Creative Software Design

10 – Polymorphism 2

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Today's Topics

- Behind Virtual Functions
- Pure Virtual Function
- The Practical Power of Polymorphism
- Some Issues about Virtual Functions
- Abstract Class / Pure Abstract Class
- Type Casting Operators

Review: Virtual Functions

- Virtual functions are keys to implement polymorphism in C++.
  - declare polymorphic member functions to be 'virtual',
  - and use the base class pointer / reference to refer an instance of the derived class,
  - then the function call from a base class pointer / reference will execute the function overridden in the derived class.

CSStudent Example with Virtual Functions

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

class Person
{
public:
    virtual void talk()
    {
        cout << "I'm a person" << endl;
    }
};

class Student : public Person
{
public:
    virtual void talk()
    {
        cout << "I'm a student" << endl;
    }
    void study()
    {
        cout << "study" << endl;
    }
};
```

```
class CSStudent : public Student
{
public:
    virtual void talk()
    {
        cout << "I'm a CS student" <<
endl;
    }
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};

int main()
{
    CSStudent csst;
    csst.talk(); //"I'm a CS student"

    Person& asPerson = csst;
    asPerson.talk(); //"I'm a CS student"

    return 0;
}
```

CSStudent Example w/o Virtual Functions

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

class Person
{
public:
    void talk()
    {
        cout << "I'm a person" << endl;
    }
};

class Student : public Person
{
public:
    void talk()
    {
        cout << "I'm a student" << endl;
    }
    void study()
    {
        cout << "study" << endl;
    }
};
```

```
class CSStudent : public Student
{
public:
    void talk()
    {
        cout << "I'm a CS student" <<
endl;
    }
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};

int main()
{
    CSStudent csst;
    csst.talk(); //"I'm a CS student"

    Person& asPerson = csst;
    asPerson.talk(); //"I'm a person"

    return 0;
}
```

Behind Virtual Functions

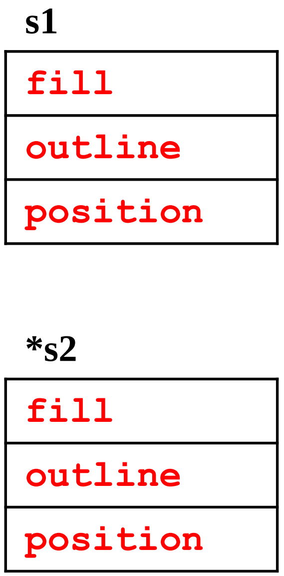
- How do virtual functions work internally in C++?
- → It depends on complier implementation. The C++ standard only specifies the behavior of virtual functions.

- But most compilers use *virtual method table* (a.k.a. ***vtable***) mechanism.

Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    double getArea();
    double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};
```

```
int main()
{
    Shape s1;
    Shape* s2 = new Shape;
    delete s2;
    return 0;
}
```



Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    double getArea();
    double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};
```

```
int main()
{
    Shape s1;
    Shape* s2 = new Shape;
    double a = s2->getArea();
    delete s2;
    return 0;
}
```

s1

fill
outline
position

***s2**

fill
outline
position

`double a = s2->getArea();` jumps to `Shape::getArea()` (in code segment)

