CS4414 Recitation 3

C++ class and template

09/2024

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Logistics

Extra learning sessions: every Monday evening

- **Session 3: const & template** (prelim preparation I)
  - Time: 7:15 PM – 8:15 PM, Monday (09/15)
  - Led by TAs: Jephthah Kwame Mensah, Nam Anh Dang
  - Location: Phillips 101

Extra HW helping & working sessions:

- **Session 1: HW1 part 1** (due on September 15th)
  - Time: 2PM – 5 PM, Sunday (9/14)
  - Led by TAs: Briaana Liu, Tina Cheng, Ruichen Bao
  - Location: Uris G01

Overview

- C++ class
  - Constructor, destructor
  - Copy constructor, move constructor
  - C++ objects and containers

- C++ template
  - Template function, template class
  - Template instantiation
  - Variadic templates

What is C++?

A federation of related languages, with four primary sublanguages

- **C:** C++ is based on C, while offering approaches superior to C. Blocks, statements, processor, built-in data types, arrays, pointers, etc., all come from C
- **Object-Oriented C++:** "C with Classes", classes including constructor, destructors, inheritance, virtual functions, etc.
- **Template C++:** generic programming language. Gives a template, define rules and pattern of computation, to be used across different classed.
- **STL(standard template library):** a special template library with conventions regarding containers, iterators, algorithms, and function objects

C++ Class

C++ Class

- A class is a user-defined type
- Usually, defined by header file (.hpp) and implementation file (.cpp)
- A class can have following members
  - Data members
  - Constructor, destructor
  - Member functions
  - Copy constructor, move constructors

C++ Class

Why do we need header files?

- The **names** of program elements must **be declared before** they can be used.
- The declaration **tells the compiler** the type of an element.
- C++ uses header files to contain declarations. Use **#include** in other files that require the declarations.

C++ Class

rectangle.hpp

--- header file

```
#pragma once
class Rectangle{
        float width;
        float length;
        float area;
public:
        Rectangle();
        Rectangle(float w, float l);
        ~Rectangle();
        float& getArea();
        ... };
```

Data members

For compiler, indicate that it only be parsed once.

C++ Class rectangle.cpp --- implementation file

Scope resolution operator

```
#include "rectangle.hpp”


Rectangle::Rectangle(){
        … …
}
Rectangle::Rectangle(float w, float l){
        … …
}
float& Rectangle::getArea(){
… }
```

Demo

C++ Class

- A class is a user-defined type
- Usually, defined by header file (.hpp) and implementation file (.cpp)
- A class can have following members
  - Data members
  - **Constructor, destructor**
  - Member functions
  - Copy constructor, move constructors

Constructor: construct and initialize objects of that class

- Default constructor: a constructor can be called with no argument

```
Rectangle::Rectangle():
        width(0),
        length(0),
        area(0)
{
    // Constructor body (can be empty or contain additional logic)

}
```

Constructor: construct and initialize objects of that class

- Implicit default constructor:
  - If there is no user-declared constructor for a class type, **the compiler** will implicitly declare a default constructor as an inline public class member.

Constructor: construct and initialize objects of that class

Parameterized constructor: a constructor that accepts argument

```
Rectangle::Rectangle(int w, int l):
                width(w),
                length(l)
{
        area = _width * _length;
}
```

Note: When the parameterized constructor is defined and no default constructor is defined explicitly, the compiler will not implicitly create the default constructor

Constructor: construct and initialize objects of that class

Parameterized constructor: a constructor that accepts argument

Note:

- When the **parameterized constructor is defined** and no default constructor is defined explicitly, the compiler will **NOT** implicitly create the default constructor

Constructors

- Constructor are used to **initialize** object of the class type
- A constructor has the **same name** as the class and **no** return type. It can have as many argument as needed
- e.g.,
  - myClass(); // default constructor
  - myClass(int x, std::string str); // Parameterized constructor
  - std::unique_ptr<myClass> my_ptr = std::make_unique< myClass>();
  - … // default constructor

