COMP6771 Week 9.1

Runtime Polymorphism

Key concepts

- **Inheritance:** ability to create new classes based on existing ones
  - Supported by class derivation
- **Polymorphism:** allows objects of a subclass to be used as if they were objects of a base class
  - Supported via virtual functions
- **Dynamic binding:** run-time resolution of the appropriate function to invoke based on the type of the object
  - Closely related to polymorphism
  - Supported via virtual functions

Thinking about programming

- Represent concepts with classes
- Represent relations with inheritance or composition
  - **Inheritance:** A is also a B, and can do everything B does
    - "is a" relationship
    - A dog **is an** animal
  - **Composition (data member):** A contains a B, but isn't a B itself
    - "has a" relationship
    - A person **has a** name
  - Choose the right one!

Protected members

- Protected is a keyword we can use instead of public / private
- Protected members are accessible only to the class, or any subclass of it

Inheritance in C++

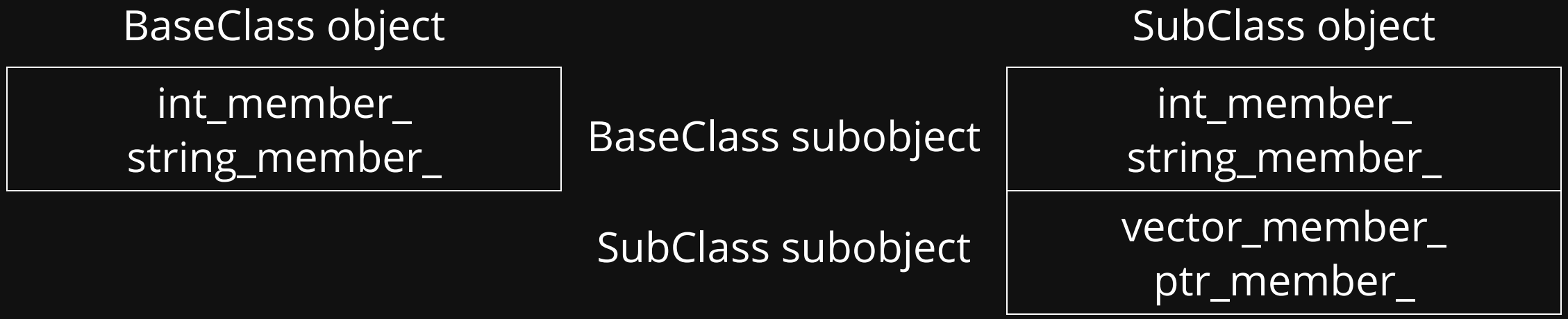
- To inherit off classes in C++, we use "class DerivedClass: public BaseClass"
- Visibility can be one of:
  - **public** (generally use this unless you have good reason not to)
    - If you don't want public, you should (usually) use composition
  - **protected**
  - **private**
- Visibility is the maximum visibility allowed
  - If you specify ": private BaseClass", then the maximum visibility is private
    - Any BaseClass members that were public or protected are now private

Tenets of C++

- Don't pay for what you don't use
  - C++ Supports OOP
    - No runtime performance penalty
  - C++ supports generic programming with the STL and templates
    - No runtime performance penalty
  - Polymorphism is extremely powerful, and we need it in C++
    - Do we need polymorphism at all when using inheritance?
      - Answer: sometimes
      - But how do we do so, considering that we don't want to make anyone who doesn't use it pay a performance penalty

Inheritance and memory layout

This is very important, as it guides the design of everything we discuss this week




```cpp
class BaseClass {
 public:
  int GetIntMember() { return int_member_; }
  std::string GetClassName() {
    return "BaseClass"
  };

 private:
  int int_member_;
  std::string string_member_;
}
```

```cpp
class SubClass: public BaseClass {
 public:
  std::string GetClassName() {
    return "SubClass";
  }

 private:
  std::vector<int> vector_member_;
  int* ptr_member_;
}
```