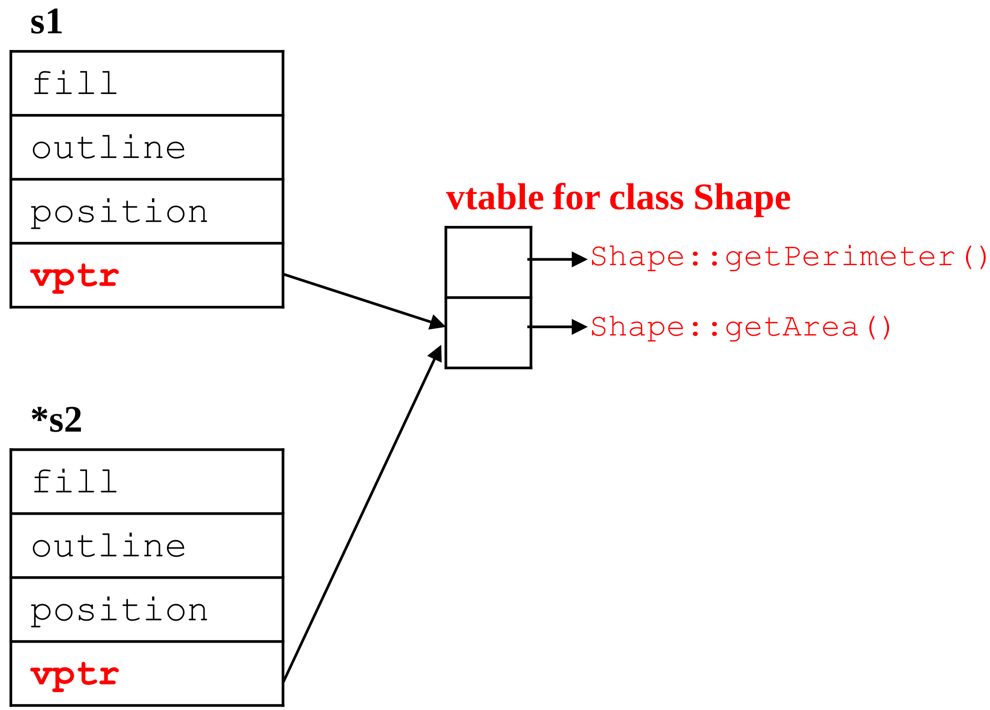
Static binding

- Compiler generates code to call (jump to the address of) **Shape::getArea()** directly.

Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};
```

```
int main()
{
    Shape s1;
    Shape* s2 = new Shape;
    delete s2;
    return 0;
}
```

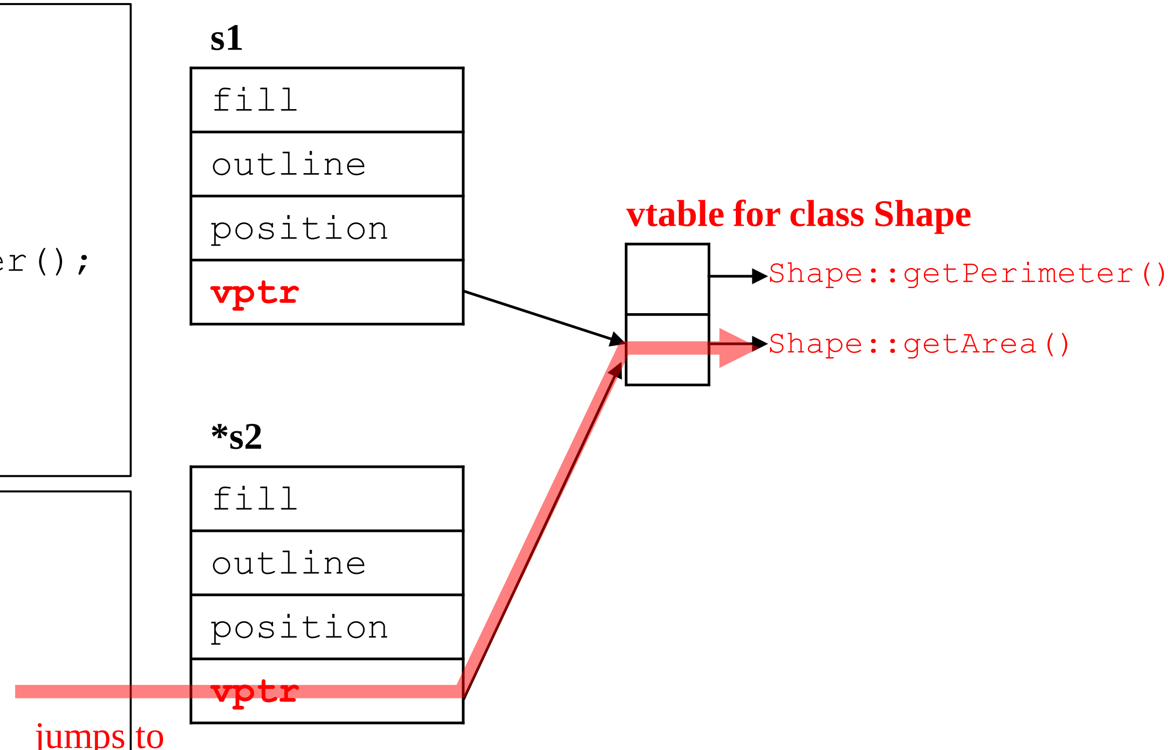


- ***vtable*** is a lookup table that contains the addresses of the object's dynamically bound virtual functions.
- ***vtable*** is created only for **classes with at least one virtual function.**
- ***vptr*** is created as a "hidden" member of **each instance of these classes** and initialized to point to the ***vtable*** **of the actual type of the instance.**

Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};
```

```
int main()
{
    Shape s1;
    Shape* s2 = new Shape;
    double a = s2->getArea();
    delete s2;
    return 0;
}
```