Destructor

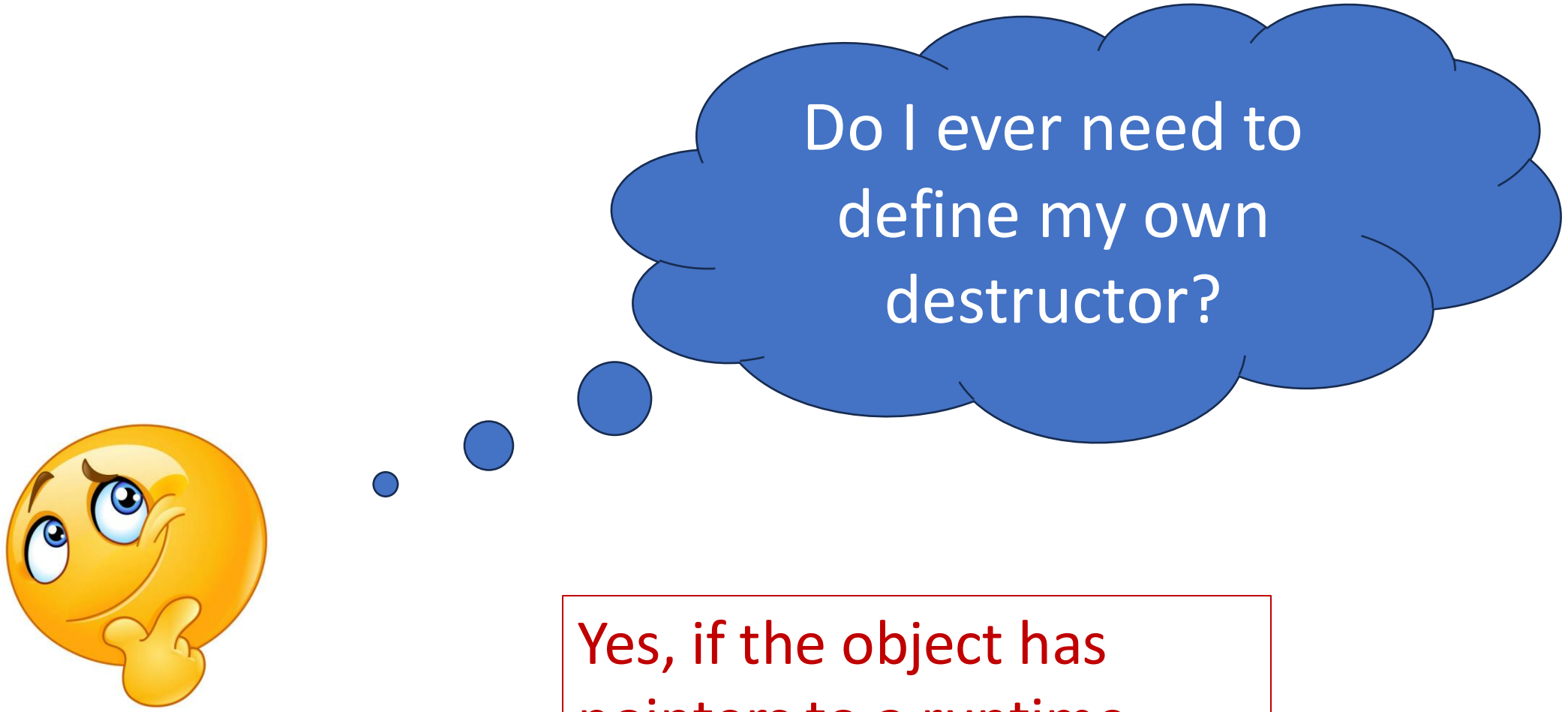
Demo

- When is the destructor called?
  - when the lifetime of an object **ends**
- It is used to **free** the resources that the object acquired during its lifetime
- e.g.,
  - ~myClass();

Implicit constructor and destructor

- Implicit default constructor:
  - If there is **no user-declared constructor** for a class type, **the compiler** implicitly provides a (public) default constructor.
  - If there **is** user-declared constructor, **the compiler** will NOT implicitly create the default constructor
- Implicit default destructor
  - The implicitly-defined destructor defined by the compiler has an empty body

