CS100 Recitation 8

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When Copy Happens


```cpp
class Point2d {
  double x, y;
 public:
  Point2d() : Point2d(0, 0) {}
  Point2d(double a, double b) : x(a), y(b) {}
};
```

Question

What member functions have been synthesized by the compiler?

When Copy Happens


```
class Point2d {
  double x, y;
 public:
  Point2d() : Point2d(0, 0) {}
  Point2d(double a, double b) : x(a), y(b) {}
};
```

When we have the class definition above, there are 3 ways of constructing an object:

```
Point2d p0;
Point2d p1(3.14, 6.28);
Point2d p2(p1); // same as Point2d p2 = p1;
```

When Copy Happens

```
class Point2d {
  double x, y;
 public:
  Point2d() : Point2d(0, 0) {}
  Point2d(double a, double b) : x(a), y(b) {}
};
```

We can also pass `Point2d` objects as arguments, or as return-values:

```
// BAD!! You should use reference-to-const.
Point2d less_in_x(Point2d lhs, Point2d rhs) {
  return lhs.get_x() < rhs.get_x() ? lhs : rhs;
}
```

When Copy Happens

How many copies are created?

```
Point2d p3 = less_in_x(p0, p1);
```

When Copy Happens

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```
Point2d p3 = less_in_x(p0, p1);
```

- Copy-initialize the parameters `lhs` and `rhs`.
- Copy-initialize a temporary object generated by the calling expression with the return value. (?)
- Copy-initialize `p3`. (not assignment!)

When Copy Happens

How many copies are created?

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Point2d p3 = less_in_x(p0, p1);
```

- Copy-initialize the parameters `lhs` and `rhs`.
- Copy-initialize a temporary object generated by the calling expression with the return value. (?)
- Copy-initialize `p3`. (not assignment!)

Copying a return-value?

- Many compilers avoid such copying by Return Value Optimization (RVO).
- Since C++11, a local object will be returned by moving instead of copying, if it is move-constructible.
- C++17 **guarantees** that such copying won't happen, even when the object is not move-constructible.

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The Copy Constructor

The copy ctor defines the behavior of copy initializing an object.

```
class Point2d {
 public:
  Point2d(const Point2d &other)
    : x(other.x), y(other.y) {}
  // other members
};
```

The Copy Constructor

The copy ctor defines the behavior of copy initializing an object.

```
class Point2d {
 public:
  Point2d(const Point2d &other)
    : x(other.x), y(other.y) {}
  // other members
};
```

- Can we define the parameter type as `Point2d` instead of reference-to-`const`?
- Can we define the parameter type as `Point2d &`?

The Copy Constructor


```cpp
class Vector {
  std::size_t m_size, m_capacity;
  int *m_data;
 public:
  Vector(const Vector &other)
    : m_size(other.m_size),
      m_capacity(other.m_capacity),
      m_data(new int[m_capacity]{}) {
    for (std::size_t i = 0; i < m_size; ++i)
      m_data[i] = other.m_data[i];
  }
  // other members
};
```

Contents

The Copy-Assignment Operator

The behavior of assignment like

```
Point2d p1, p2;
p1 = p2;
```

is defined by the copy-assignment operator. It is defined by overloading the assignment operator.

```
class Point2d {
 public:
  Point2d &operator=(const Point2d &other) {
    x = other.x;
    y = other.y;
    return *this;
  }
};
```

The Copy-Assignment Operator

```
class Point2d {
 public:
  Point2d &operator=(const Point2d &other) {
    x = other.x;
    y = other.y;
    // return reference to the object itself
    return *this;
  }
};
```

Notice

You should make the overloaded operator behave in consistence with the built-in one.