Dynamic binding

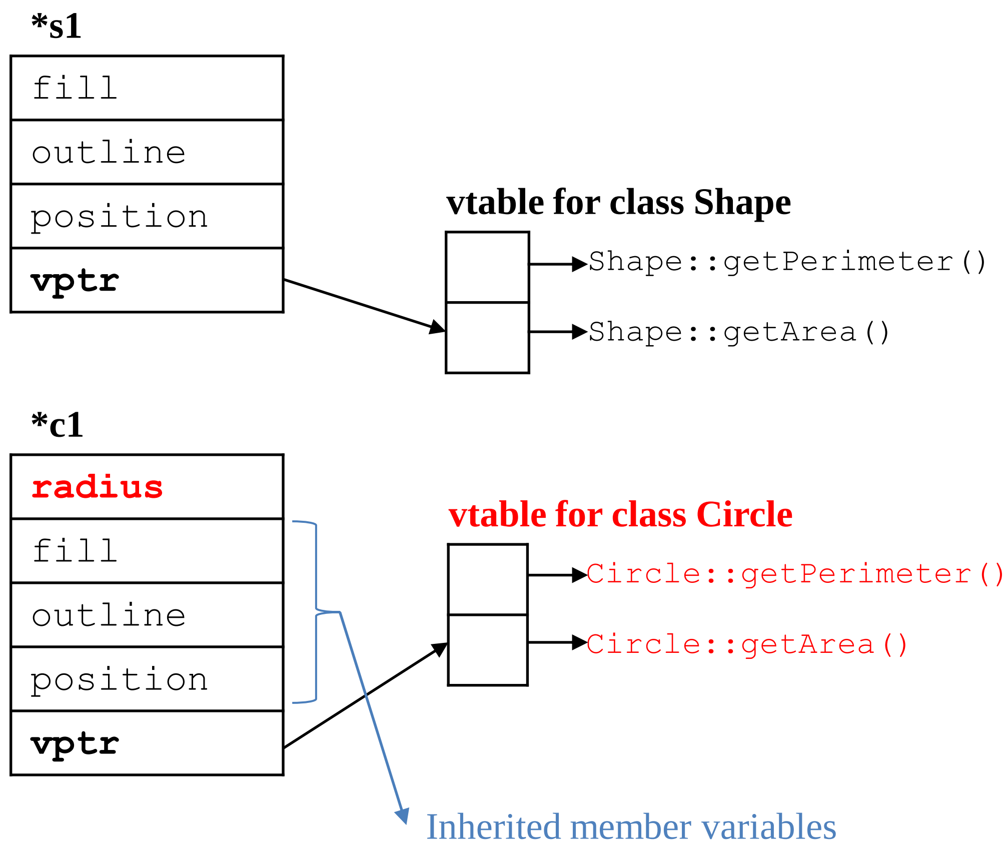
- Compiler generates code to call (jump to) **the 'getArea' entry** (index 0 in this example) **of the vtable through the vptr**.

Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};

class Circle: public Shape
{
public:
    Circle(double r);
    virtual double getArea();
    double getPerimeter();
private:
    double radius;
};
```