Implicit constructor and destructor



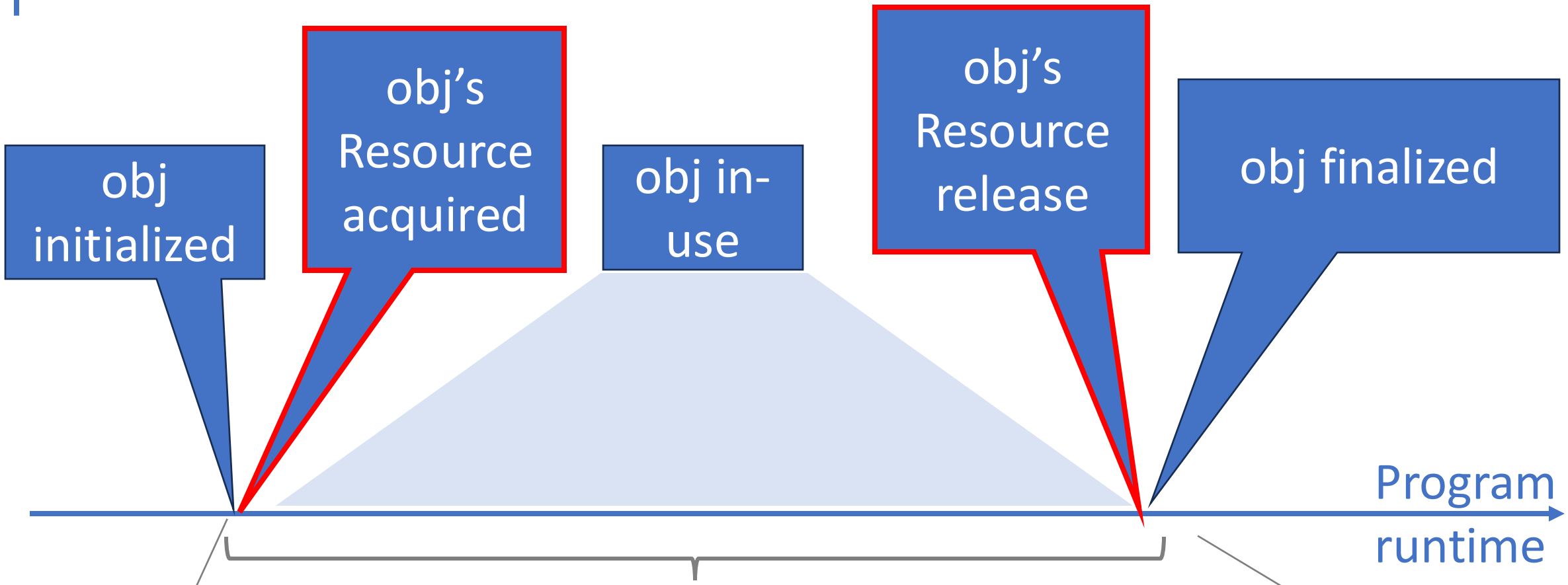
Yes, if the object has pointers to a runtime allocation of resources

MyIntVector example

```
class MyIntVector {
private:
    int* data;          // Pointer to dynamically allocated array
    size_t size;    // Number of elements in the vector
public:
     MyIntVector(size_t s) : size(s), data(new int[s]) {
          for (size_t i = 0; i < size; ++i) {
               data[i] = 0;
          }
     }       ……
};
```

