remember its length.

```cpp
class Dynarray {
  int *m_storage;
  std::size_t m_length;
};
```

- `m` stands for **member**.

[Best practice] <u>Make data members `private`, to achieve good encapsulation.</u>

Dynarray: constructors

- We want `Dynarray a(n);` to construct a `Dynarray` that contains `n` elements.
  - To avoid troubles, we want the elements to be **value-initialized**!
    - **Value-initialization** is like "empty-initialization" in C. (In this week's recitation.)
  - `new int[n]{}`: Allocate a block of heap memory that stores `n` `int`s, and value-initialize them.
- Do we need a default constructor?
  - Review: What is a default constructor?
    - The constructor with no parameters.
  - What should be the correct behavior of it?

Dynarray: constructors

- We want `Dynarray a(n);` to construct a `Dynarray` that contains `n` elements.
  - To avoid troubles, we want the elements to be **value-initialized**!
- Suppose we don't want a default constructor.

```
class Dynarray {
  int *m_storage;
  std::size_t m_length;
 public:
  Dynarray(std::size_t n) : m_storage(new int[n]{}), m_length(n) {}
};
```

If the class has a user-declared constructor, the compiler will not generate a default constructor.

Dynarray: constructors

```cpp
class Dynarray {
  int *m_storage;
  std::size_t m_length;
 public:
  Dynarray(std::size_t n) : m_storage(new int[n]{}), m_length(n) {}
};
```

Since `Dynarray` has a user-declared constructor, it does not have a default constructor:

```cpp
Dynarray a; // Error.
```

Dynarray: destructor

- Remember: The destructor is (automatically) called when the object is "dead".
- The memory is obtained in the constructor, and released in the destructor.

```cpp
class Dynarray {
  int *m_storage;
  std::size_t m_length;
 public:
  Dynarray(std::size_t n)
    : m_storage(new int[n]{}), m_length(n) {}
  ~Dynarray() {
    delete[] m_storage; // Pay attention to `[]`!
  }
};
```

Dynarray: destructor

Is this correct?

```cpp
class Dynarray {
  // ...
  ~Dynarray() {
    if (m_length != 0)
      delete[] m_storage;
  }
};
```

Dynarray: destructor

Is this correct?

```cpp
class Dynarray {
  // ...
  ~Dynarray() {
    if (m_length != 0)
      delete[] m_storage;
  }
};
```

NO! `new [0]` may also allocate some memory (implementation-defined, like `malloc`), which should also be deallocated.

Dynarray: destructor

Is this correct?

```
class Dynarray {
  // ...
  ~Dynarray() {
    delete[] m_storage;
    m_length = 0;
  }
};
```

Dynarray: destructor

Is this correct?

```cpp
class Dynarray {
  // ...
  ~Dynarray() {
    delete[] m_storage;
    m_length = 0;
  }
};
```

It is correct, but `m_length = 0;` is not needed. The destructor is executed **right before the `Dynarray` object "dies"**, so the value of `m_length` does not matter!

Dynarray: some member functions

Design some useful member functions.

- A function to obtain its length (size).
- A function telling whether it is empty.

```cpp
class Dynarray {
  // ...
 public:
  std::size_t size() const {
    return m_length;
  }
  bool empty() const {
    return m_length != 0;
  }
};
```

Dynarray: some member functions

Design some useful member functions.

- A function returning **reference** to an element.

```
class Dynarray {
  // ...
 public:
  int &at(std::size_t i) {
    return m_storage[i];
  }
  const int &at(std::size_t i) const {
    return m_storage[i];
  }
};
```

Why do we need this "`const` vs non-`const`" overloading? $\Rightarrow$ Learn it in recitations.

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```cpp
void print(const Dynarray &a) {
  for (std::size_t i = 0;
       i != a.size(); ++i)
    std::cout << a.at(i) << ' ';
  std::cout << std::endl;
}
void reverse(Dynarray &a) {
  for (std::size_t i = 0,
    j = a.size() - 1; i < j; ++i, --j)
    std::swap(a.at(i), a.at(j));
}
```

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```cpp
int main() {
  int n; std::cin >> n;
  Dynarray array(n);
  for (int i = 0; i != n; ++i)
    std::cin >> array.at(i);
  reverse(array);
  print(array);
  return 0;
  // Dtor of `array` is called here,
  // which deallocates the memory
```

Copy control

Copy-initialization

We can easily construct a `std::string` to be a copy of another:

```
std::string s1 = some_value();
std::string s2 = s1; // s2 is initialized to be a copy of s1
std::string s3(s1); // equivalent
std::string s4{s1}; // equivalent, but modern
```

Can we do this for our `Dynarray` ?

