C++ PROGRAMMING

Lecture 8

Secure Software Engineering Group
Philipp Dominik Schubert

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CONTENTS

1. Static memory
2. Object oriented programming I

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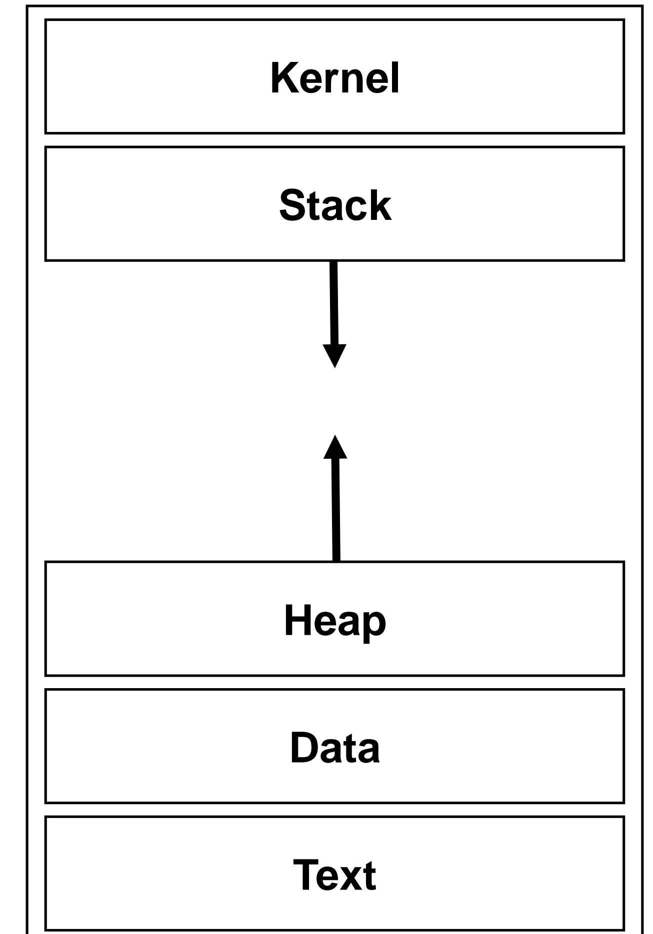
Memory classes

- Stack memory
  - Local variables / automatic variables
  - Function calls
- Heap memory
  - Variables allocated with `new` / `new[]`
- Static memory
  - Static because its size does not change at runtime
  - Stored in programs data segment
  - Global variables are static
  - Variables in functions, classes / structs and modules can be declared static
    - A static variable is a global variable that cannot be accessed globally!



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Using static variables and functions in classes

```
struct S {
  int i;
  static int j;
  S(int a) : i(a) {}
  static void foo() {}
  friend ostream& operator<< (ostream& os,
                              const S &s){
    return os << s.i << " " << s.j;
  }
};

// static data members are defined “outside”
int S::j = 42;

int main() {
  S s(10);
  std::cout << s << '\n';
  std::cout << s.j << '\n';
  std::cout << S::j << '\n';
  S::foo();
  return 0;
}
```

- Classes / structs can contain (constant) static variables
  - Static data members are part of the type
- `j` is shared across all variables of type `S`
- Does not require an instance to access it
  - Why is that useful?
    - Constant variables are only stored once
    - Saves memory
    - (Template metaprogramming)
- `foo()` is also shared across all instances of type `S`

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Static variables in functions

```
#include <iostream>
void function() {
  // counter is initialized only once
  static size_t counter = 0;
  counter++;
  std::cout << "called " << counter
            << " times!\n";
}
int main() {
  size_t n = 10;
  while (n--) {
    function();
  }
  return 0;
}
```

- Static variables are initialized only once
- SV's lifetime == program's lifetime
- Can be useful sometimes
  - E.g. count number of function calls
- Caution when running programs in parallel
  - Caused real trouble within the Linux kernel

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Static variables and static (non-member-)functions in modules

```cpp
// module.h
#ifndef SOME_HEADER_H_
#define SOME_HEADER_H_

static int value;

static void foo();

#endif

// module.cpp
int value = 42;

void foo() {}
```

- Restrict visibility
  - Variables
    - Static variables are only initialized once
    - Only visible to the module it is defined in
  - Functions
    - Static (non-member-)functions are only visible to the module they are defined in
- The C++17 way: anonymous namespaces

```cpp
namespace {
int value = 42;
void foo() {}
} // anonymous namespace
```


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More on the `this` pointer

- Pointer
- Contains address of the receiver object (on which the member function is being called on)
- Where can the this pointer be used?
  - Within non-static member functions
  - … (and two more situations)

```
class T {
  int x, y;
  void foo() {
    x = 6;        // same as this->x = 6;
    this->x = 5; // explicit use of this->
  }
  // parameter x shadows the member with the same name
  void foo(int x) {
    this->x = x; // unqualified x refers to the parameter
                 // 'this->' used for disambiguation
  }
  T(int x) : x(x),  // uses parameter x to initialize member x
      y(this->x)    // uses member x to initialize member y
      {}
  T& operator= (const T& b) {
    x = b.x;
    return *this; // many overloaded operators return *this
  }
};
```


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Ideas of OO-Languages

- “Concept of describing ‘real world’ objects.”
  - Kind of (nonsense), and the least important idea!