https://en.cppreference.com/w/cpp/language/lifetime

Object lifetime

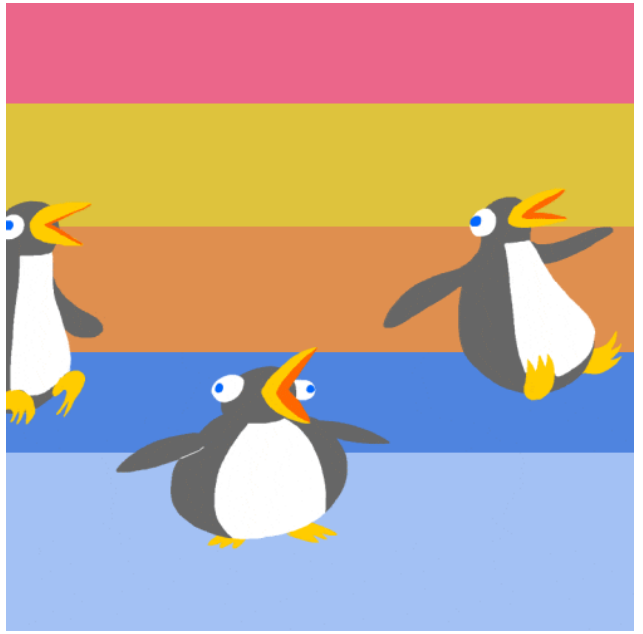


An object, obj's lifetime

Begin:
- Object constructor is called

End
- Object destructor is called
  - Release the resources

Copying in C++



- Copying data, copying memory from one place to another
- Copying takes time

Copying in C++

PollEv.com/cs4414c552

```
Rectangle* obj1 = new Rectangle(10.0, 11.0);
Rectangle* obj2 = obj1;
obj2->width = 100.0;
```

the values of
obj1.wdith?
obj3.width?

```
Rectangle obj3 = Rectangle(10.0, 11.0);
Rectangle obj4 = obj3;
obj4.width = 100.0;
```

Copying in C++

```
int a = 5;
int b = a;
```

// creating a copy of int a

```
Rectangle obj1 = Rectangle(10.0, 11.0);
Rectangle obj2 = obj1;
```

// obj2 is a copy of object obj1

Copy constructor

```
class Rectangle{

        Rectangle(const Rectangle& other);

}
```

// Construct an object of class Rectangle by copying Rectangle object, other, passing by reference.

Copy constructor

- **Create** a new object by **initializing** it with an object of the same class
- Called when
  - Initialization `Rectangle obj2 (obj1);`
  - Function argument passing by value `func(Rectangle obj);`
  - Function return by value `return obj;`

// Note: returning a local created variable by value, will be optimized by c++ 17+, via RVO(copy elision) that could avoid copy.
It constructs the return object directly in return's storage. (https://en.cppreference.com/w/cpp/language/copy_elision.html)

Implicitly-defined default copy-constructor

- If no user-defined copy con… …d define a copy constructo…
  - It performs member-wise … …and …s to the new object it initializes

Do I ever need to define my own copy-constructor?

Yes, if an object has pointers or any runtime allocation of resources

Copy assignment

- Defines what happens when an **already existing object** is **assigned** the value of **another object** of the same class.
- Called when
  - Assign to an already existing object

```
Rectangle obj2;
obj2  = obj1;
```

Implicitly-defined default copy-constructor

- If no user-defined copy constructor, the compiler declare and define a copy constructor
  - It performs member-wise copy of the object's bases and members to the new object it initializes
  - Default constructor does only **shallow** copy

myIntVector example

Demo

```
class myIntVector{
public:
        int* data;
        size_t size;
        size_t capacity;

        myIntVector();
        myIntVector(size_t s);
        ~myIntVector();
        ...
};
```