Copy-initialization

Before we add anything, let's try what will happen:

```
Dynarray a(3);
a.at(0) = 2; a.at(1) = 3; a.at(2) = 5;
Dynarray b = a; // It compiles.
print(b); // 2 3 5
a.at(0) = 70;
print(b); // 70 3 5
```

Ooops! Although it compiles, the pointers `a.m_storage` and `b.m_storage` are pointing to the same address!

Copy-initialization

Before we add anything, let's try what will happen:

```cpp
Dynarray a(3);
Dynarray b = a;
```

Although it compiles, the pointers `a.m_storage` and `b.m_storage` are pointing to the same address!

This will cause disaster: consider the case if `b` "dies" before `a`:

```cpp
Dynarray a(3);
if (some_condition) {
  Dynarray b = a; // `a.m_storage` and `b.m_storage` point to the same memory!
  // ...
} // At this point, dtor of `b` is invoked, which deallocates the memory.
std::cout << a.at(0); // Invalid memory access!
```

Copy constructor

Let `a` be an object of type `Type`. The behaviors of **copy-initialization** (in one of the following forms)

```
Type b = a;
Type b(a);
Type b{a};
```

are determined by a constructor: **the copy constructor**.

- Note! The `=` in `Type b = a;` **is not an assignment operator**!

Copy constructor

The copy constructor of a class `X` has a parameter of type `const X &`:

```
class Dynarray {
 public:
  Dynarray(const Dynarray &other);
};
```

Why `const`?

- Logically, it should not modify the object being copied.

Why `&`?

- **Avoid copying.** Pass-by-value is actually **copy-initialization** of the parameter, which will cause infinite recursion here!

Dynarray: copy constructor

What should be the correct behavior of it?

```
class Dynarray {
 public:
  Dynarray(const Dynarray &other);
};
```

Dynarray: copy constructor

- We want a copy of the content of `other`.

```
class Dynarray {
 public:
  Dynarray(const Dynarray &other)
    : m_storage(new int[other.size()]{}), m_length(other.size()) {
    for (std::size_t i = 0; i != other.size(); ++i)
      m_storage[i] = other.at(i);
  }
};
```

Now the copy-initialization of `Dynarray` does the correct thing:

- The new object allocates a new block of memory.
- The **contents** are copied, not just the address.

Synthesized copy constructor

If the class does not have a user-declared copy constructor, the compiler will try to synthesize one:

- The synthesized copy constructor will **copy-initialize** all the members, as if

  ```
  class Dynarray {
   public:
    Dynarray(const Dynarray &other)
      : m_storage(other.m_storage), m_length(other.m_length) {}
  };
  ```

- If the synthesized copy constructor does not behave as you expect, **define it on your own!**

Defaulted copy constructor

If the synthesized copy constructor behaves as we expect, we can explicitly require it:

```cpp
class Dynarray {
 public:
  Dynarray(const Dynarray &) = default;
  // Explicitly defaulted: Explicitly requires the compiler to synthesize
  // a copy constructor, with default behavior.
};
```

Deleted copy constructor

What if we don't want a copy constructor?

```cpp
class ComplicatedDevice {
  // some members
  // Suppose this class represents some complicated device,
  // for which there is no correct and suitable behavior for "copying".
};
```

Simply not defining the copy constructor does not work:

- The compiler will synthesize one for you.

Deleted copy constructor

What if we don't want a copy constructor?

```
class ComplicatedDevice {
  // some members
  // Suppose this class represents some complicated device,
  // for which there is no correct and suitable behavior for "copying".
 public:
  ComplicatedDevice(const ComplicatedDevice &) = delete;
};
```

By saying `= delete`, we define a **deleted** copy constructor:

```
ComplicatedDevice a = something();
ComplicatedDevice b = a; // Error: calling deleted function
```

Copy-assignment operator

Apart from copy-initialization, there is another form of copying:

```
std::string s1 = "hello", s2 = "world";
s1 = s2; // s1 becomes a copy of s2, representing "world"
```

In `s1 = s2`, `=` is the **assignment operator**.

`=` is the assignment operator **only when it is in an expression.**

- `s1 = s2` is an expression.
- `std::string s1 = s2` is in a **declaration statement**, not an expression. `=` here is a part of the initialization syntax.

Dynarray: copy-assignment operator

The copy-assignent operator is defined in the form of **operator overloading**:

- `a = b` is equivalent to `a.operator=(b)`.
- We will talk about more on operator overloading in a few weeks.

```
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other);
};
```

- The function name is `operator=`.
- In consistent with built-in assignment operators, `operator=` returns **reference to the left-hand side object** (the object being assigned).
  - It is `*this`.

