C++ Class Details, Heap

CSE 333

Instructor: Hannah C. Tang

Teaching Assistants:

Deeksha Vatwani	Hannah Jiang	Jen Xu
Leanna Nguyen	Nam Nguyen	Sayuj Shahi
Tanay Vakharia	Wei Wu	Yiqing Wang
Zohar Le		

About Exercise Grading …

- The stakes feel too high …
  - … also, let's add an extra 24h to Ex9's deadline

Gradescope "Score"	Name	
3	Check Plus	
2	Check	
1	Check Minus	
0	Minus	

Administrivia

- Homework 2 due Wednesday night
  - **Check your work!!** Allocate time to clone the repo when you're done, do `git checkout hw2-final`; `cd hw1` and copy/build `libhw1.a`; `cd hw2; make`; then test everything looks good
  - Reminder: **do not modify header files**
  - Reminder: commit/push your work regularly, not all at once at the en

Lecture Outline

- Class Details
  - **Rule of Three / Making Copies**
  - Access Controls and Friends
  - Namespaces
  - Implicit Conversions

- Using the Heap
  - `new` / `delete` / `delete[]`

Rule of Three

- If you define any of:
  1) Destructor
  2) Copy Constructor
  3) Assignment (`operator=`)

- Then you should normally define all three
  - Can explicitly ask for default synthesized versions (C++11 & later):

```
class Point {
 public:
  Point() = default;                                   // the default ctor
  ~Point() = default;                                  // the default dtor
  Point(const Point& copyme) = default;                // the default cctor
  Point& operator=(const Point& rhs) = default;  // the default "="
  ...
```

Dealing with the instanity

- C++ style guide tip:
  - If possible, disable the copy constructor and assignment operator if not needed – avoids implicit invocation and excessive copying. C++11 and later have direct syntax to indicate this:

Point_2011.h

```
class Point {
 public:
  Point(const int x, const int y) : x_(x), y_(y) { }  // ctor
  ...
  Point(const Point& copyme) = delete;   // declare cctor and "=" to
  Point& operator=(const Point& rhs) = delete; // be deleted (C++11)
 private:
  ...
}; // class Point

Point w;          // compiler error (no default constructor)
Point x(1, 2);    // OK!
Point y = w;      // compiler error (no copy constructor)
y = x;            // compiler error (no assignment operator)
```

If you're dealing with old code …

- In pre-C++11 code the copy constructor and assignment were often disabled by making them private and not implementing them (you may see this)…

Point.h

```
class Point {
 public:
  Point(const int x, const int y) : x_(x), y_(y) { }  // ctor
  ...
 private:
  Point(const Point& copyme);             // disable cctor (no def.)
  Point& operator=(const Point& rhs);    // disable "=" (no def.)
  ...
}; // class Point

Point w;           // compiler error (no default constructor)
Point x(1, 2);     // OK!
Point y = w;       // compiler error (no copy constructor)
y = x;             // compiler error (no assignment operator)
```

If you're dealing with old code ...

- C++11 style guide tip:
  - If you disable them, then you instead may want an explicit "CopyFrom" function that can be used when occasionally needed
  - Google advice has changed over time – these days prefer copy ctr, op=

Point.h

```
class Point {
 public:
  Point(const int x, const int y) : x_(x), y_(y) { }  // ctor
  void CopyFrom(const Point& copy_from_me);
  ...
  Point(Point& copyme) = delete;            // disable cctor
  Point& operator=(Point& rhs) = delete;   // disable "="
 private:
  ...
};  // class Point
```

sanepoint.cc

```
Point x(1, 2);   // OK
Point y(3, 4);   // OK
x.CopyFrom(y);   // OK
```

Lecture Outline

- Class Details
  - Rule of Three / Making Copies
  - **Access Controls and Friends**
  - Namespaces
  - Implicit Conversions
- Using the Heap
  - `new` / `delete` / `delete[]`

`struct` vs. `class`

- In C, a `struct` can only contain data fields
  - Has no methods and all fields are always accessible
  - In `struct foo`, the `foo` is a “struct tag”, not an ordinary data type