- Three foundations
  1. Encapsulation
  2. Inheritance
  3. Polymorphism

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Spoiler

- Foundations of OOP
  1. Encapsulation
  2. Inheritance
  3. Polymorphism

- You have to understand the concepts and ideas, of course
  - But you will only need the above when designing and implementing large software systems
  - Almost never happens at universities
  - Be prepared for reality
  - Know the mechanisms

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Model objects using classes and structs

- What is an object in C++?
  - “An object is a region of storage.”
- Object oriented thinking
  - For a real-world object
    - Model it as a class / struct
    - Abstract away from a concrete object and model essential properties as data members
    - Model capabilities of an object using member functions
    - An object might interact with other objects
  - Example: matrix from mathematics
    - Has a number of rows, columns, some entries
    - Can be multiplied with another matrix object

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Model objects using classes and structs

- Another example
  - A triangle from $\mathbb{R}^3$
    - Properties
      - Three points
      - …
    - Capabilities
      - Calculate area
      - Calculate circumference
      - …
    - Interaction
      - Calculate intersections
      - …
  - … as it is used in computer graphics

- Use a class / struct to model a …
  - description
  - blueprint

- Creating a variable of that class / struct …
  - creates an instance of that blueprint
  - a concrete object

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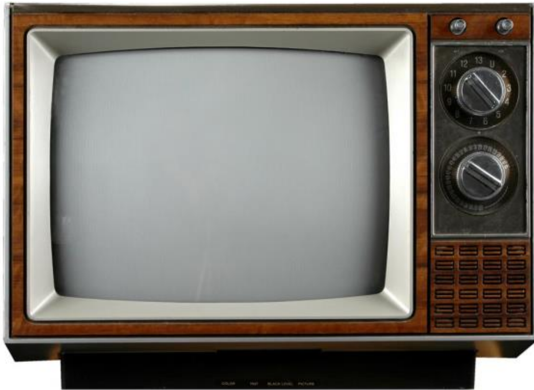
Encapsulation

- “Hide” programming details
  1. Separation of interface and implementation using header / implementations files
  2. Separation of data and interface using …
     - `public`
     - `private`
     - `protected`
- Example
  - TVs



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Encapsulation

- Header file matrix.h

```
#ifndef MATRIX_H_
#define MATRIX_H_

#include <iostream>
#include <vector>

class matrix {
 private:
  size_t rows;
  size_t columns;
  std::vector<double> data;

 public:
  matrix(size_t rows, size_t cols);
  size_t get_rows();
  size_t get_columns();
  size_t get_elements();
  friend matrix operator* (const matrix& lhs,
                           const double scale);
  friend matrix operator* (const matrix& lhs,
                           const matrix& rhs);
};

#endif
```

- Implementation file matrix.cpp

```
#include "matrix.h"

matrix::matrix(size_t rows, size_t cols)
         : rows(rows), columns(cols), ...

size_t matrix::get_rows() {
// code
}

size_t matrix::get_columns() {
// more code
}

// other function implementations
```


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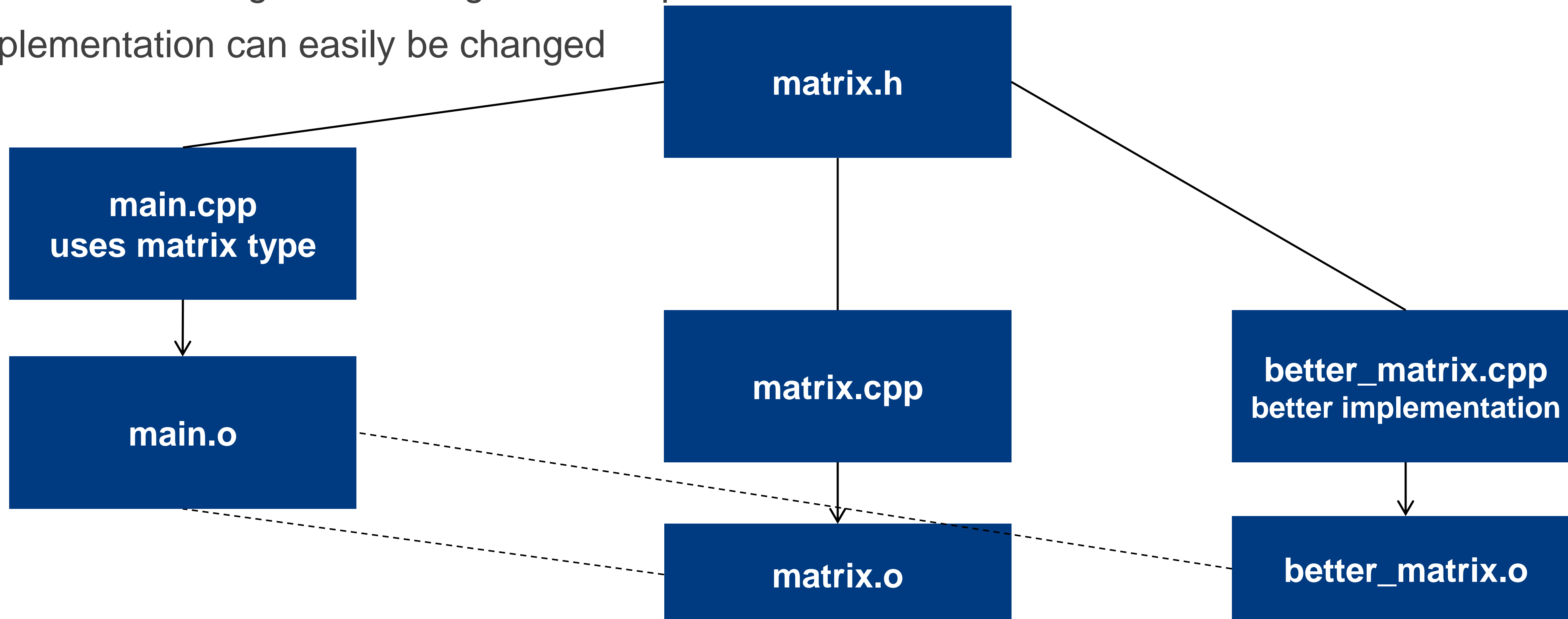
Encapsulation

- User only needs to know the interface
- Concrete implementation is “hidden”
- User will not recognize a change in the implementation
- Implementation can easily be changed