Dynarray: copy-assignment operator

We also want the copy-assignment operator to copy the contents, not only an address.

```
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other) {
    m_storage = new int[other.size()];
    for (std::size_t i = 0; i != other.size(); ++i)
      m_storage[i] = other.at(i);
    m_length = other.size();
    return *this;
  }
};
```

Is this correct?

Dynarray: copy-assignment operator

Avoid memory leaks! Deallocate the memory you don't use!

```cpp
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other) {
    delete[] m_storage; // !!!
    m_storage = new int[other.size()];
    for (std::size_t i = 0; i != other.size(); ++i)
      m_storage[i] = other.at(i);
    m_length = other.size();
    return *this;
  }
};
```

Is this correct?

Dynarray: copy-assignment operator

What if **self-assignment** happens?

```cpp
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other) {
    // If `other` and `*this` are actually the same object,
    // the memory is deallocated and the data are lost! (DISASTER)
    delete[] m_storage;
    m_storage = new int[other.size()];
    for (std::size_t i = 0; i != other.size(); ++i)
      m_storage[i] = other.at(i);
    m_length = other.size();
    return *this;
  }
};
```

Dynarray: copy-assignment operator

Assignment operators should be **self-assignment-safe**.

```
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other) {
    int *new_data = new int[other.size()];
    for (std::size_t i = 0; i != other.size(); ++i)
      new_data[i] = other.at(i);
    delete[] m_storage;
    m_storage = new_data;
    m_length = other.size();
    return *this;
  }
};
```

This is self-assignment-safe. (Think about it.)

Synthesized, defaulted and deleted copy-assignment operator

Like the copy constructor:

- The copy-assignment operator can also be **deleted**, by declaring it as `= delete;`.
- If you don't define it, the compiler will generate one that copy-assigns all the members, as if it is defined as:

```cpp
class Dynarray {
 public:
  Dynarray &operator=(const Dynarray &other) {
    m_storage = other.m_storage;
    m_length = other.m_length;
    return *this;
  }
};
```

- You can also require a synthesized one explicitly by saying `= default;`.

[IMPORTANT] The rule of three: Reasoning

Among the **copy constructor**, the **copy-assignment operator** and the **destructor**:

- If a class needs a user-provided version of one of them, **usually**, it needs a user-provided version of **each** of them.
- Why?

[IMPORTANT] The rule of three: Reasoning

Among the **copy constructor**, the **copy-assignment operator** and the **destructor**:

- If a class needs a user-provided version of one of them,
- **usually**, it is a class that **manages some resources**,
- for which **the default behavior of the copy-control members does not suffice**.
- Therefore, all of the three special functions need a user-provided version.
    - Define them in a correct, well-defined manner.
    - If a class should not be copy-constructible or copy-assignable, **delete that function**.

[IMPORTANT] The rule of three: Rules

Let $S = \{$ copy constructor , copy assignment operator , destructor $\}$.

If for a class, $\exists x, y \in S$ such that

- x is user-declared, and y is not user-declared,

then the compiler *should not* generate y, according to the idea of "the rule of three".

[IMPORTANT] The rule of three: Rules

Let $S = \{$ copy constructor , copy assignment operator , destructor $\}$.

If for a class, $\exists x, y \in S$ such that

- x is user-declared, and y is not user-declared,

then the compiler **still generates** y, but **this behavior has been deprecated since C++11**.

- This is a problem left over from history: At the time C++98 was adopted, the significance of the rule of three was not fully appreciated.

[IMPORTANT] The rule of three

Into modern C++: **The Rule of Five**.

- $\Rightarrow$ We will talk about it in later lectures.

Read *Effective Modern C++* Item 17 for a thorough understanding of this.

Summary

Lifetime of an object:

- depends on its **storage**: local non-`static`, global, allocated, ...
- **Initialization** marks the beginning of the lifetime of an object.
  - Classes can control the way of initialization using **constructors**.
- When the lifetime of an object ends, it is **destroyed**.
  - If it is an object of class type, its **destructor** is called right before it is destroyed.

Summary

Copy control

- Usually, the **copy control members** refer to the copy constructor, the copy assignment operator and the destructor.
- Copy constructor: `ClassName(const ClassName &)`
- Copy assignment operator: `ClassName &operator=(const ClassName &)`
    - It needs to be **self-assignment safe**.
- Destructor: `~ClassName()`
- `=default`, `=delete`
- The rule of three.