- In C++, `struct` and `class` are (nearly) the same!
  - Both define a new type (the `struct` or `class` name)
  - Both can have methods and member visibility (public/private/protected)
  - Only real (minor) difference: members are default *public* in a `struct` and default *private* in a `class`

- Common style/usage convention:
  - Use `struct` for simple bundles of data
    - Convenience constructors can make sense though
  - Use `class` for abstractions with data + functions

Access Control

- Access modifiers for members:
  - `public`: accessible to *all* parts of the program
  - `private`: accessible to the member functions of the class
    - Private to *class*, not object instances
  - `protected`: accessible to member functions of the class and any *derived* classes (subclasses – more to come, later)

- Reminders:
  - Access modifiers apply to *all* members that follow until another access modifier is reached
  - If no access modifier is specified, `struct` members default to `public` and `class` members default to `private`

Nonmember Functions

- "Nonmember functions" are just normal functions that happen to use some class
  - Called like a regular function instead of as a member of a class object instance
  - These do *not* have access to the class' private members
- Useful nonmember functions often included as part of the interface to a class
  - Declaration goes in header file, but *outside* of class definition
    - But *inside* the same namespace as the class, if it has one

Nonmember Functions

- "Nonmember functions" are just normal functions that happen to use some class
  - Called like a regular function instead of as a member of a class object instance
  - These do *not* have access to the class' private members
  - Often included as part of the interface to a class

```
class Complex {  ... };

void ReadFromStream(std::istream& in, Complex& a);
```

```
void ReadFromStream(std::istream& in, Complex& a) {
  double r;
  in >> r
  a.set_real(r);
// … etc …
}
```

Nonmember Operators

- Operators can be member methods or non-member functions
  - Eg, overloaded operators (`operator+`, etc.), stream I/O (`operator<<`), etc. …

Review: Operator Overloading

- Can overload operators using **member functions**
  - Restriction: left-hand side argument must be a class you are implementing

```
Complex& operator+=(const Complex &a) { ... }
```

- Can overload operators using **nonmember functions**
  - No restriction on arguments (can specify any two)
    - **Our only option** when the left-hand side is a class you do not have control over, like `ostream` or `istream`.
  - But no access to private data members

```
Complex operator+(const Complex &a, const Complex &b) { ... }
```

`friend` Nonmember Functions

- A class can give a nonmember function (or class) access to its non`public` members by declaring it as a `friend` within its definition
  - `friend` function is not a class member, but has access privileges as if it were
  - `friend` functions are usually unnecessary if your class includes appropriate "getter" public functions

Complex.h

```
class Complex {
  ...
  friend std::istream& operator>>(std::istream& in, Complex& a);
  ...
}; // class Complex
```

```
std::istream& operator>>(std::istream& in, Complex& a) {
  ...
}
```

Complex.cc

When to use Nonmember and `friend`

- Member functions:
  - Operators that modify the object being called on
    - Assignment operator (`operator=`)
  - "Core" non-operator functionality that is part of the class interface
- Nonmember functions:
  - Used for commutative operators
    - *e.g.*, so `v1 + v2` is invoked as `operator+(v1, v2)` instead of `v1.operator+(v2)`
  - If operating on two types and the class is on the right-hand side
    - *e.g.*, `cin >> complex;`
  - Returning a "new" object, not modifying an existing one
  - Only grant `friend` permission if you NEED to

Poll Everywhere pollev.com/uwcse333

- For exercise 9, which of these should be:

	Member	Non-member	Non-member Friend
operator=	✓		
operator+=, operator-=	✓		
operator-, operator+		✓	
Operator* (scalar)		✓	
Operator* (dot-product)		✓	
Operator<<		✓	

Poll Everywhere

pollev.com/uwcse333

- Which constructors get called?

```
int main() {
  Point p1;                  // line 1
  Point p2[20];              // line 2
  Point p3 = p1;             // line 3
  Point* p4 = &(arr[3]);     // line 4
  Point p5 = Point(1, 2);    // line 5

  return 0;
}
```