Inheritance and constructors

- Every subclass constructor must call a base class constructor
  - If none is manually called, the default constructor is used
  - A subclass cannot initialise fields defined in the base class
  - Abstract classes must have constructors

```
1  class BaseClass {
2   public:
3    BaseClass(int member): int_member_{member} {}
4
5   private:
6    int int_member_;
7    std::string string_member_;
8  }
9
10 class SubClass: public BaseClass {
11  public:
12   SubClass(int member, int* ptr): BaseClass{member}, ptr_member_{ptr} {}
13   // Won't compile.
14   SubClass(int member, int* ptr): int_member_{member}, ptr_member_{ptr} {}
15
16  private:
17   std::vector<int> vector_member_;
18   int* ptr_member_;
19 }
```

Polymorphism and values

- How many bytes is a BaseClass instance?
- How many bytes is a SubClass instance?
- One of the guiding principles of C++ is "You don't pay for what you don't use"
  - Let's discuss the following code, but pay great consideration to the memory layout

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_;
4    std::string GetClassName() {
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1  void PrintClassName(BaseClass base_class) {
2    std::cout << base_class.GetClassName()
3              << '\n';
4  }
5
6  int main() {
7    BaseClass base_class;
8    SubClass subclass;
9    PrintClassName(base_class);
10   PrintClassName(subclass);
11 }
```

```
1  class SubClass: public BaseClass {
2   public:
3    std::string GetClassName() {
4      return "SubClass";
5    }
6
7   private:
8    int subclass_data_;
9  }
```

The object slicing problem

- If you declare a BaseClass variable, how big is it?
- How can the compiler allocate space for it on the stack, when it doesn't know how big it could be?
- The solution: since we care about performance, a BaseClass can only store a BaseClass, not a SubClass
  - If we try to fill that value with a SubClass, then it just fills it with the BaseClass subobject, and drops the SubClass subobject

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_;
4    std::string GetClassName() {
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1  void PrintClassName(BaseClass base_class) {
2    std::cout << base_class.GetClassName()
3              << '\n';
4  }
5
6  int main() {
7    BaseClass base_class;
8    SubClass subclass;
9    PrintClassName(base_class);
10   PrintClassName(subclass);
11 }
```

```
1  class SubClass: public BaseClass {
2   public:
3    std::string GetClassName() {
4      return "SubClass";
5    }
6
7   private:
8    int subclass_data_;
9  }
```

Polymorphism and References

- How big is a reference/pointer to a BaseClass
- How big is a reference/pointer to a SubClass
- Object slicing problem solved (but still another problem)
- One of the guiding principles of C++ is "You don't pay for what you don't use"
  - How does the compiler decide which version of GetClassName to call?
    - When does the compiler decide this? Compile or runtime?
  - How can it ensure that calling GetMember doesn't have similar overhead

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_;
4    std::string GetClassName() {
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1  void PrintClassName(
2      const BaseClass& base_class) {
3    std::cout << base_class.GetClassName()
4        << ' ' << base_class.GetMember()
5        << '\n';
6  }
7
8  int main() {
9    BaseClass base_class;
10   SubClass subclass;
11   PrintClassName(base_class);
12   PrintClassName(subclass);
13 }
```

```
1  class SubClass: public BaseClass {
2   public:
3    std::string GetClassName() {
4      return "SubClass";
5    }
6
7   private:
8    int subclass_data_;
9  }
```

Virtual functions

- How does the compiler decide which version of GetClassName to call?
- How can it ensure that calling GetMember doesn't have similar overhead
  - Explicitly tell the compiler that GetClassName is a function designed to be modified by subclasses
  - Use the keyword "virtual" in the base class
  - Use the keyword "override" in the subclass

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_; }
4    virtual std::string GetClassName()
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1  void PrintClassName(
2      const BaseClass& base_class) {
3    std::cout << base_class.GetClassName()
4        << ' ' << base_class.GetMember()
5        << '\n';
6  }
7
8  int main() {
9    BaseClass base_class;
10   SubClass subclass;
11   PrintClassName(base_class);
12   PrintClassName(subclass);
13 }
```

```
1  class SubClass: public BaseClass {
2   public:
3    std::string GetClassName() override
4      return "SubClass";
5    }
6
7   private:
8    int subclass_data_;
9  }
```

Override

- While override isn't required by the compiler, you should **always** use it
- Override fails to compile if the function doesn't exist in the base class. This helps with:
  - Typos
  - Refactoring
  - Const / non-const methods
  - Slightly different signatures