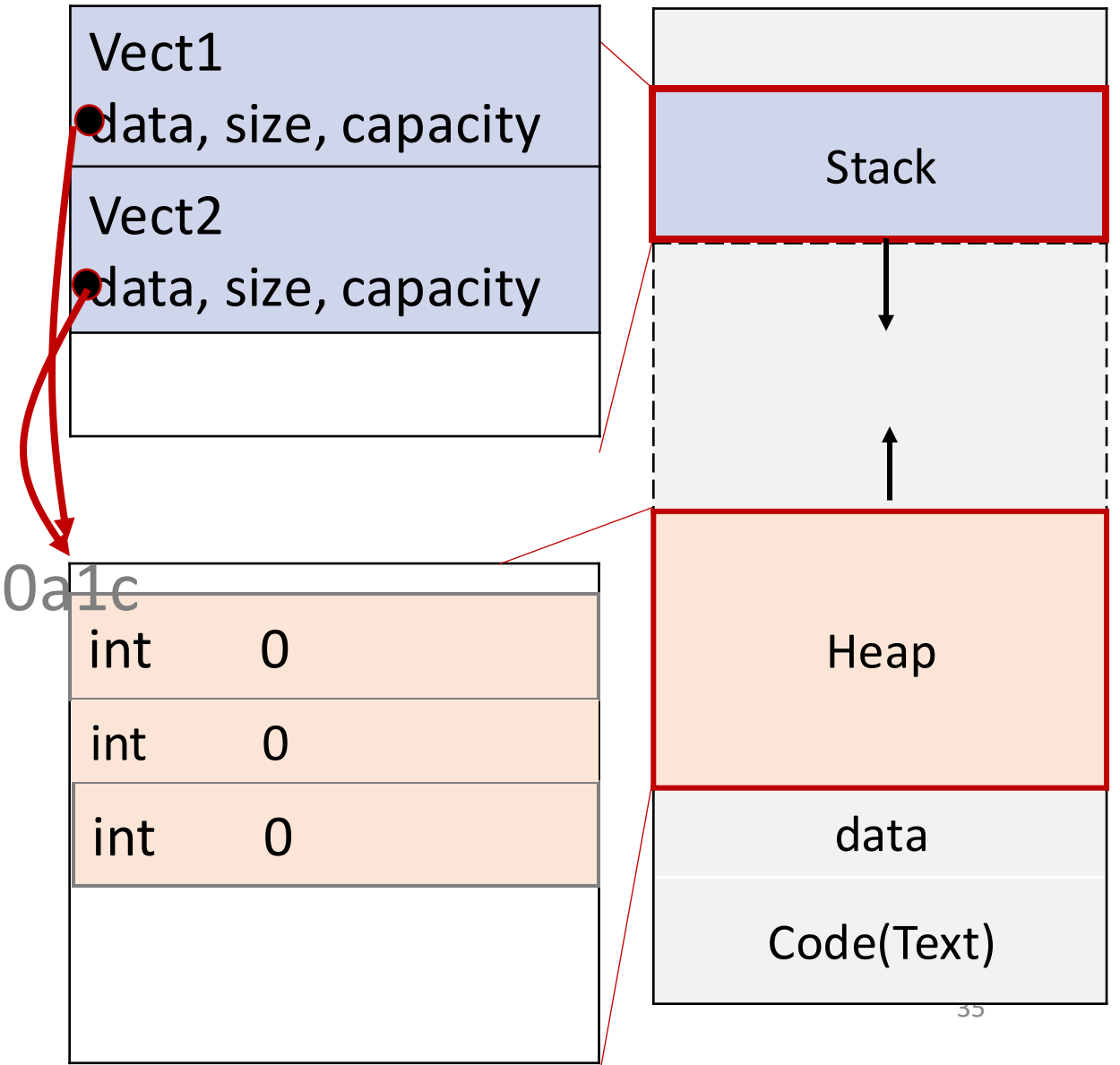
```
myIntVector::myIntVector(size_t s) {
        size = s;
        capacity = s;
        data = new int[capacity];
        for (size_t i = 0; i < size; ++i) {
            data[i] = 0;
        }
}
myIntVector::~myIntVector(){
          delete[] data;
}
```

Default copy-constructor

shallow copy

```
myIntVector vect1 = myIntVector(3);

myIntVector vect2 = vect1;

vect1.data = 5;
```

Not ideal, because changing only one changes both of them. Want two identical independent objects