Administrivia

- Homework 2 due TONIGHT
  - File system crawler, indexer, and search engine
  - Don’t forget to clone your repo to double-/triple-/quadruple-check compilation, execution, and tests!
    - If your code won’t build or run when we clone it, well … you should have caught that …

Lecture Outline

- Class Details
  - Rule of Three / Making Copies
  - Access Controls and Friends
  - **Namespaces**
  - Implicit Conversions
- Using the Heap
  - `new` / `delete` / `delete[]`

Namespaces

- Each namespace is a separate scope
  - Useful for avoiding symbol collisions
- Namespace definition:
  - ```
    namespace name {
      // declarations go here
    }
    ```
  - Creates a new namespace name if it did not exist, otherwise *adds to the existing namespace* (!)
    - This means that components (classes, functions, etc.) of a namespace can be defined in multiple source files
      - All of the standard library is in namespace `std` but it has many source files
    ```

Classes vs. Namespaces

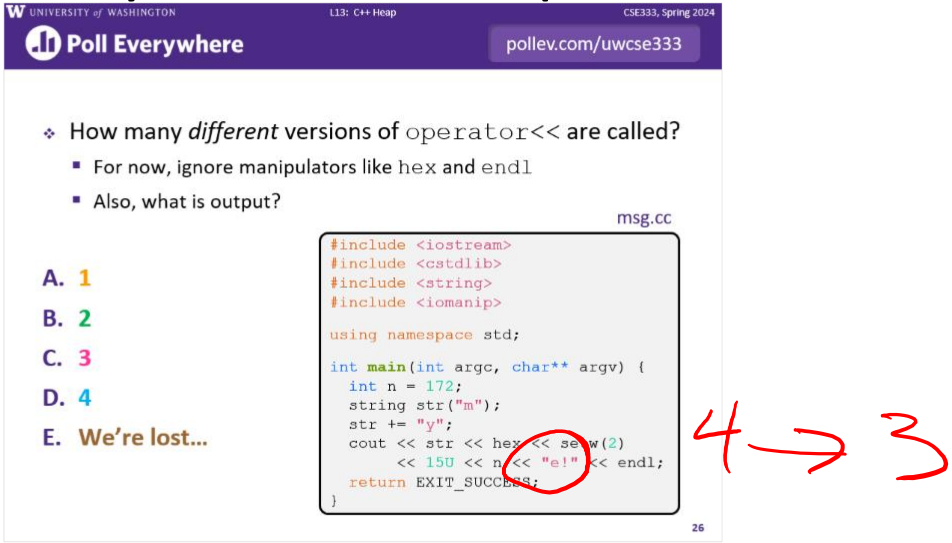
- They seems somewhat similar, but classes are *not* namespaces:
  - There are no instances/objects of a namespace; a namespace is just a group of logically-related things (classes, functions, etc.)
  - To access a member of a namespace, you must use the fully qualified name (*i.e.* `nsp_name::member`)
    - Unless you are `using` that namespace or individual member item
    - You only used the fully qualified name of a class member when you are defining it outside of the scope of the class definition

Lecture Outline

- Class Details
  - Rule of Three / Making Copies
  - Access Controls and Friends
  - Namespaces
  - **Implicit Conversions**
- Using the Heap
  - `new` / `delete` / `delete[]`

Flashback

- Recall this activity from C++ output streams:



- String literals like `"n!"` have type `const char *`
- Can we convert a `const char *` to a `std::string`?
  - Yes, but …

Implicit Type Conversions

- C++ can use single-argument constructors to convert between user-defined types
  - Eg, converting `const char *` into a `std::string` before invoking **`operator<<`**`(const std::string& s)` on it

Implicit Type Conversion: Example

```
class MyString {
 public:
  MyString(const char* s /* must be non-NULL */ ) { Copy(s) }
 ~MyString() { delete s_; }

  void Copy(const char* copyme) { /* allocate s_ and copy */ }
  const char* get_string() { return s_; }
private:
  const char* s_;
};

int main() {
  MyString s1("Hello CSE 333!");  // invoke 1-arg ctor
  return 0;
}
```

Implicit Type Conversion: Example