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_; }
4    virtual std::string GetClassName() {
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1  class SubClass: public BaseClass {
2   public:
3    // This compiles. But this is a
4    // different function to the
5    // BaseClass GetClassName.
6    std::string GetClassName() const {
7      return "SubClass";
8    }
9
10  private:
11   int subclass_data_;
12 }
```

Virtual functions

```
1  class BaseClass {
2   public:
3    virtual std::string GetClassName() {
4      return "BaseClass"
5    };
6
7   ~BaseClass() {
8     std::cout << "Destructing base class\n";
9   }
10 }
11
12 class SubClass: public BaseClass {
13  public:
14   std::string GetClassName() override {
15     return "SubClass";
16   }
17
18  ~SubClass() {
19    std::cout << "Destructing subclass\n";
20  }
21 }
```

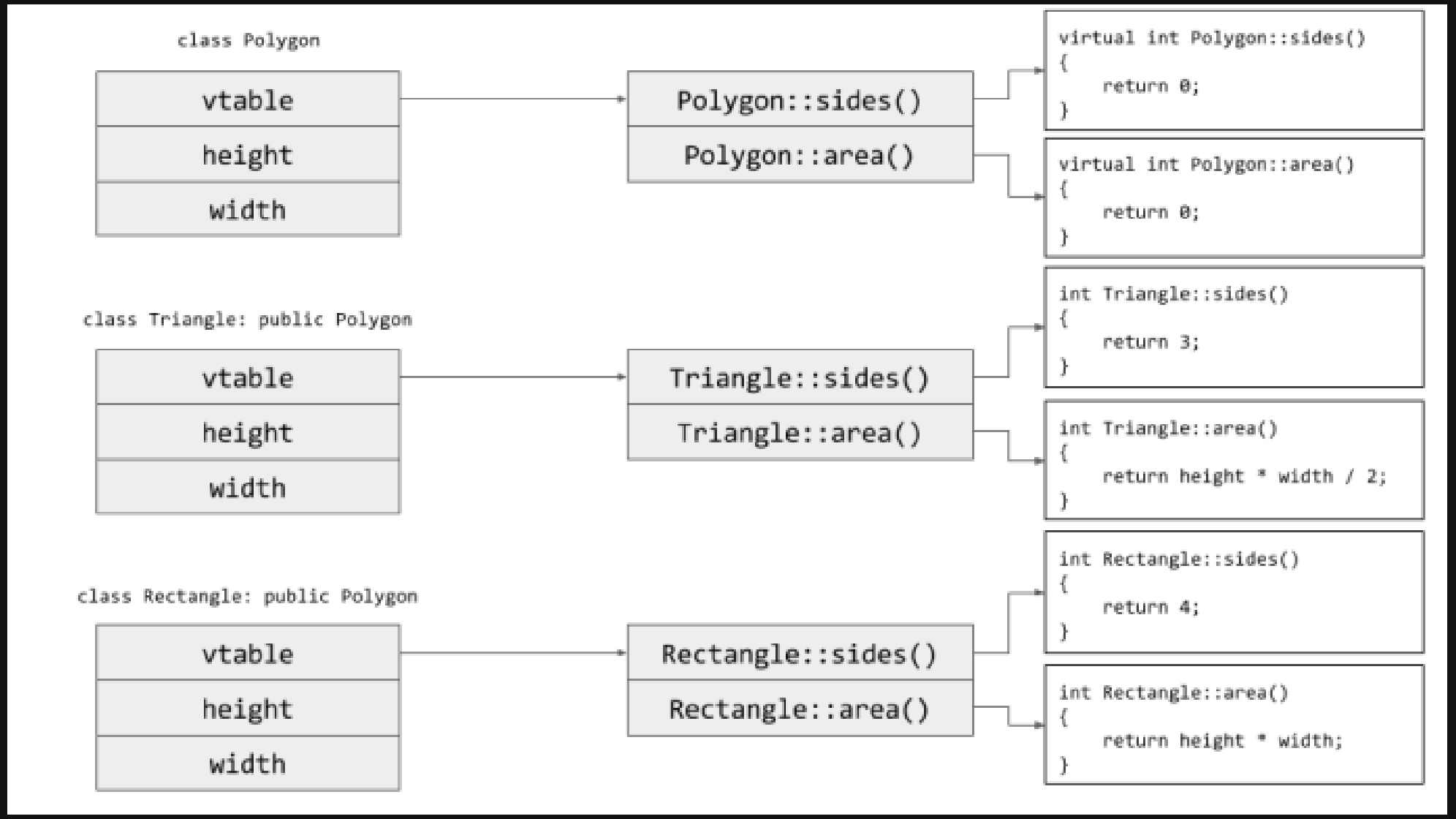
- What do we expect to see?
- What do we actually see?