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Inheritance

- Classes / structs can inherit from each other
  - This results in inheritance of features
- Child classes inherit capabilities of parent class(es)
  - Child obtains
    - Data members
    - Function members
  - Child classes / structs can be further extended and / or specialized
- Inheritance follows an “is a” structure
  - A duck is some kind of bird
    - A bird is some kind of animal
      - An animal is some kind of creature

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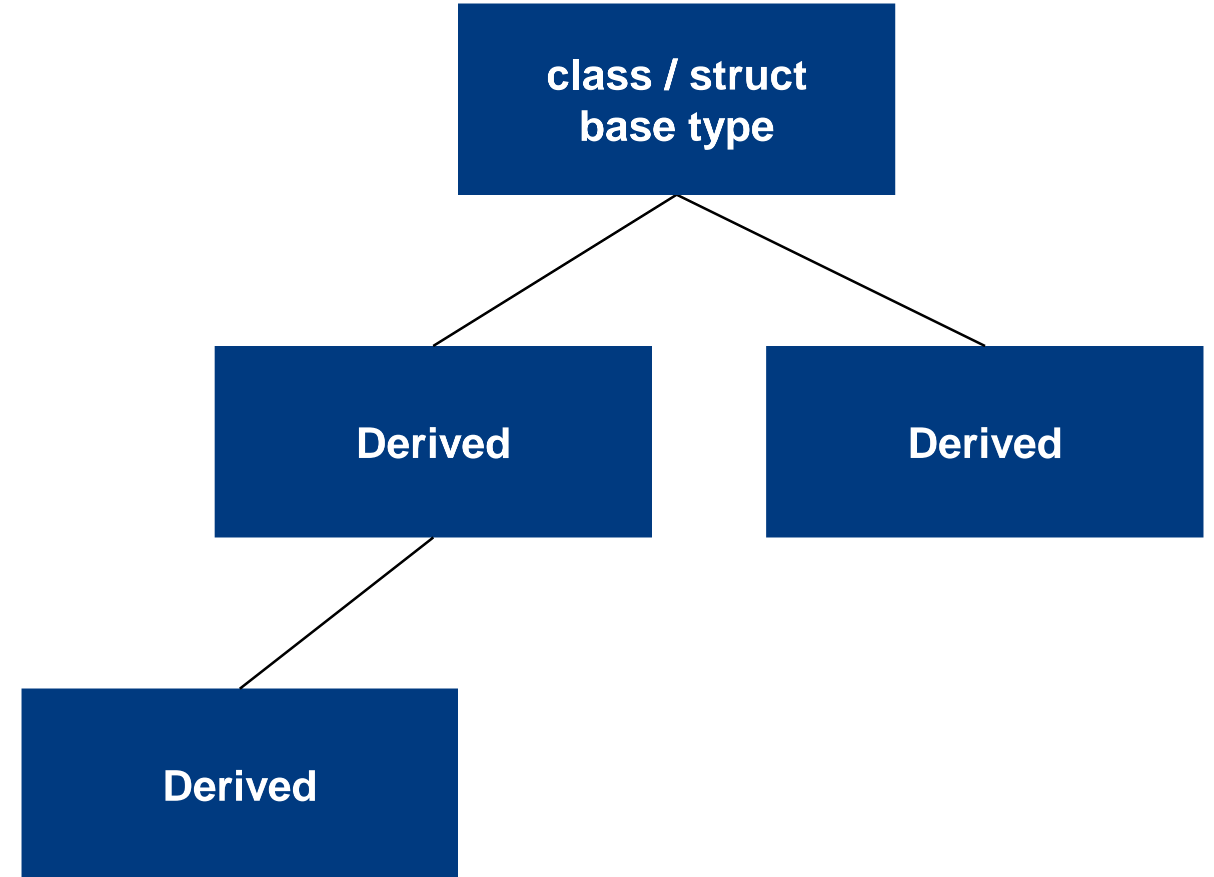
Inheritance

- Inheritance of data members and function members
  - Saves typing same code over and over again
  - It’s about code re-use
    - Imagine a change in a class has to be made
      - Extension to class logic
    - Copy version:
      - Terrible
    - Inheritance version:
      - Much easier



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Inheritance

```
#include <iostream>

class parent {
 private:
  int parent_value;

public:
  parent(int i) : parent_value(i) {}
  void print() {
    std::cout << parent_value << '\n';
  }
};
```

```
class child : public parent {
 private:
  int child_value;

 public:
  child(int i, int j) : parent(j),
                         child_value(i)
                         {}
  void print() {
    std::cout << child_value << '\n';
    parent::print();
  }
};

int main() {
  parent p(10);
  p.print();

  child c (20, 30);
  c.print();
  return 0;
}
```


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Inheritance

- Visibility / inheritance modes
  - `public`
  - `private`
  - `protected`

```
class base {
 public:
  int i;
 private:
  int j;
 protected:
  int k;
};
```

- Visibility modes
  - Variables of base
    - Everything aware of `base` is aware of `i`
    - Only children of `base` (and their children) are aware of `k`
    - No one, but `base` is aware of `j`
- Inheritance modes

```
class derived1 : public base {
 // everything is aware that derived1 inherits from base
};
class derived2 : private base {
 // no one but derived2 is aware of the inheritance
};
class derived3 : protected base {
 // only derived3 and its children are aware that they inherit from base
};
```