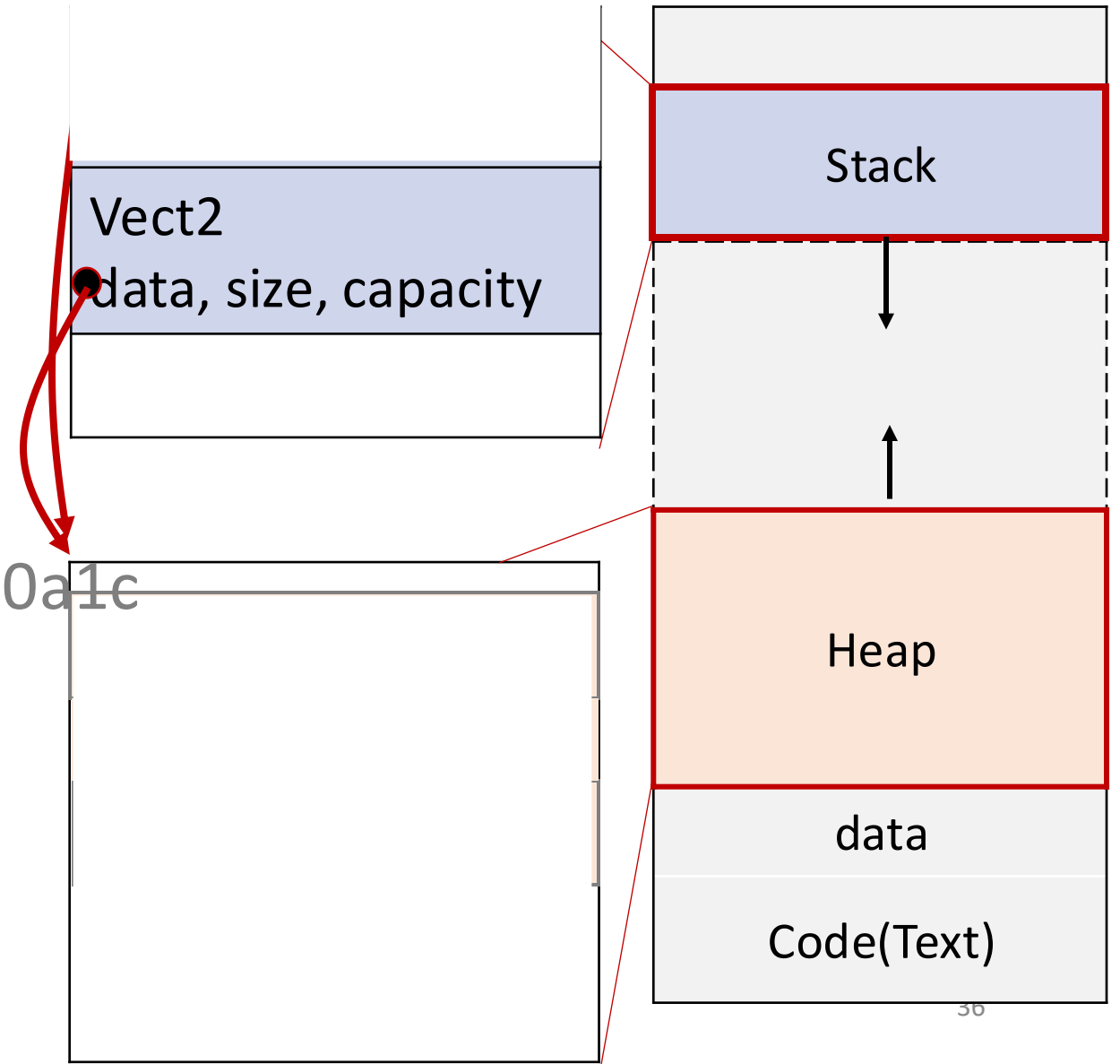


Default copy-constructor

shallow copy

```
myIntVector func(){

  myIntVector vect1 = myIntVector(3);

  myIntVector vect2 = vect1;

}

myIntVector vect = func();
```

Bad, because now vect2.data points to nothing



Fix: User-defined copy constructor

```
myIntVector(const myIntVector& other) :
    size(other.size), data(new int[other.size]) {
      for (size_t i = 0; i < size; ++i) {
          data[i] = other.data[i];
      }
}
```

Deep copy the object's members

Move constructor

```
class myIntVector{

        myIntVector(myIntVector && other);

}
```

// Transfer the ownership of the resources from the object, other, to the new object

Move constructor

- Transfer the ownership of resources from one object to another, instead of making a copy
- Called when
  - Initialization
  - Move smart pointers
  - Function return with Return Value Optimization(RVO), or return a named local and want to force a move without(RVO)

```
Rectangle obj2(std::move(obj1));
std::unique_ptr<int> p2 = std::move(p1);
return std::move(obj);
```

Why use move constructor?