```
1  void PrintClassName(
2      const BaseClass& base_class) {
3    std::cout << base_class.GetClassName()
4        << ' ' << base_class.GetMember()
5        << '\n';
6  }
7
8  int main() {
9    std::unique_ptr<BaseClass> subclass{
10     std::make_unique<SubClass>()};
11   std::cout << subclass->GetClassName();
12 }
```

VTables

- Each class has a VTable stored in the data segment
  - A vtable is an array of function pointers that says which definition each virtual function points to for that class
- If the VTable for a class is non-empty, then every member of that class has an additional data member that is a pointer to the vtable
- When a virtual function is called **on a reference or pointer type**, then the program actually does the following
  1. Follow the vtable pointer to get to the vtable
  2. Increment by an offset, which is a constant for each function
  3. Follow the function pointer at vtable[offset] and call the function

VTable example



Final

- Specifies to the compiler "this is not virtual for any subclasses"
- If the compiler has a variable of type SubClass&, it now no longer needs to look it up in the vtable
- This means static binding if you have a SubClass&, but dynamic binding for BaseClass&

```
1  class BaseClass {
2   public:
3    int GetMember() { return member_; }
4    virtual std::string GetClassName() {
5      return "BaseClass"
6    };
7
8   private:
9    int member_;
10 }
```

```
1 class SubClass: public BaseClass {
2  public:
3   std::string GetClassName() override final {
4     return "SubClass";
5   }
6
7  private:
8   int subclass_data_;
9 }
```

Abstract Base Classes (ABCs)

- Might want to deal with a base class, but the base class by itself is nonsense
  - What is the default way to draw a shape? How many sides by default?
  - A function takes in a "Clickable"
- Might want some default behaviour and data, but need others
  - All files have a name, but are reads done over the network or from a disk
- If a class has at least one "abstract" (pure virtual in C++) method, the class is abstract and cannot be constructed
  - It can, however, have constructors and destructors
  - These provide semantics for constructing and destructing the ABC subobject of any derived classes

Pure virtual functions

- Virtual functions are good for when you have a default implementation that subclasses may want to overwrite
- Sometimes there is no default available
- A pure virtual function specifies a function that a class **must** override in order to not be abstract

```
1  class Shape {
2    // Your derived class "Circle" may forget to write this.
3    virtual void draw(Canvas&) {}
4
5    // Fails at link time because there's no definition.
6    virtual void draw(Canvas&);
7
8    // Pure virtual function.
9    virtual void draw(Canvas&) = 0;
10 };
```

Creating polymorphic objects

- In a language like Java, everything is a pointer
  - This allows for code like on the left
  - Not possible in C++ due to objects being stored inline
- If you want to store a polymorphic object, use a pointer

```
1 // Java-style C++ here
2 // Don't do this.
3
4 std::vector<BaseClass> base;
5 base.push_back(BaseClass{});
6 base.push_back(SubClass1{});
7 base.push_back(SubClass2{});
```

```
1 // Good C++ code
2 // But there's a potential problem here.
3 // (*very* hard to spot)
4
5 std::vector<std::unique_ptr<BaseClass>> base;
6 base.push_back(std::make_unique<BaseClass>());
7 base.push_back(std::make_unique<Subclass1>());
8 base.push_back(std::make_unique<Subclass2>());
```

Destructing polymorphic objects

- Which constructor is called?
- Which destructor is called?
- What could the problem be?
  - What would the consequences be?
- How might we fix it, using the techniques we've already learnt?