- For the most parts nobody cares and `public` inheritance mode is used

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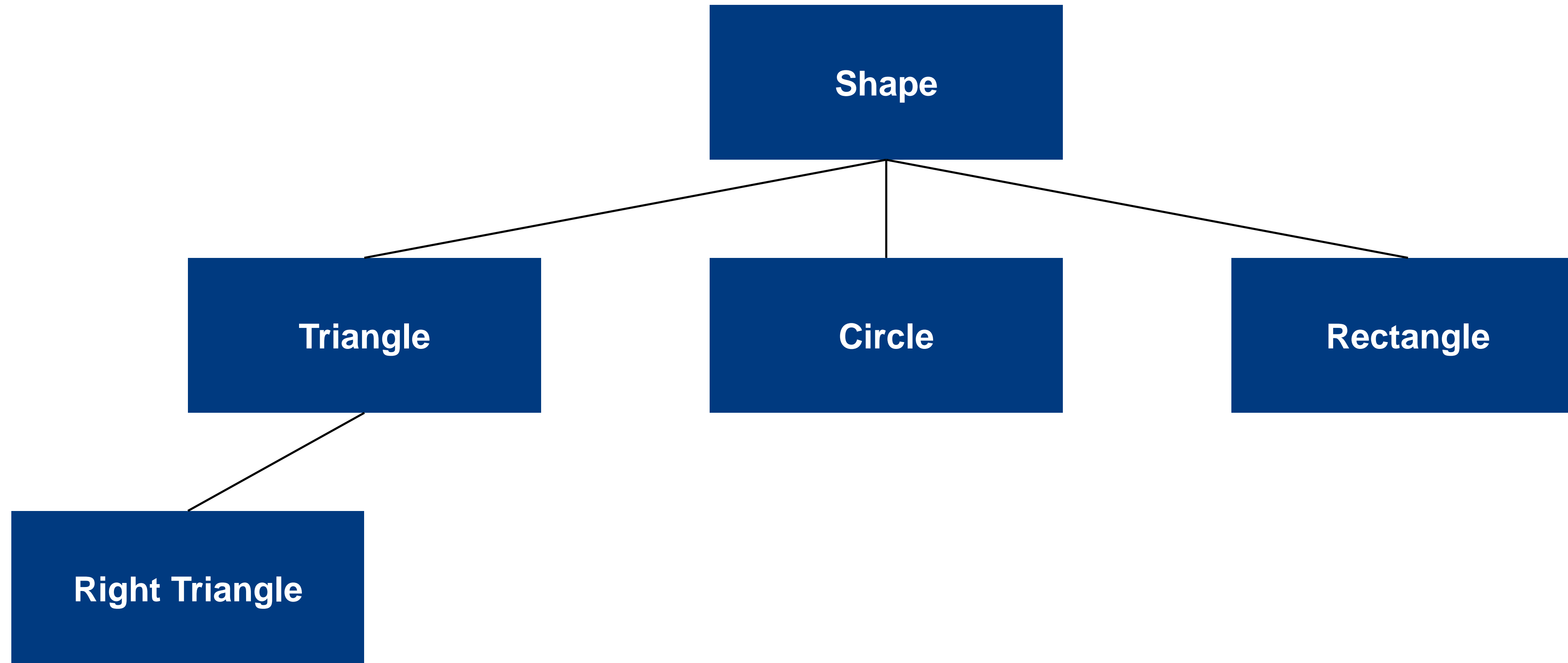
Build a type hierarchy



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Build a type hierarchy

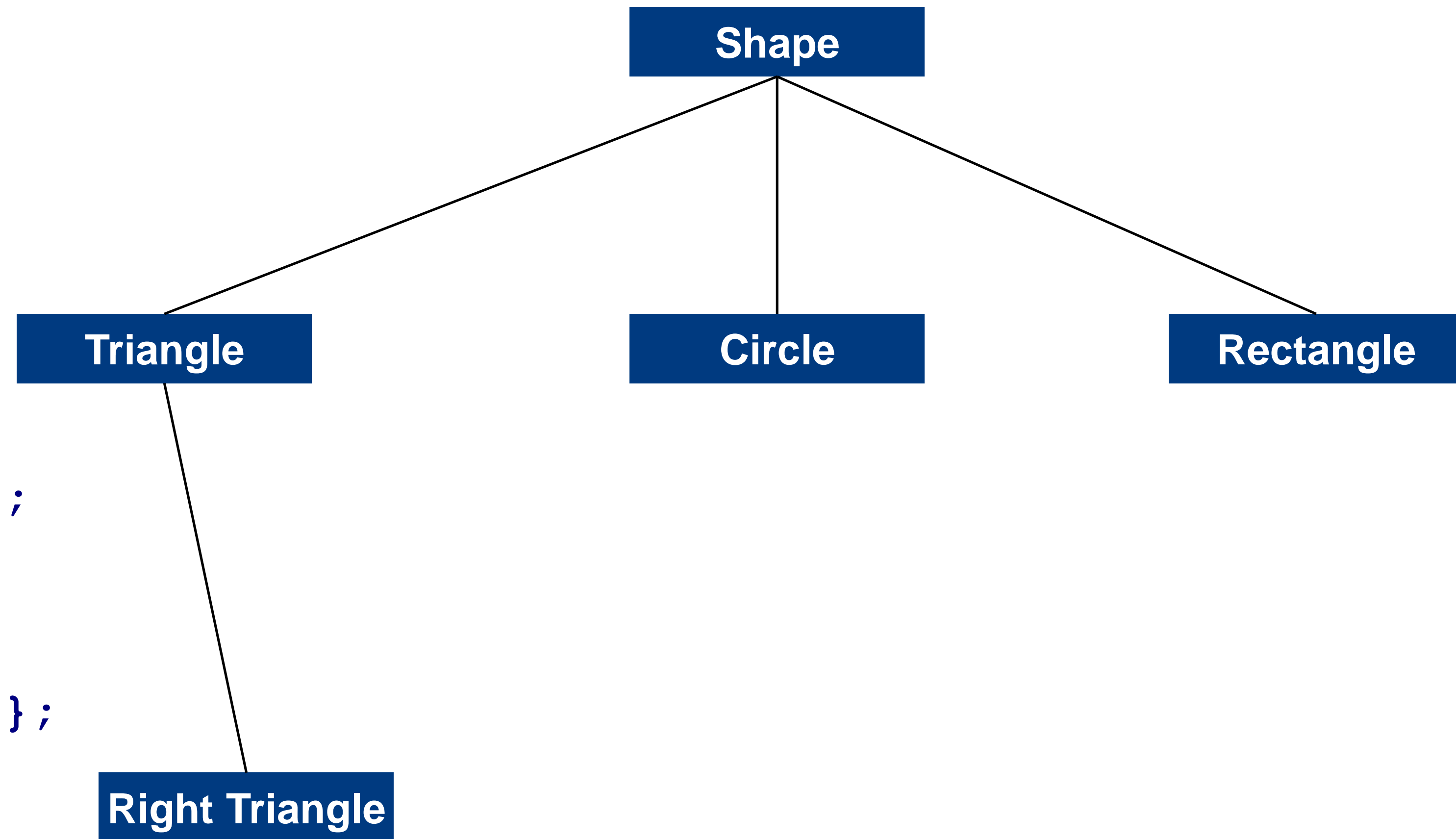
```
class shape {};

class triangle : public shape {};

class rectangle : public shape {};

class circle : public shape {};

class right_triangle : public triangle {};
```