- Improve the performance of the program by avoiding the overhead caused by unnecessary copying.

```
myIntVector(myIntVector&& other)  : size(0), data(nullptr) {
    data = other.data;          // copy the pointer of the memory address of other.data
    size = other.size;
    other.data = nullptr;       // Transfer the ownership of other's resource to this new object
    other.size = 0;
}
```

Combining what we learnt about classes with vector

std::vector

```
template<
    class T,
    class Allocator = std::allocator<T>
> class vector;
```

https://en.cppreference.com/w/cpp/container/vector

push_back

- Appends the given element value to the end of the container.
- The new element could be constructed via

```
std::vector<Rectangle> rec_vec;

Rectangle rec1;

rec_vec.push_back(rec1);                    // Copy constructor

rec_vec.push_back(std::move(rec1));   // Move constructor
```


https://en.cppreference.com/w/cpp/container/vector

emplace_back

- Appends a new element to the end of the container
- Besides the capabilities of push_back, it allows construct the new element **in-place**

```
std::vector<Rectangle> rec_vec;

rec_vec.emplace_back(10.0, 11.0);      // parameterized constructor

Rectangle rec1;

rec_vec.emplace_back(rec1);            // Copy constructor
```


https://en.cppreference.com/w/cpp/container/vector

Exercise: Find the error

```
class myClass {
public:
    myClass(int x) {}
private:
     int myInt;
};
std::vector<myClass> myObjects(4);
```

Exercise: Find the error

```
class myClass {
public:
    myClass(int x) {}
private:
     int myInt;
};
std::vector<myClass> myObjects( 4 );
```

Compiler no longer provides default constructor, because of user-defined constructor

std::vector needs a way to create default-constructed elements when resizing or initializing the vector with a specified size.

https://en.cppreference.com/w/cpp/container/vector/vector.html

Exercise: Find the error

Fix

```
std::vector<myClass> myObjects; // size 0
myClass obj1(5);
                                  // constructed elements
myClass obj2(7);
myObjects.push_back(obj1);
myObjects.push_back(obj2);        // push_back invokes the
                                  copy constructor to copy
                                  the object into the vector
```

C++ Template

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Motivation

- You got assigned a task at work to build a digital calculator
- You come up with something like this

```
int subtract(int a, int b){
        return a-b;
}
int main(){
        int x = 10;
        int y = 7;
        int z = subtract(x,y);
        std::cout << z << std::endl;
…}
```

Motivation

I don't want to copy-paste code just because the type changes?

```
int subtract(int a, int b){
        return a - b;
}
double subtract (double a, double b){
        return a - b;
}
float subtract(float a, float b){
        return a - b;
}

int main(){
        ……
}
```

- But calculators should be able to subtract floats and doubles too!

  And much more...

- So you come up with this...

Solution: generic programming

- What if you could just replace int with a generic data type
- How? Let's code!
- Limitation in shown example: parameters in subtract() must share type
- Uh-oh!
- No worries actually – let's code again!

https://en.cppreference.com/w/cpp/language/templates.html

Templated function

template < *parameter-list* > *function-declaration*

```
template <typename T>
T subtract(T a, T b) {
    return a - b;
}

int main(){
    int x = 10;
    int y = 7;
    std::cout << subtract(x, y) << std::endl;

    double p = 5.5;
    double q = 2.2;
    std::cout << subtract(p, q) << std::endl;
…}
```

typename is **the type-parameter-key,** which could be either **typename** or **class**.

T is **the name** of **type template parameter**.