```
1 // Simplification of previous slides code.
2
3 std::unique_ptr<BaseClass> base = std::make_unique<BaseClass>();
4 std::unique_ptr<BaseClass> base = std::make_unique<Subclass>();
```

Destructing polymorphic objects

- Whenever you write a class intended to be inherited from, **always** make your destructor virtual
- Remember: When you declare a destructor, the move constructor and assignment are not synthesized

```
1 class BaseClass {
2   BaseClass(BaseClass&&) = default;
3   BaseClass& operator=(BaseClass&&) = default;
4   virtual ~BaseClass() = default;
5 }
```

Forgetting this can be a hard bug to spot

Static and dynamic types

- Static type is the type it is declared as
- Dynamic type is the type of the object itself
- Static means compile-time, and dynamic means runtime
  - Due to object slicing, an object that is neither reference or pointer **always** has the same static and dynamic type

Quiz - What's the static and dynamic types of each of these?

```
1  int main() {
2    BaseClass base_class;
3    SubClass subclass;
4    BaseClass sub_copy{subclass};
5    // The following could all be replaced with pointers
6    // and have the same effect.
7    const BaseClass& base_to_base{base_class};
8    const BaseClass& base_to_sub{subclass};
9    // Fails to compile
10   const SubClass& sub_to_base{base_class};
11   const SubClass& sub_to_sub{subclass};
12   // Fails to compile (even though it refers to at a sub);
13   const SubClass& sub_to_base_to_sub{base_to_sub};
14 }
```

Static and dynamic binding

- Static binding: Decide which function to call at compile time (based on static type)
- Dynamic binding: Decide which function to call at runtime (based on dynamic type)
- C++
  - Statically typed (types are calculated at compile time)
  - Static binding for non-virtual functions
  - Dynamic binding for virtual functions
- Java
  - Statically typed
  - Dynamic binding

Up-casting

- Casting from a derived class to a base class is called up-casting
- This cast is always safe
  - All dogs are animals

```
1 Dog dog;
2
3 // Up-cast with references.
4 Animal& animal{dog};
5 // Up-cast with pointers.
6 Animal* animal{&dog};
7
8 // What's this (hint: not an up-cast)?
9 Animal animal{dog};
```

Down-casting

- Casting from a base class to a derived class is called down-casting
- This cast is not safe
  - Not all animals are dogs

```
1  Dog dog;
2  Cat cat;
3  Animal& animal_dog{dog};
4  Animal& animal_cat{cat};
5
6  // Attempt to down-cast with references.
7  // Neither of these compile.
8  // Why not?
9  Dog& dog_ref{animal_dog};
10 Dog& dog_ref{animal_cat};
```

How to down cast

- The compiler doesn't know if an Animal happens to be a Dog
  - If you **know** it is, you can use **static_cast**
  - Otherwise, you can use **dynamic_cast**
    - Returns null pointer for pointer types if it doesn't match
    - Throws exceptions for reference types if it doesn't match

```
1  Dog dog;
2  Cat cat;
3  Animal& animal_dog{dog};
4  Animal& animal_cat{cat};
5
6  // Attempt to down-cast with references.
7  Dog& dog_ref{static_cast<Dog&>(animal_dog)};
8  Dog& dog_ref{dynamic_cast<Dog&>(animal_dog)};
9  // Undefined behaviour (incorrect static cast).
10 Dog& dog_ref{static_cast<Dog&>(animal_cat)};
11 // Throws exception
12 Dog& dog_ref{dynamic_cast<Dog&>(animal_cat)};
```

```
1  Dog dog;
2  Cat cat;
3  Animal& animal_dog{dog};
4  Animal& animal_cat{cat};
5
6  // Attempt to down-cast with pointers.
7  Dog* dog_ref{static_cast<Dog*>(animal_dog)};
8  Dog* dog_ref{dynamic_cast<Dog*>(animal_dog)};
9  // Undefined behaviour (incorrect static cast).
10 Dog* dog_ref{static_cast<Dog*>(animal_cat)};
11 // returns null pointer
12 Dog* dog_ref{dynamic_cast<Dog*>(animal_cat)};
```

Types of functions

Syntax	Name	Meaning
virtual void fn() = 0;	pure virtual	Inherit interface only
virtual void fn() {}	virtual	Inherit interface with optional implementation
void fn() {}	nonvirtual	Inherit interface and mandatory implementation

Note: nonvirtuals can be hidden by writing a function with the same name in a subclass

DO NOT DO THIS

Covariants

- If a function overrides a base, which type can it return?
  - If a base specifies that it returns a LandAnimal, a derived also needs to return a LandAnimal
- Every possible return type for the derived must be a valid return type for the base