```
void Print(const MyString& m) {
  cout << m.get_string() << endl;
}









int main() {
  MyString s1("Hello CSE 333!");

  // implicitly invoke 1-arg ctor
  Print("Gosh, an implicit type conversion!");

  Print(NULL);  // ???
  return 0;
}
```

Implicit Type Conversions

- C++ can use single-argument constructors to convert between user-defined types

- Sometimes it's not clear when a constructor is being called
- Sometimes you **don't** want the constructor to be called (eg, on unexpected input)

- To disable implicit type conversions via the single-argument constructor, declare it `explicit`

Implicit Type Conversion: Example

```
class MyString {
 public:
  explicit MyString(const char* s /* must be non-NULL */ ) {
    Copy(s)
  }
  // … rest of class remains the same …
};




int main() {
  MyString s1("Hello CSE 333!");

  PrintMyString("An implicit type conversion?");     // nope
  PrintMyString(NULL);                                // also nope

  PrintMyString(MyString("Explicit invocation!"));   // yup
  return 0;
}
```

Lecture Outline

- Class Details
  - Rule of Three / Making Copies
  - Access Controls and Friends
  - Namespaces
  - Implicit Conversions
- **Using the Heap**
  - `new` / `delete` / `delete[]`

C++11 `nullptr`

- C and C++ have long used `NULL` as a pointer value that references nothing
- C++11 introduced a new literal for this: `nullptr`
  - New reserved word
  - Interchangeable with `NULL` for all practical purposes, but it has type `T*` for any/every `T`, and is not an integer value
    - Avoids funny edge cases, especially with function overloading (`f(int)` vs `f(T*)`; see C++ references for details)
    - Still can convert to/from integer `0` for tests, assignment, etc.
  - Advice: prefer `nullptr` in C++11 code
    - Though NULL will also be around for a long, long time

`new`/`delete`

- To allocate on the heap using C++, you use the `new` keyword instead of `malloc()` from `stdlib.h`
  - You can use new to allocate an object (*e.g.* `new Point`)
    - Will execute appropriate constructor as part of object allocate/create
  - You can use new to allocate a primitive type (*e.g.* `new int`)

- To deallocate a heap-allocated object or primitive, use the `delete` keyword instead of `free()` from `stdlib.h`
  - Don't mix and match!
    - ***Never*** `free()` something allocated with `new`
    - ***Never*** `delete` something allocated with `malloc()`
    - Careful if you're using a legacy C code library or module in C++

new/delete Example

```
int* AllocateInt(int x) {
  int* heapy_int = new int;
  *heapy_int = x;
  return heapy_int;
}
```

```
Point* AllocatePoint(int x, int y) {
  Point* heapy_pt = new Point(x,y);
  return heapy_pt;
}
```

heappoint.cc

```
#include "Point.h"
using namespace std;

...  // definitions of AllocateInt() and AllocatePoint()

int main() {
  Point* x = AllocatePoint(1, 2);
  int* y = AllocateInt(3);

  cout << "x's x_ coord: " << x->get_x() << endl;
  cout << "y: " << y << ", *y: " << *y << endl;

  delete x;
  delete y;
  return 0;
}
```

`new`/`delete` Behavior

- `new` behavior:
  - When allocating you can specify a constructor or initial value
    - *e.g.*, `new Point(1, 2)`, `new int(333)`
  - If no initialization specified, it will use default constructor for objects and uninitialized ("mystery") data for primitives
  - You don't need to check that `new` returns `nullptr`
    - When an error is encountered, an exception is thrown (that we won't worry about)

- `delete` behavior:
  - If you `delete` already `delete`d memory, then you will get undefined behavior (same as when you double **`free`** in C)

Dynamically Allocated Arrays

- To dynamically allocate an array:
  - Default initialize: `type* name = new type[size];`
- To dynamically deallocate an array:
  - Use `delete[] name;`
  - It is an *incorrect* to use "`delete name;`" on an array
    - The compiler probably won't catch this, though (**!**) because it can't always tell if `name*` was allocated with `new type[size];` or `new type;`
      - Especially inside a function where a pointer parameter could point to a single item or an array and there's no way to tell which!
    - Result of wrong `delete` is undefined behavior

Arrays Example (primitive)

arrays.cc