```
int main()
{
    Shape* s1 = new Shape;
    Shape* c1 = new Circle;
    return 0;
}
```

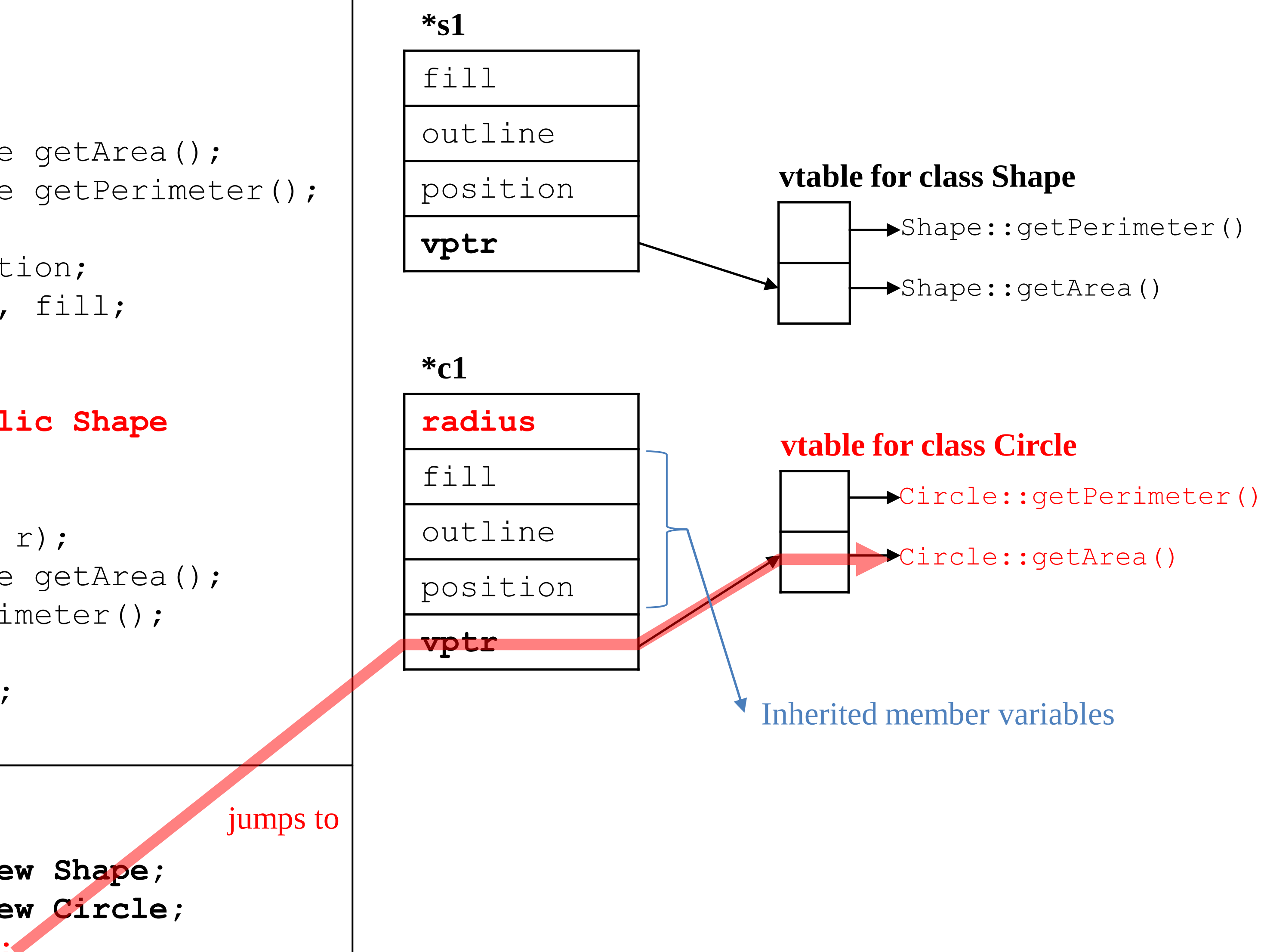


Memory Layout of C++ Object

```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};

class Circle: public Shape
{
public:
    Circle(double r);
    virtual double getArea();
    double getPerimeter();
private:
    double radius;
};
```