The Copy-Assignment Operator

When an assignment happens, the left-hand operand is bound to the implicit `this`. The right-hand operand is passed as the parameter.

```
Point2d p1, p2;
p1 = p2;
p1.operator=(p2); // equivalent way
```

The Copy-Assignment Operator

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```
Point2d p1, p2;
p1 = p2;
p1.operator=(p2); // equivalent way
```

Since the assignment operator returns the object on the left-hand side, we can chain assignments together:

```
p1 = p2 = p3;
```

Copy-Assignment of Vector

```
class Vector {
 public:
  Vector &operator=(const Vector &other) {
    delete[] m_data;
    m_size = other.m_size;
    m_capacity = other.m_capacity;
    m_data = new int[m_capacity];
    for (std::size_t i = 0; i < m_size; ++i)
      m_data[i] = other.m_data[i];
    return *this;
  }
  // other members
};
```

Copy-Assignment of Vector

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    m_data = new int[m_capacity];
    for (std::size_t i = 0; i < m_size; ++i)
      m_data[i] = other.m_data[i];
    return *this;
  }
  // other members
};
```

- Anything wrong with this assignment operator?

Self-assignment Safety

- Should self-assignment happen, the data is `delete`d at first! It becomes a disaster.
- Exception-safety issue.

Self-assignment Safety

- Should self-assignment happen, the data is `delete`d at first! It becomes a disaster.
- Exception-safety issue.

Self-assignment may happen unnoticed and without a warning:

```
Vector v = some_value();
Vector &rv = some_function(v);
v = rv;
```

Notice

Assignment operator should always be self-assignment-safe.

The Correct Way


```
class Vector {
 public:
  Vector &operator=(const Vector &other) {
    int *new_data = new int[other.m_capacity];
    for (std::size_t i = 0; i < other.m_size; ++i)
      new_data[i] = other.m_data[i];
    m_size = other.m_size;
    m_capacity = other.m_capacity;
    delete[] m_data;
    m_data = new_data;
    return *this;
  }
};
```

Still Problematic Way

```
Vector &Vector::operator=(const Vector &other) {
  // test self-assignment directly
  if (this != &other) {
    delete[] m_data;
    m_size = other.m_size;
    m_capacity = other.m_capacity;
    m_data = new int[m_capacity];
    for (std::size_t i = 0; i < m_size; ++i)
      m_data[i] = other.m_data[i];
  }
  return *this;
}
```

- This handles self-assignment correctly, but **still has exception-safety issue**.

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Synthesized Copy Ctor

The compiler will synthesize a copy ctor if

- the copy ctor is not defined, and
- every member is copy-constructible.

The synthesized copy ctor will copy-initialize the members one-by-one, and has an empty function body.

Question

Is it ok for `Point2d` to use the synthesized copy ctor? What about `Vector`?

Synthesized Copy-Assignment Operator

The compiler will synthesize a copy-assignment operator if

- the copy-assignment operator is not defined, and
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Question

Is it ok for `Point2d` to use the synthesized copy-assignment operator? What about `Vector`?

Copying Array Members

It is not allowed to copy arrays directly like

```cpp
int a[100], b[100];
a = b;
```

But if there's an array member, the synthesized copy operations will copy the elements in the array one-by-one. Don't worry!

Use =default

For a default ctor, a copy ctor, a copy-assignment operator or a destructor, we can explicitly require the compiler to synthesize one with defaulted behavior by `=default`:

```
class Point2d {
  double x, y;
 public:
  Point2d() = default;
  Point2d(const Point2d &) = default;
  Point2d &operator=(const Point2d &) = default;
  ~Point2d() = default;
  // other members
};
```

The Rule of Three

Theorem (The Rule of Three)

If a class needs one of the three copy-controlling operations (copy-ctor, copy-assignment operator and destructor), it is highly possible that all of them are needed.

- Such idea was not so widely acknowledged when C++98 came out. Therefore, the compiler will still generate the others if you only define one or two of them.
- We will see changes in C++11 when we talk about **moving**.

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Prevent Copying

Some class, like `std::istream`, should avoid copying. (Why?)

Question

Can we prevent copying by simply not defining the copy operations?

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Question

Can we prevent copying by simply not defining the copy operations?

Before C++11, people prevent copying by **declaring the copying operations as private, and not defining them**.

- Attempts to copy such an object outside the class and out of a friend will cause an error in access-level.
- Attempts to copy inside the class or in a friend will cause a linking error.