```
1  class Base {
2    virtual LandAnimal& GetFavoriteAnimal();
3  };
4
5  class Derived: public Base {
6    // Fails to compile: Not all animals are land animals.
7    Animal& GetFavoriteAnimal() override;
8    // Compiles: All land animals are land animals.
9    LandAnimal& GetFavoriteAnimal() override;
10   // Compiles: All dogs are land animals.
11   Dog& GetFavoriteAnimal() override;
12 };
```

Contravariants

- If a function overrides a base, which types can it take in?
  - If a base specifies that it takes in a LandAnimal, a LandAnimal must always be valid input in the derived
- Every possible parameter to the base must be a possible parameter for the derived

```
1  class Base {
2    virtual void UseAnimal(LandAnimal&);
3  };
4
5  class Derived: public Base {
6    // Compiles: All land animals are valid input (animals).
7    void UseAnimal(Animal&) override;
8    // Compiles: All land animals are valid input (land animals).
9    void UseAnimal(LandAnimal&) override;
10   // Fails to compile: Not All land animals are valid input (dogs).
11   void UseAnimal(Dog&) override;
12 };
```

Default arguments and virtuals

- Default arguments are determined at compile time for efficiency's sake
- Hence, default arguments need to use the **static** type of the function
- Avoid default arguments when overriding virtual functions

```
1  class Base {
2    virtual void PrintNum(int i = 1) {
3      std::cout << "Base " << i << '\n';
4    }
5  };
6
7  class Derived: public Base {
8    void PrintNum(int i = 2) override {
9      std::cout << "Derived " << i << '\n';
10   }
11 };
12
13 int main() {
14   Derived derived;
15   Base& base;
16   derived.PrintNum(); // Prints "Derived 2"
17   base->PrintNum(); // Prints "Derived 1"
18 }
```

Construction of derived classes

- Base classes are always constructed before the derived class is constructed
  - The base class is never dependent on the derived class
  - The derived may be dependent on the base

```
1  class Animal {...}
2  class LandAnimal: public Animal {...}
3  class Dog: public LandAnimals {...}
4
5  Dog d;
6
7  // Dog() calls LandAnimal()
8    // LandAnimal() calls Animal()
9      // Animal members constructed using initialiser list
10     // Animal constructor body runs
11   // LandAnimal members constructed using initialiser list
12   // LandAnimal constructor body runs
13 // Dog members constructed using initialiser list
14 // Dog constructor body runs
```

Virtuals in constructors

If a class is not fully constructed, cannot perform dynamic binding

```
1  class Animal {...};
2  class LandAnimal: public Animal {
3    LandAnimal() {
4      Run();
5    }
6
7    virtual void Run() {
8      std::cout << "Land animal running\n";
9    }
10 };
11 class Dog: public LandAnimals {
12   void Run() override {
13     std::cout << "Dog running\n";
14   }
15 };
16
17 // When the LandAnimal constructor is being called,
18 // the Dog part of the object has not been created yet.
19 // C++ chooses to not allow dynamic binding in constructors
20 // because Dog::Run() might depend upon Dog's members.
21 Dog d;
```

Destruction of derived classes

- Easy to remember order: Always opposite to construction order

```
1  class Animal {...}
2  class LandAnimal: public Animal {...}
3  class Dog: public LandAnimals {...}
4
5  Dog d;
6
7  // ~Dog() destructor body runs
8  // Dog members destructed in reverse order of declaration
9  // ~LandAnimal() destructor body runs
10 // LandAnimal members destructed in reverse order of declaration
11 // ~Animal() destructor body runs
12 // Animal members destructed in reverse order of declaration.
```

Virtuals in destructors

- If a class is partially destructed, cannot perform dynamic binding
- Unrelated to the destructor itself being virtual

```
1  class Animal {...};
2  class LandAnimal: public Animal {
3    virtual ~LandAnimal() {
4      Run();
5    }
6
7    virtual void Run() {
8      std::cout << "Land animal running\n";
9    }
10 };
11 class Dog: public LandAnimals {
12   void Run() override {
13     std::cout << "Dog running\n";
14   }
15 };
16
17 // When the LandAnimal constructor is being called,
18 // the Dog part of the object has already been destroyed.
19 // C++ chooses to not allow dynamic binding in destructors
20 // because Dog::Run() might depend upon Dog's members.
21 Dog d;
```