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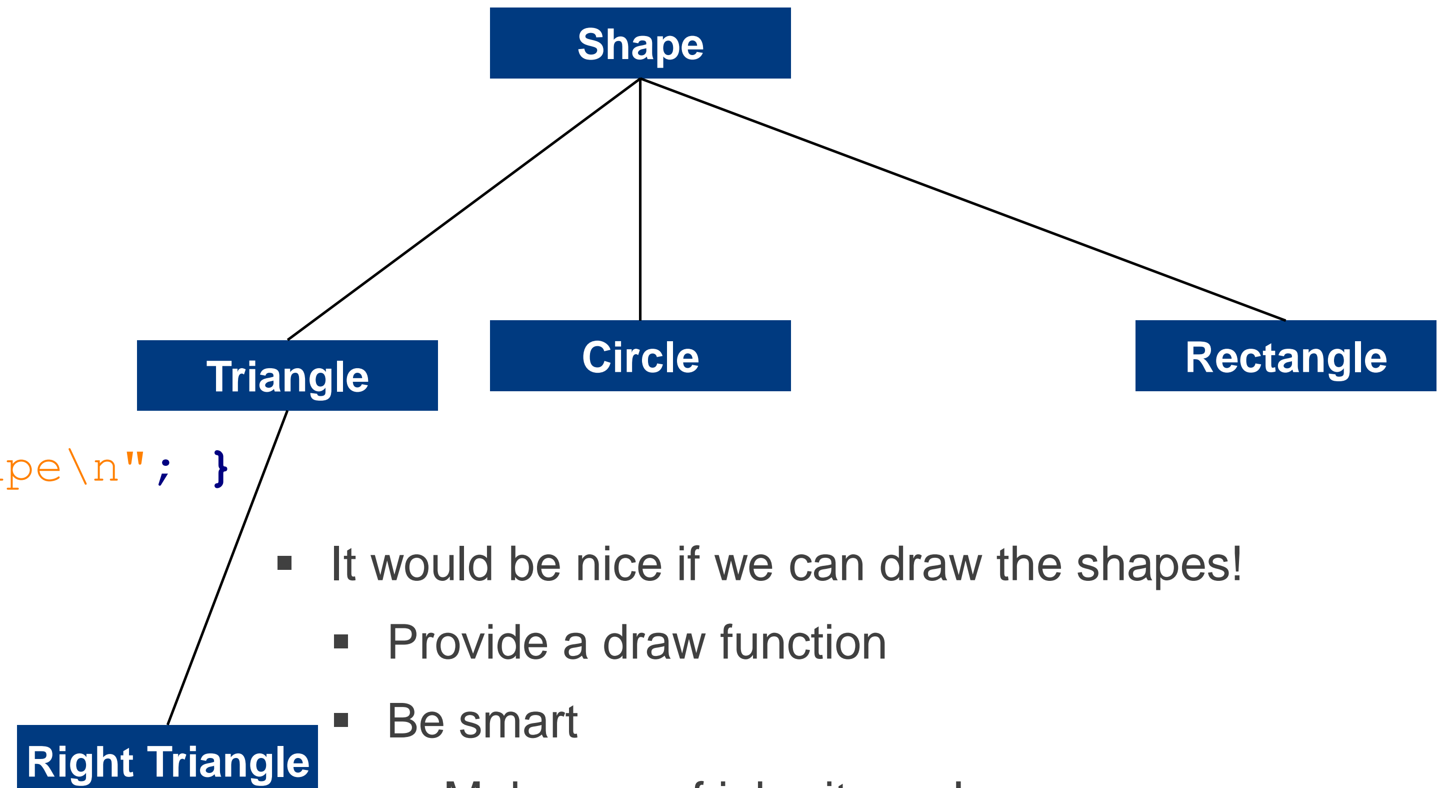
Build a type hierarchy




```
class shape {
 public:
  void draw() { std::cout << "shape\n"; }
};

class circle : public shape {};

class rectangle : public shape {};

class triangle : public shape {};

class right_triangle : public triangle {};
```

- It would be nice if we can draw the shapes!
  - Provide a draw function
  - Be smart
    - Make use of inheritance!
  - Now every child has a function `draw()`
  - But wait
    - Not all shapes shall be printed as a “shape”
    - We want to specialize `draw()`
      - Depending on the subtype