Deleted Functions

Since C++11, we can define a function as **deleted** by defining it to be =delete.

```
class Uncopyable {
 public:
  Uncopyable(const Uncopyable &) = delete;
  Uncopyable &operator=(const Uncopyable &) = delete;
};
```

Deleted Functions

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Use `=delete` to avoid copying in modern C++!

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```

Use `=delete` to avoid copying in modern C++!

Notice

If we define a special member function to be `=default` but the compiler cannot synthesize it, it is implicitly **deleted** and will not cause an error (but will generate a warning).

Recommended Reading Materials

- *Effective C++*, Item 5: Know what functions C++ silently writes and calls.
- *Effective C++*, Item 6: Explicitly disallow the use of compiler-generated functions you do not want.

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Constructors and Type-casting

A constructor also defines a type-casting:

```
void fun(std::string s) {
  // do something
}
int main() {
  fun("Hello world");
  return 0;
}
```

- `std::string` has a constructor that accepts a `const char *` parameter.
- When calling `fun("Hello")`, the initialization of the parameter could be seen as a **conversion** from `const char *` to `std::string`.

Constructors and Type-casting

Sometimes this will be confusing.

```
class Vector {
 public:
  Vector(std::size_t n)
    : m_size(n), m_capacity(n),
      m_data(new int[n]()) {}
};
int main() {
  Vector v = 10; // What??
  return 0;
}
```

`explicit` Constructors

By defining a constructor as `explicit`, we disallow such conversion from happening implicitly.

```
class Vector {
 public:
  explicit Vector(std::size_t n)
    : m_size(n), m_capacity(n),
      m_data(new int[n]()) {}
};
int main() {
  Vector v1 = 10; // Error
  Vector v2(10);  // ok
  return 0;
}
```

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Friends

Code inside a `friend` of a class can access the private members of that class.

```
class Vector {
  friend bool equal_to(const Vector &, const Vector &);
  friend class SomeOtherClass;
  // other members
};
inline bool equal_to
    (const Vector &lhs, const Vector &rhs) {
  if (lhs.m_size != rhs.m_size)
    return false;
  for (std::size_t i = 0; i < lhs.m_size; ++i)
    if (lhs.m_data[i] != rhs.m_data[i])
      return false;
  return true;
}
```

Friends

- A `friend` declaration is not a member of the class.
- Access-modifiers do not apply to `friend` declarations.
- `friend`s are often declared together at the beginning or end of the class.

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Access Elements of Vector


```
class Vector {
 public:
  int &at(std::size_t n) {
    return m_data[n];
  }
  // other members
};
```

What will happen on a `const` object?

```
void print_vector(const Vector &v) {
  for (std::size_t i = 0; i < v.size(); ++i)
    std::cout << v.at(i) << " "; // Error!
}
```

Access Elements of Vector

```
class Vector {
 public:
  int &at(std::size_t n) const {
    return m_data[n];
  }
  // other members
};
```

Access Elements of Vector

```
class Vector {
 public:
  int &at(std::size_t n) const {
    return m_data[n];
  }
  // other members
};
```

Still problematic:

```
const Vector v = some_value();
v.at(10) = 42;
```

Compilers may fail to detect such modification, but it is undefined behavior!

Correct Way

Const overloading.

```
class Vector {
 public:
  int &at(std::size_t n) {
    return m_data[n];
  }
  const int &at(std::size_t n) const {
    return m_data[n];
  }
  // other members
};
```

Calling a `const` member function is actually **adding low-level const** to the `this` pointer.

Bitwise `const` vs Logical `const`

- A member function is bitwise-`const` if it does not modify any data member.
- A member function is logical-`const` if it makes the object *appear* unchanged to users.
  - A logical-`const` member function should prevent potential modification.
  - A logical-`const` member function may modify some data member, but the object seems unchanged to users.

The compiler can only check bitwise constness.

Bitwise `const` vs Logical `const`

Bitwise-`const` but not logical-`const` :

```
class Vector {
 public:
  int &at(std::size_t n) const {
    return m_data[n];
  }
};
```

Directly returning a non-const reference to a data member is not allowed, but compilers may fail to detect this one.