```
int main()
{
    Shape* s1 = new Shape;
    Shape* c1 = new Circle;
    c1->getArea();
    return 0;
```

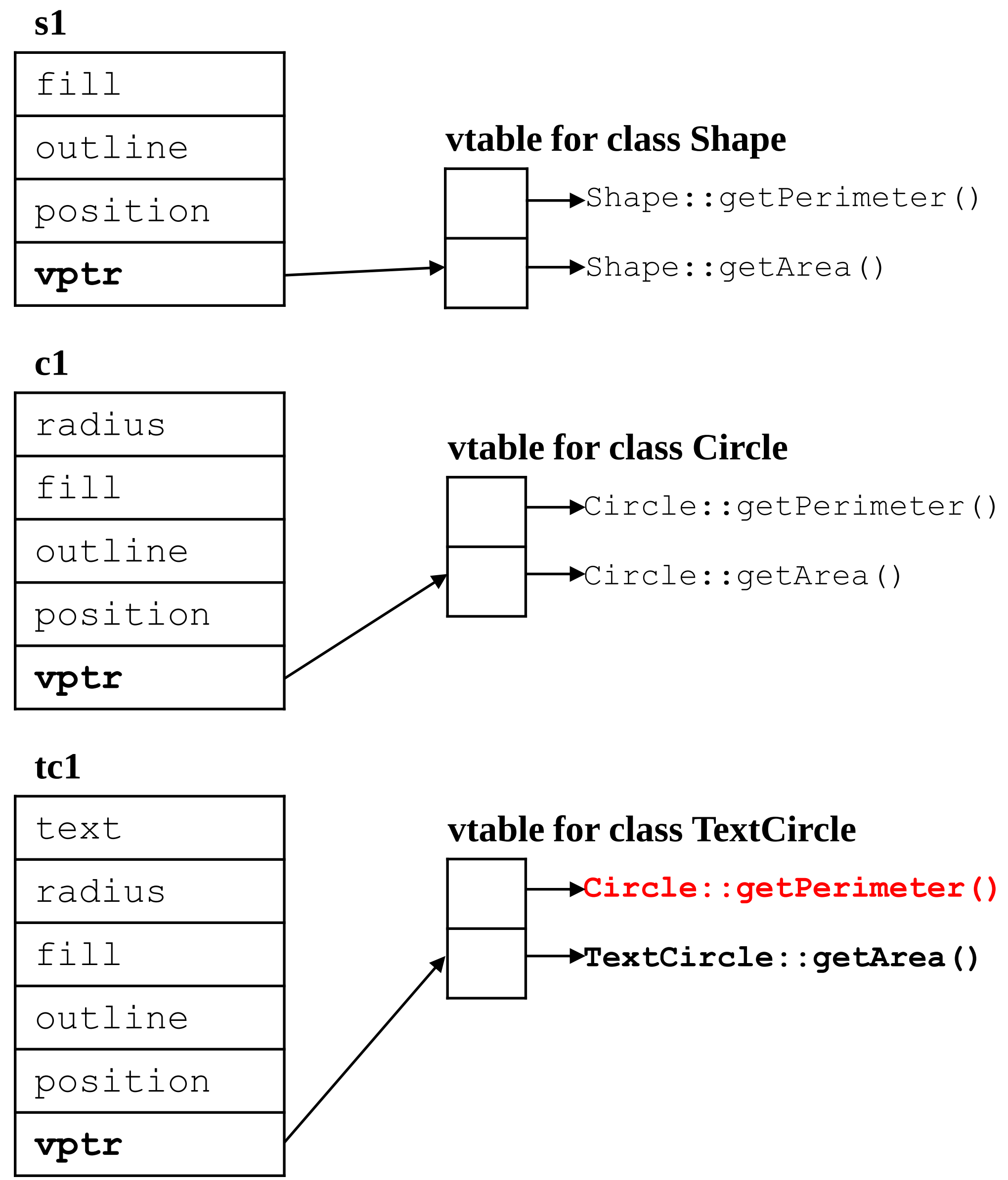


```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};

class Circle: public Shape
{
public:
    Circle(double r);
    virtual double getArea();
    double getPerimeter();
private:
    double radius;
};

class TextCircle: public Circle
{
public:
    TextCircle(string s);
    double getArea();
private:
    string text;
};
```

```
int main(){
    Shape s1; Circle c1; TextCircle tc1;
    return 0;
}
```

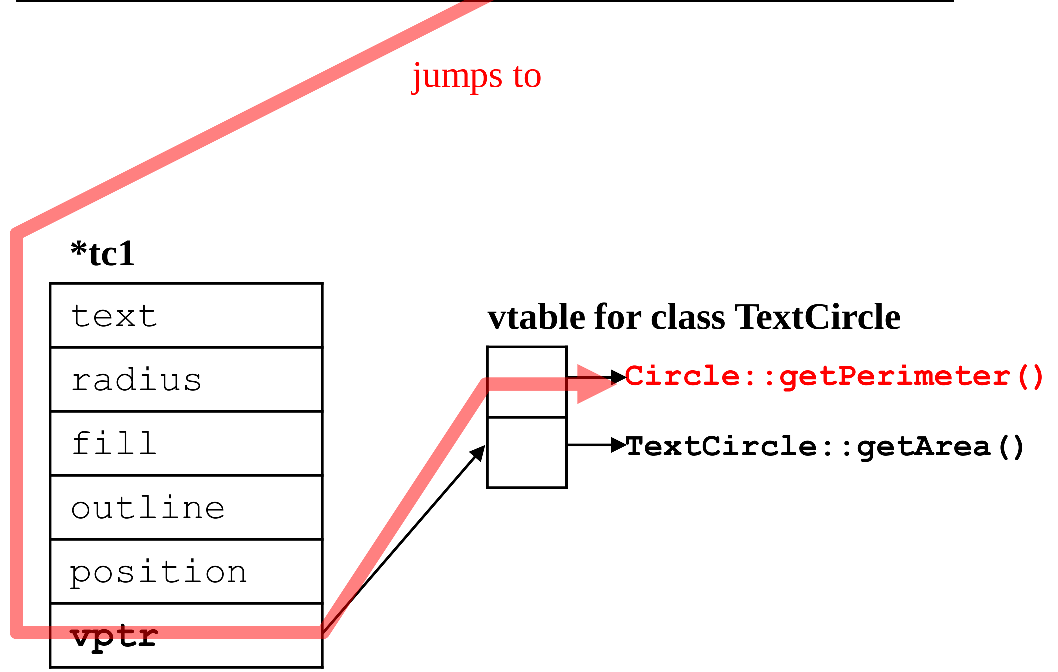