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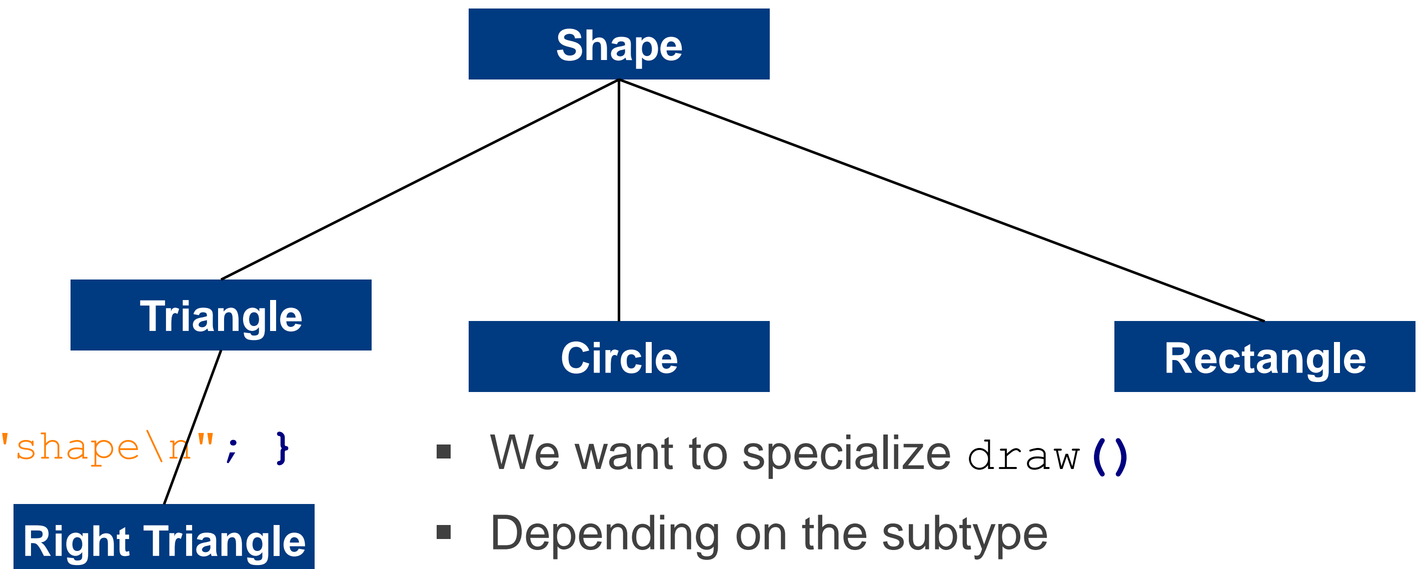
Build a type hierarchy




```
class shape {
 public:
  virtual ~shape() = default;
  virtual void draw() { std::cout << "shape\n"; }
};
class circle : public shape {
 public:
  void draw() override { std::cout << "circle\n"; }
};
class rectangle : public shape {
 public:
  void draw() override { std::cout << "rectangle\n"; }
};
class triangle : public shape {
 public:
  void draw() override { std::cout << "triangle\n" ; }
};
class right_triangle : public triangle {
 public:
  void draw() override { std::cout << "R triangle\n"; }
};
```

- We want to specialize `draw()`
- Depending on the subtype
- Make draw `virtual`
- `virtual` functions can be overridden
  - That is called specialization
- Be smart
  - Use `override` to denote specialized functions
  - Not using `override` is dangerous
- Make the destructor `virtual` too

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Polymorphism

- Why is it useful to specialize functions (override them)?
- Doesn't this result in?

class / struct | class / struct | class / struct ...

- No!
- Because
  - We have specialized the `draw()` implementation
  - We achieved polymorphism
    - Types in that type hierarchy behave polymorphic
    - Example: `circle` type
      - `circle` has type `circle`, but also type `shape` (since it inherits from `shape`)

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Polymorphism

```cpp
#include <iostream>

void print_shape(const shape& s) {
  s.draw();
}

int main() {
  circle c;
  right_triangle rt;
  print_shape(c);
  print_shape(rt);
  return 0;
}
```

```cpp
class shape {
 public:
  virtual ~shape() = default;
  virtual void draw() { std::cout << "shape\n"; }
};
class circle : public shape {
 public:
  void draw() override { std::cout << "circle\n"; }
};
class rectangle : public shape {
 public:
  void draw() override { std::cout << "rectangle\n"; }
};
class triangle : public shape {
 public:
  virtual void draw() override { std::cout << "triangle\n"; }
};
class right_triangle : public triangle {
 public:
  void draw() override { std::cout << "R triangle\n"; }
};
```


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Caution: need for virtual destructors

If a C++ type is meant to be used polymorphically its destructor has to be declared virtual.
Otherwise, if the static type of an object to be deleted differs from its dynamic type, the behavior is undefined.

```
class shape {
 public:
  virtual ~shape() = default;
  virtual void draw() { std::cout << "shape\n"; }
};
```

- Example

```
int main() {
  shape *s = new circle;
  s->draw();
  delete s;
  return 0;
};
```


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Polymorphism

```
#include <iostream>
void print_shape(const shape& s) {
  s.draw();
}
void print_triangle(
    const triangle& t) {
  t.draw();
}

int main() {
  circle c;
  right_triangle rt;
  print_shape(c);
  print_triangle(rt);
  return 0;
}
```

- `print_shape()` accepts a shape and any of its subtypes
- `print_triangle()` accepts a triangle and any of its subtypes
- Note that we pass by reference!
- Such behavior is only possible when passing by

  A. Reference

  B. Pointer

  - Why not by value?