Tells the complier *"I will use a placeholder type T in this function."*

https://en.cppreference.com/w/cpp/language/function_template.html

Templated class

template < *parameter-list* > *class-declaration*

```
template <typename T>
class Subtracter {
public:
    T subtract(T a, T b) {
        return a - b;
    }
};

int main() {
   Subtracter<double> double_sub;
   std::cout << double_sub.subtract(5.5, 2.2) << std::endl;
…}
```

Parameter list

```
template <typename T, int N>
class Array {
    T data[N];  // size N known at compile time

public:
    int size() const { return N; }
};


int main() {
    Array<int, 5> arr1;   // array of 5 ints
    std::cout << arr1.size() << std::endl;  // 5
…}
```

Non-type template parameter

- A variable for a constant (e.g., an int …)
- Known at compile time

Type template parameter

- A variable for a type
- Known at compile time

https://en.cppreference.com/w/cpp/language/template_parameters.html

Template instantiation

- A function template or a class template **by itself** is **not** a type, or a function, or any other entity.
- **No code is generated** from a source file that contains **only** template definitions.
- For any code to appear, a template must be **instantiated**: the template arguments must be determined so that the compiler can generate an actual function

Template instantiation - explicit instantiation

```
template <typename T>
T subtract(T a, T b) {
    return a - b;
}
```

```
template int subtract<int>(int, int);      // Explicit instantiation declarations
template double subtract<double>(double, double);      // Explicit instantiation declarations

int main(){
    int x = 10, y = 7;
    std::cout << subtract(x, y) << std::endl;      // Use subtract<int>
    double p = 5.5, q = 2.2;
     std::cout << subtract(p, q) << std::endl;      // Use subtract<double>
…}
```


https://en.cppreference.com/w/cpp/language/function_template.html

demo

Template instantiation - implicit instantiation (default)

```
template <typename T>
T subtract(T a, T b) {
    return a - b;
}
```

- The compiler generates code, in this case **subtract<int>**
- If subtract was called on a double another function subtract (overload) will be generated with T = double

```
int main(){
    int x = 10;
    int y = 7;
    std::cout << subtract(x, y) << std::endl; // Compiler generate subtract<int>
     double p = 5.5, q = 2.2;
     std::cout << subtract(p, q) << std::endl; // Compiler generate subtract<double>
…}
```


https://en.cppreference.com/w/cpp/language/function_template.html

Quick aside: template hpp files don't come with associated cpp files

- A template is a "pattern" that the compiler uses to generate a family of classes or functions
- For the compiler to generate the code, it must see both the template definition and the specific types used to "fill in" the template.
  - For example, if you're trying to use a subtract<int>, the compiler must see both the subtract template and the fact that you're trying to make a specific subtract<int>

https://isocpp.org/wiki/faq/templates#templates-defn-vs-decl

How do we use templates when our function has an arbitrary number of parameters?

- Common issue…
  - Solution: Variadic templates
  - Let’s code

Variadic templates

```
class car {
public:
        int price;
        car(int price) :price(price) {}
};

class pc {
public:
        int price;
        pc(int price) : price(price) {}
};
```

```
class pen {
public:
        int price;
        pen(int price) : price(price) {}
};
```

Variadic templates

```
int sum() {
        return 0;
}
template <typename T, typename... Args>
int sum (T item, Args... rest) {
        return item.price + sum(rest...);
}

int main() {
        car c(100);
        pc pc(10);
        pen p(1);
        std::cout << "The sum is " << sum(c, pc, p);
}
```

Templates in the perspective of programming

- Avoid code duplication
  - Functions are blocks of organized
  - Reusable code that model a particular action
  - Classes model similar set of objects
  - Libraries provide a consistent set of features
- Performance (compile-time resolution)
  - Templates are expanded by the compiler for the types you use

Where to find the resources?

- Copy constructor: https://www.geeksforgeeks.org/copy-constructor-in-cpp/
- Move semantics: https://www.cprogramming.com/c++11/rvalue-references-and-move-semantics-in-c++11.html
- Operator overload: https://www.geeksforgeeks.org/operator-overloading-cpp/
- Effective C++: 55 specific ways to improve your programs and designs, Scott Meyers, 3rd edition
- A Tour of C++, Bjarne Stroustrup