```
class Shape
{
public:
    Shape();
    virtual double getArea();
    virtual double getPerimeter();
private:
    Vector2D position;
    Color outline, fill;
};

class Circle: public Shape
{
public:
    Circle(double r);
    virtual double getArea();
    double getPerimeter();
private:
    double radius;
};

class TextCircle: public Circle
{
public:
    TextCircle(string s);
    double getArea();
private:
    string text;
};
```

```
int main(){
    Shape* tc1 = new TextCircle;
    double p = tc1->getPerimeter();
    return 0;
}
```



Behind Virtual Functions

- ***vtable*** is created only for **classes with at least one virtual function (a.k.a. *polymorphic classes*)**, generally at compile time.
  - It is a lookup table that contains the addresses of the object's dynamically bound virtual functions.

- ***vptr*** is created & initialized at runtime, when a *polymorphic class* instance is constructed.
  - created as a “hidden” member of the instance.
  - initialized to point to the *vtable* of the actual type of the instance.
  - The actual name of vtpr depends on the compiler: __vptr, __vfptr, ...

Behind Virtual Functions

- Compiling non-virtual function calls:
  - Compiler generates code to call (jump to the address of) the non-virtual function directly.

- Compiling virtual function calls:
  - Compiler generates code to call (jump to) a certain entry of the *vtable* (the index for each function is known at compile time) through the *vptr*.
  - Which *vtable* is pointed by *vptr* is determined at run time (when an object is constructed).

Quiz #1

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers **in this format** to be counted as attendance.

Pure Virtual Function

- What if you cannot define the base class' member function? (no 'default' behavior)

```
#include <vector>
#include <iostream>
using namespace std;
class Shape {
public:
  virtual void Draw() const {
    // Nothing to do here
  }
};

class Rectangle : public Shape {
public:
  virtual void Draw() const {
    cout << "rect" << endl;
  }
};

class Triangle : public Shape {
  // What if we forget to override
  // Draw() here?
};
```

```
int main() {
  vector<Shape*> v;
  v.push_back(new Rectangle);
  v.push_back(new Triangle);

  for (size_t i = 0; i < v.size(); ++i) {
    v[i]->Draw();
  }
  for (size_t i = 0; i < v.size(); ++i) {
    delete v[i];
  }
  return 0;
}
```

Pure Virtual Function

- In such cases, you can use ***pure*** *virtual functions*.
  - Just declare a virtual function and end it with '= 0'

```
class Shape {
public:
  // Pure virtual Draw function.
  virtual void Draw() const = 0;
};
```

Pure Virtual Function

- A class with pure virtual functions cannot be instantiated.
- For its subclass to be instantiated, you must implement (override) all pure virtual functions.
  - or the subclass itself become an abstract class and will give a compilation error if you try to instantiate it.

```
#include <vector>
#include <iostream>
using namespace std;
class Shape {
public:
  virtual void Draw() const = 0;
};

class Rectangle : public Shape {
public:
  virtual void Draw() const {
    cout << "rect" << endl;
  }
};

class Triangle : public Shape {
  // What if we forget to override
  // Draw() here? => Error!
};
```

```
int main() {
  Shape s1; // => Error!

  vector<Shape*> v;
  v.push_back(new Rectangle);
  v.push_back(new Triangle);

  for (size_t i = 0; i < v.size(); ++i) {
    v[i]->Draw();
  }
  for (size_t i = 0; i < v.size(); ++i) {
    delete v[i];
  }
  return 0;
}
```

Pure Virtual Function

- A pure virtual function in a base class specifies **"what to do"**.
- Each overridden virtual function in derived classes describes **"how to do"**.
- You can think a pure virtual function provides *interface* to do something.
- FYI, a pure virtual function (C++ term) is often called an *abstract method* in other programming languages (java, python, ...).

The Practical Power of (Subtype) Polymorphism

- When coding ***type-specific details***, polymorphism allows you to avoid using *if...else* or *switch* statements which are often error-prone.

- With polymorphism...
  - It's easier to add a new type (just adding a new subclass without touching the existing class code).
  - Each type-specific implementations are isolated from each other (in different classes).
  - It does not allow an exceptional case with an unexpected type.
  - It removes duplicate if...else or switch statements.