    ```
    void print_shape(shape s) {
      s.draw();
    }
    ```

    - Accepts a shape?
    - Yes, but creates a copy of a shape which is of type shape!
    - Passing any subtype results in passing a shape
    - Would print “shape” every time

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Polymorphism

- Example using smart pointers

```
#include <iostream>
#include <memory>
#include <random>
struct shape {
 virtual ~shape() = default;
 virtual void draw() { std::cout << "shape\n"; }
};
struct rectangle : shape {
 void draw() override { std::cout << "rectangle\n"; }
};
struct circle : shape {
 void draw() override { std::cout << "circle\n"; }
};

void print_shape(shared_ptr<shape> s) {
 s->draw();
}
```

```
std::vector<std::shared_ptr<shape>> rand_shapes(size_t n) {
  std::vector<std::shared_ptr<shape>> shapes;
  std::mt19937 rng(1);
  std::uniform_int_distribution<int> gen(0, 2);
  while (n--) {
    switch (gen(rng)) {
    case 0: shapes.push_back(std::make_shared<shape>()); break;
    case 1: shapes.push_back(std::make_shared<rectangle>()); break;
    case 2: shapes.push_back(std::make_shared<circle>()); break;
    }
  }
  return shapes;
}
```

```
int main() {
  auto shapes = rand_shapes(10);
  for (auto shape : shapes){
    print_shape(shape);
  }
  return 0;
}
```


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Static polymorphism versus dynamic polymorphism

- Static binding (at compile time)

```
struct shape {
  void draw() { std::cout << "shape\n"; }
};
struct rectangle {
  void draw() { std::cout << "rectangle\n"; }
};
void print_shape(const shape &s) {
  s.draw(); // binds statically
}
void print_shape(const rectangle &s) {
  s.draw(); // binds statically
}
int main() {
  shape s;
  rectangle r;
  print_shape(s);
  print_shape(r);
   return 0;
}
```

Compiler will generate two versions of `print_shape`

Compiler applies name mangling

- Dynamic binding (at runtime)

```
struct shape {
  virtual ~shape() = default;
  virtual void draw() {
    std::cout << "shape\n";
  }
};
struct rectangle : shape {
  void draw() override {
    std::cout << "rectangle\n";
  }
};
void print_shape(const shape& s) {
  s.draw(); // cannot bind statically
}
int main() {
  shape s;
  rectangle r;
  print_shape(s);
  print_shape(r);
  return 0;
}
```

Only one `print_shape` function will be generated

Uses dynamic dispatch

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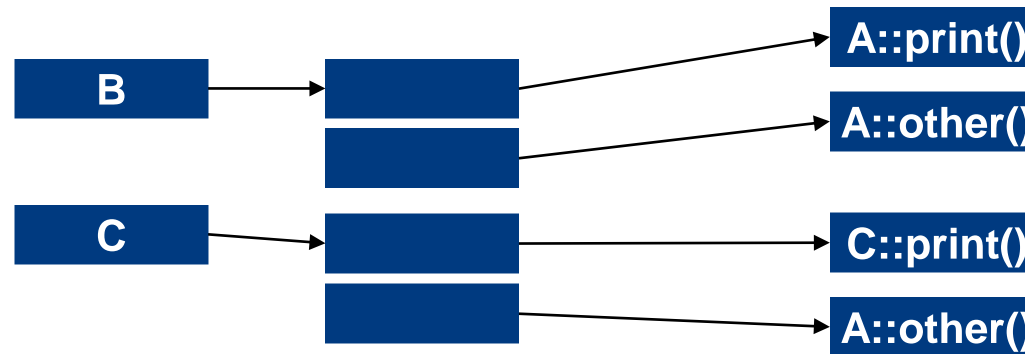
Virtual function table (vtable)




```
#include <iostream>
struct A {
  virtual ~A() = default;
  virtual void print() { std::cout << "A\n"; }
  virtual void other() { std::cout << "other\n"; }
};
struct B : A {};
struct C : A {
  void print() override { std::cout << "C\n"; }
};
// How can call_print() choose the right print()
// function?
// size and layout of B and C is unkown to
// call_print()!
void call_print(A& a) {
  a.print();
}
```

- `A` has virtual functions
- Use virtual function table (aka vtable or vtbl)

```
int main() {
  B b;
  C c;
  call_print(b);
  call_print(c);
  return 0;
}
```

- `call_print()` only needs to follow vtbl pointer
- An index is used for each virtual function
- Efficiency compared to normal function call:
  - Time: within 25%, but in reality much faster
  - Space: one pointer to vtabl per variable + one vtabl per type

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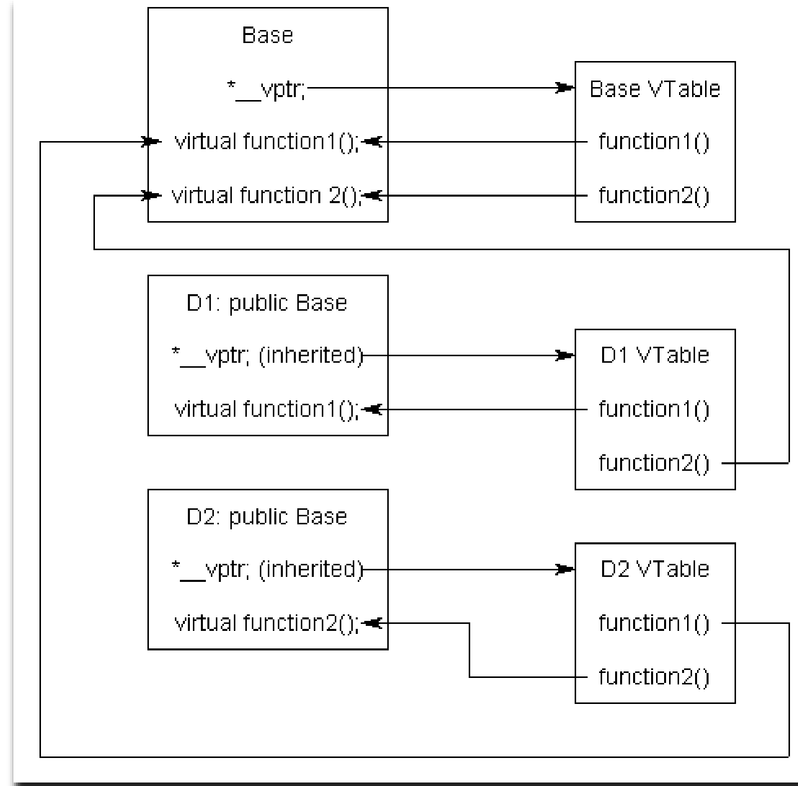
Virtual function table (Idea)

```
class Base {
 public:
  virtual ~Base() = default;
  virtual void function1() {};
  virtual void function2() {};
};

class D1: public Base {
 public:
  void function1() override {};
};

class D2: public Base {
 public:
  void function2() override {};
};
```




```
class Base {
 public:
  FunctionPointer *__vptr;
  virtual void function1() {};
  virtual void function2() {};
};

class D1: public Base {
 public:
  void function1() override {};
};
class D2: public Base {
 public:
  void function2() override {};
};
```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Special case: interfaces