```
#include "Point.h"
using namespace std;

int main() {
  int stack_int;
  int* heap_int = new int;
  int* heap_init_int = new int(12);

  int stack_arr[10];
  int* heap_arr = new int[10];

  int* heap_init_arr = new int[10](); // uncommon usage
  int* heap_init_error = new int[10](12); // bad syntax
  int* heap_init_error = new int[10]{12}; // C++11 allows
  ...                                     //    (uncommon)

  delete heap_int;          // ok
  delete heap_init_int;     // ok
  delete heap_arr;          // error - must be delete[]
  delete[] heap_init_arr;   // ok

  return 0;
}
```

Arrays Example (class objects)

arrays.cc

```
#include "Point.h"
using namespace std;

int main() {
  ...

  Point stack_point(1, 2);
  Point* heap_point = new Point(1, 2);

  Point* err_pt_arr = new Point[10];// bug-no Point() ctr

  Point* err2_pt_arr = new Point[10](1,2); // bad syntax
  Point* err2_pt_arr = new Point[10]{1,2}; // C++11 allows
  ...                                      //   (uncommon)

  delete heap_point;

  ...

  return 0;
}
```

`malloc` vs. `new`

	`malloc()`	`new`
What is it?	a function	an operator or keyword
How often used (in C)?	often	never
How often used (in C++)?	rarely	often
Allocated memory for	anything	arrays, structs, objects, primitives
Returns	a `void*` (*should be cast*)	appropriate pointer type (*doesn't need a cast*)
When out of memory	returns `NULL`	throws an exception
Deallocating	`free()`	`delete` or `delete[]`

Poll Everywhere

pollev.com/uwcse333

- What will happen when we invoke `bar()`?
  - If there is an error, how would you fix it?

```
Foo::Foo(int val) { Init(val); }
Foo::~Foo() { delete foo_ptr_; }

void Foo::Init(int val) {
   foo_ptr_ = new int;
  *foo_ptr_ = val;
}

Foo& Foo::operator=(const Foo& rhs) {
  delete foo_ptr_;
  Init(*(rhs.foo_ptr_));
  return *this;
}

void bar() {
  Foo a(10);
  Foo b(20);
  a = a;
}
```

this != &rhs

A. Bad dereference
B. Bad delete
C. Memory leak
D. "Works" fine
E. We're lost…

Heap Member Example

- Let's build a class to simulate some of the functionality of the C++ string
  - Internal representation: c-string to hold characters

- What might we want to implement in the class?

Str Class Walkthrough

Str.h

```
#include <iostream>
using namespace std;

class Str {
 public:
  Str();                      // default ctor
  explicit Str(const char* s);  // c-string ctor
  Str(const Str& s);          // copy ctor
  ~Str();                     // dtor

  int length() const;         // return length of string
  char* c_str() const;        // return a copy of st_ on heap
  void append(const Str& s);

  Str& operator=(const Str& s);  // string assignment

  friend std::ostream& operator<<(std::ostream& out, const Str& s);

 private:
  char* st_;  // c-string on heap (terminated by '\0')
};  // class Str
```

Str Example Walkthrough

See:

`Str.h`

`Str.cc`

`strtest.cc`

- Look carefully at assignment `operator=`
  - self-assignment test is especially important here

Extra Exercise #1

- Write a C++ function that:
  - Uses `new` to dynamically allocate an array of strings and uses `delete[]` to free it
  - Uses `new` to dynamically allocate an array of pointers to strings
    - Assign each entry of the array to a string allocated using `new`
  - Cleans up before exiting
    - Use `delete` to delete each allocated string
    - Uses `delete[]` to delete the string pointer array
    - (whew!)