```cpp
class Animal
{
public:
    AnimalType type;

    virtual string talk() {
        switch(type) {
        case CAT: return "Meow!";
        case DOG: return "Woof!";
        case DUCK: return "Quack!";
        case PIG: return "Oink!";
        default:
            assert(0);
            return string();
        }
    }

    virtual int getNumLegs() {
        switch(type) {
        case CAT: return 4;
        case DOG: return 4;
        case DUCK: return 2;
        case PIG: return 4;
        default:
            assert(0);
            return -1;
        }
    }

    virtual void walk() {
        switch(type) {
        case CAT:
            ...
            break;
        case DOG:
            ...
            break;
        case DUCK:
            ...
```

```cpp
class Animal
{
public:
    virtual string talk() = 0;
    virtual int getNumLegs() = 0;
    virtual void walk() = 0;
};

class Cat : public Animal
{
public:
    virtual string talk() { return "Meow!"; }
    virtual int getNumLegs() { return 4; }
    virtual void walk() {...}
};

class Dog : public Animal
{
public:
    virtual string talk() { return "Woof!"; }
    virtual int getNumLegs() { return 4; }
    virtual void walk() {...}
};

class Duck : public Animal
{
public:
    virtual string talk() { return "Quack!"; }
    virtual int getNumLegs() { return 2; }
    virtual void walk() {...}
};

class Pig : public Animal
{
public:
    virtual string talk() { return "Oink!"; }
    virtual int getNumLegs() { return 4; }
    virtual void walk() {...}
};
```

Some Issues with Virtual Functions

- You may have heard that virtual functions have some disadvantages.
  - More memory: an object of a class with virtual functions has an additional member, a *vptr*
  - Slower speed: pointer indirection to call functions, limited possibilities to be inlined or optimized

Some Issues with Virtual Functions

- But, when coding *type-specific details*, these issues are too tiny to matter.

- Because replacing virtual function calls with if...else or switch
  - has disadvantages described in “The Practical Power of (Subtype) Polymorphism” page.
  - and might be even slower.

Some Issues with Virtual Functions

- But if your classes are not designed to be inherited,

- Then there is no reason to use virtual functions.
  - It's better to avoid using virtual functions not to have (slightly) more memory and (slightly) slower speed in this case.

Abstract Class

- An *abstract class* is a class that **cannot be instantiated.**
  - a.k.a. *abstract base class*
  - A class that can be instantiated is called *concrete class*.

- In C++, a class **with one or more pure virtual functions** is an abstract class.
  - For its subclass to be instantiated, you must implement (override) all pure virtual functions.
    - or the subclass itself become an abstract class and will give a compilation error if you try to instantiate it.

```
class Shape {
public:
  virtual void Draw() const = 0;
};

int main() {
  Shape shape; // error! cannot be instantiated!
  return 0;
}
```

Constructors in Abstract Classes

- Do we need to define a constructor for an abstract class? An abstract class will never be instantiated!

Constructors in Abstract Classes

- Do we need to define a constructor for an abstract class? An abstract class will never be instantiated!

- Yes! You should still provide a constructor to initialize its member variables, since they will be inherited by its subclasses.

```
class Animal
{
private:
    string name;
public:
    Animal(const string& name_):name(name_) {}
    virtual string talk() = 0;
    virtual int getNumLegs() = 0;
    virtual void walk() = 0;
};

class Cat : public Animal
{
public:
    Cat(const string& name_):Animal(name_) {}
    virtual string talk() { return "Meow!"; }
    virtual int getNumLegs() = { return 4; }
    virtual void walk() {...};
};

class Dog : public Animal
{
public:
    Dog(const string& name_):Animal(name_) {}
    virtual string talk() { return "Woof!"; }
    virtual int getNumLegs() = { return 4; }
    virtual void walk() {...};
};
```

Destructors in Abstract Classes

- Then do we need to define a destructor for an abstract class?

Destructors in Abstract Classes

- Then do we need to define a destructor for an abstract class?

- Yes! An abstract class SHOULD have a *virtual destructor* even if it does nothing.

Destructors in Abstract Classes

- An abstract class SHOULD have a *virtual destructor* even if it does nothing.

- Recall that:
- A destructor of a *base* class **should be** `virtual` if
  - its descendant class instance is **deleted by the base class pointer.** (..or)
  - any of member function is **virtual** (which means it's a polymorphic base class).

- An abstract class
  - has at least one pure **virtual function.**
  - can be used as "base class reference(or pointer)".

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

class Shape
{
public:
    Shape() {}
    virtual ~Shape() {}
    virtual void draw() = 0;
};

class Rectangle : public Shape
{
private:
    int* width;
    int* height;
public:
    Rectangle()
    {
        width = new int;
        height = new int;
    }
    virtual ~Rectangle()
    {
        delete width;
        delete height;
    }
    virtual void draw()
    { ... }
};
```

```cpp
int main()
{
    Shape* shape1 = new Rectangle;
    shape1->draw();
    delete shape1;

    return 0;
}
```