- Abstract classes / structs
  - Miss one or more function implementation
  - Cannot be instantiated
    - Why? Because an interface is an abstract class with missing function definitions!
  - Why is there a need for interfaces?
  - Example
    - A bird might quack
    - But it is not useful to inherit from base class “quacker”
    - Make it an interface!
      - A duck might inherit from bird
        - And additionally implement the quack interface
- An interface specifies what needs to be implemented

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Special case: interfaces

```
#include <iostream>
class bird {
 public:
  virtual ~bird() = default;
  virtual void fly() { std::cout << "fly\n"; }
};
class quack {
 public:
  virtual ~quack() = default;
  //provide no implementation
  virtual void do_quack() = 0;
};
class duck : public bird, public quack {
 public:
  void quack() override { std::cout << "quack, quack!\n";}
};
```

```
int main() {
  duck d;
  d.fly();
  d.do_quack();
  // the following line does not work
  quack q; // cannot instantiate abstract class!
  return 0;
}
```


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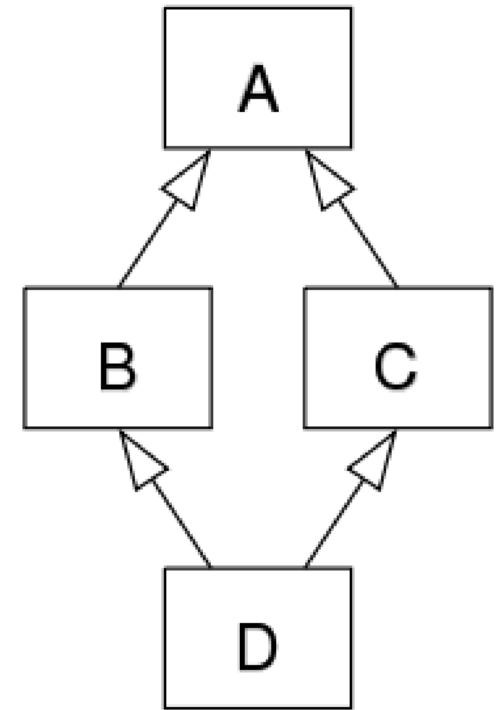
Multiple inheritance



- More than one parent is possible
  - This is quite useful sometimes
- Some languages such as Java do not support that, considered to be dangerous
  - “Deadly diamond of death” (diamond problem)

```
#include <iostream>
struct A {
  virtual ~A() = default;
  virtual void print() { std::cout << "A\n"; } };
struct B : A { void print() override { std::cout << "B\n"; } };
struct C : A { void print() override { std::cout << "C\n"; } };
struct D : B, C {};
int main() {
    D d;
    d.print();
    return 0;
}
```

- What `print()` should be called?
- C++ warns you when this happens
- Problem can be mitigated
  - Use virtual inheritance or override `print()` in `D` to manually direct the call

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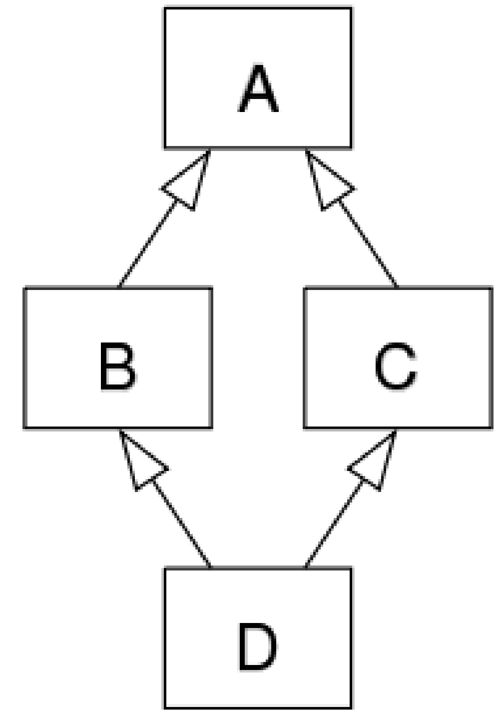
Multiple inheritance

- “Deadly diamond of death” (diamond problem) → fixed

```
#include <iostream>
struct A {
  virtual ~A() = default;
  virtual void print() { std::cout << "A\n"; } };
struct B : A { void print() override { std::cout << "B\n"; } };
struct C : A { void print() override { std::cout << "C\n"; } };
struct D : B, C {
  void print() override { B::print(); }
};
int main() {
  D d;
  d.print();
  return 0;
}
```



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Nice talks about OOP

- “Intro to the C++ Object Model”, by Richard Powell (CppCon 2015)
  - https://www.youtube.com/watch?v=iLiDezv_Frk
- An excellent, more general talk “SOLID Principles of Object Oriented & Agile Design”, by “Uncle Bob” Robert Martin (Yale school of management 2014)
  - https://www.youtube.com/watch?v=TMuno5RZNeE

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Thank you for your attention
Questions?