`mutable` Member

What if we want to count how many times the function is called?

```
class Vector {
  int access_cnt;
 public:
  int &at(std::size_t n) {
    ++access_cnt;
    return m_data[n];
  }
  const int &at(std::size_t n) const {
    ++access_cnt;   // Oops! It is not bitwise-const!
    return m_data[n];
  }
};
```

mutable Member

Define a member to be `mutable`, so that it is modifiable even in a `const` member function.

```
class Vector {
  mutable int access_cnt;
 public:
  int &at(std::size_t n) {
    ++access_cnt;
    return m_data[n];
  }
  const int &at(std::size_t n) const {
    ++access_cnt;
    return m_data[n];
  }
};
```

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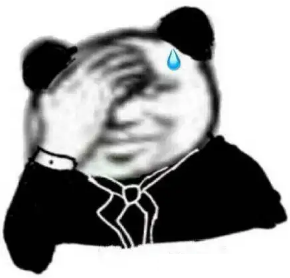
Before C++11...

In C and before C++11, the `auto` specifier is used like this:

```
auto int x = 42;
```

It indicates 'automatic storage duration': the variable `x` should be destroyed at the end of its scope...



Since C++11

Since C++11, the `auto` specifier is used to let the compiler deduct the type:

```
auto x = 42;      // x is int
auto y = 3.14;    // y is double
```

The variable declared by `auto` must be explicitly initialized, so that the compiler can know the type.

```
auto z;           // ???
```

If more than one variables are declared in one statement, all of them should be explicitly initialized, and the initializers should have a same type.

```
auto a = 1, b;    // Error.
auto c = 42, d = 3.14; // Error.
```

The auto Type Specifier

Compound types are allowed:

```
std::string s = "Hello";
const auto &sr = s; // const std::string &
auto *p = &s;       // std::string *
```

The auto Type Specifier

Compound types are allowed:

```
std::string s = "Hello";
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auto *p = &s;       // std::string *
```

Low-level const will be preserved, but reference and top-level const will be ignored (Why?):

```
const int ci = 42;
auto i2 = ci;       // int
auto *pi = &ci;     // const int *
auto &ri = ci;      // const int &
auto i3 = ri;       // int; & and const are ignored.
```

Why we Need `auto` ?

The C++ type system is much more complex than C.

- Sometimes the name of the type is too long, e.g.

```
std::shared_ptr<std::map<std::string, std::vector<
    std::string>::size_type>>
```

- Sometimes we have no idea what type it is:

```
// a lambda expression
auto f = [](int a, int b) -> int { return a + b; };
```

The compiler knows everything! (C++ is statically-typed!)

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The decltype Type Specifier

Sometimes we want to use the **type** of an expression to declare an object, but we don't want to evaluate that expression.

```
int fun() {
  // do something
}
decltype(f()) x;    // x is int, but f is not called!
```

The compiler can know the type of the expression without evaluating it. (statically-typed!)

`decltype` is Honest

`decltype` does not ignore top-level `const` or reference. It just says the exact type of the expression.

```
const int i = 0;     // decltype(i) is const int
int f(const Widget &w);
// decltype(w) is const Widget &
// decltype(f) is int(const Widget &)
const std::string s = "Hello";
// decltype(s) is const std::string
// decltype(s[0]) is const char &
```

decltype is Honest

When decltype is used on an expression that yields an lvalue, the result is a reference (Why?).

```
int i = 42, *p = &i;
int j = 50;
decltype(*p) r = j;   // r is int & bound to j.
```

An object itself can be used as an expression (which yields an lvalue!), but you should place it in a pair of parentheses to show this explicitly.

```
decltype(i) k = 65;   // k is int
decltype((i)) l = k;  // l is int & bound to k.
```

Reading Materials

C++ has a very complex type system and type deduction rules. These rules are explained thoroughly in *Effective Modern C++* Item 1, 2, 3, 4, 5, 6. But it is too early to understand them for you now.