Pure Abstract Class

- A class **only with pure virtual functions.**
  - No member variables or non-pure-virtual functions (except destructor)
  - Defines an **interface** to a service -
    "What does the class do", "How it should be used"
  - "How to do it" should be implemented in derived concrete classes

- In general, a pure abstract class is used to define an interface and is intended to be inherited by concrete classes.

```
class Shape {
public:
  virtual ~Shape() {}
  virtual void Draw() const = 0;
  virtual int GetArea() const = 0;
  virtual void MoveTo(int x, int y) = 0;
};

void DrawShapes(const vector<Shape*>& v) {
  for (int i = 0; i < v.size(); ++i) v[i]->Draw();
}
```

Quiz #2

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Type Casting Operators in C

- C-style casting operator: `(T)var`

- Problems:
  - Programmer's intention is not clear
  - No type checking (unsafe)
  - Not easy to search (C/C++ code has a very large number of parentheses!)

Type Casting Operators in C++

- C++ casting operators
  - static_cast<T>(var)
  - dynamic_cast<T>(ptr)
  - const_cast<T>(ptr)
  - reinterpret_cast<T>(ptr)

- Each operator is designed to be used for specific purpose.

static_cast

- `static_cast<T>` performs type checking at *compile time.*
  - If T is a pointer or reference type:
    - Safe for upcast (derived -> base)
    - Unsafe for downcast (base -> derived)
      - It’s the programmer's responsibility to make sure that *base class pointer* is actually pointing to the specified *derived class object.*
  - If T is a primitive type:

```
int i = static_cast<int>(2.0);
```

    - Can be used for casting between primitive types

static_cast

```
class B {};

class D : public B
{
public:
    int member_D;
    void test_D() { member_D=10; }
};

class X {};

int main() {
   B b; D d; char ch; int i=65;
   B* pb = &b; D* pd = &d;

   D* pd2 = static_cast<D*>(pb);   // Unsafe. If you access pd2's members not
                                    // in B, you get a run time error.
   pd2->test_D();               // Runtime error!

   B* pb2 = static_cast<B*>(pd);    // Safe, D always contains all of B.

   X* px = static_cast<X*>(pd);   // Compile error!

   ch = static_cast<char>(i);    // int to char
}
```

dynamic_cast

- `dynamic_cast<T>` performs type checking at *run time*.
  - Safe for downcast
    - If *base class pointer* is **not** pointing to the specified *derived class object*, `dynamic_cast` of base to derived pointer returns **null pointer** (0).
  - Note that `dynamic_cast` can only downcast polymorphic types.
    - The base class should have at least one virtual function.

dynamic_cast

```
#include <iostream>

class B
{
public:
    virtual ~B() {}
};

class D : public B
{
public:
    void test_D() { std::cout << "test_D()" << std::endl; }
};

int main() {
   B b; D d;

   B* pb = &b;
   //B* pb = &d;

   D* pd2 = dynamic_cast<D*>(pb);
   if(pd2)
       pd2->test_D();
}
```

const_cast, reinterpret_cast

- `const_cast<T*>` removes 'constness' from `const T* ptr`
- `reinterpret_cast` is just like C-style cast; avoid using it.

```
class B {};
class X {};

int main() {
    B b;
    B* pb = &b;

    const B* cpb = pb;
    B* pb2 = const_cast<B*>(cpb);

    X* px = reinterpret_cast<X*>(pb);
}
```

Quiz #3

- Go to https://www.slido.com/
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- Click "Polls"

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Notes for C++ Casting Operators

- Hard to type! (too many characters!)
- Actually, C++ casting operators are *ugly by design*.

"Maybe, because static_cast is so ugly and so relatively hard to type, you're more likely to think twice before using one? That would be good, because casts really are mostly avoidable in modern C++."

\- *Bjarne Stroustrup (C++ creator)* *http://www.stroustrup.com/bs_faq2.html#static-cast*

- Avoid casting as far as possible. Prefer polymorphism.

Next Time

- Labs in this week:
  - Lab1: Assignment 10-1
  - Lab2: Assignment 10-2

- Next lecture:
  - 11 – Copy Constructor, Operator Overloading