Contemporary C++: Learning Modern C++ in a Modern Way

الماس فناوری ابری پاسارگاد- آلفا

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Agenda 19/24

Session 19. More on Object-Oriented Programming: Polymorphic codes, Abstract classes and Class Hierarchies

- Access control: protected
- Protected members
- Polymorphic code
- Virtual functions
- Pure virtual functions and abstract classes
- Virtual destructors
- Class hierarchies
- Protected Inheritance
- Private inheritance
- Q&A

150 min (incl. Q & A)

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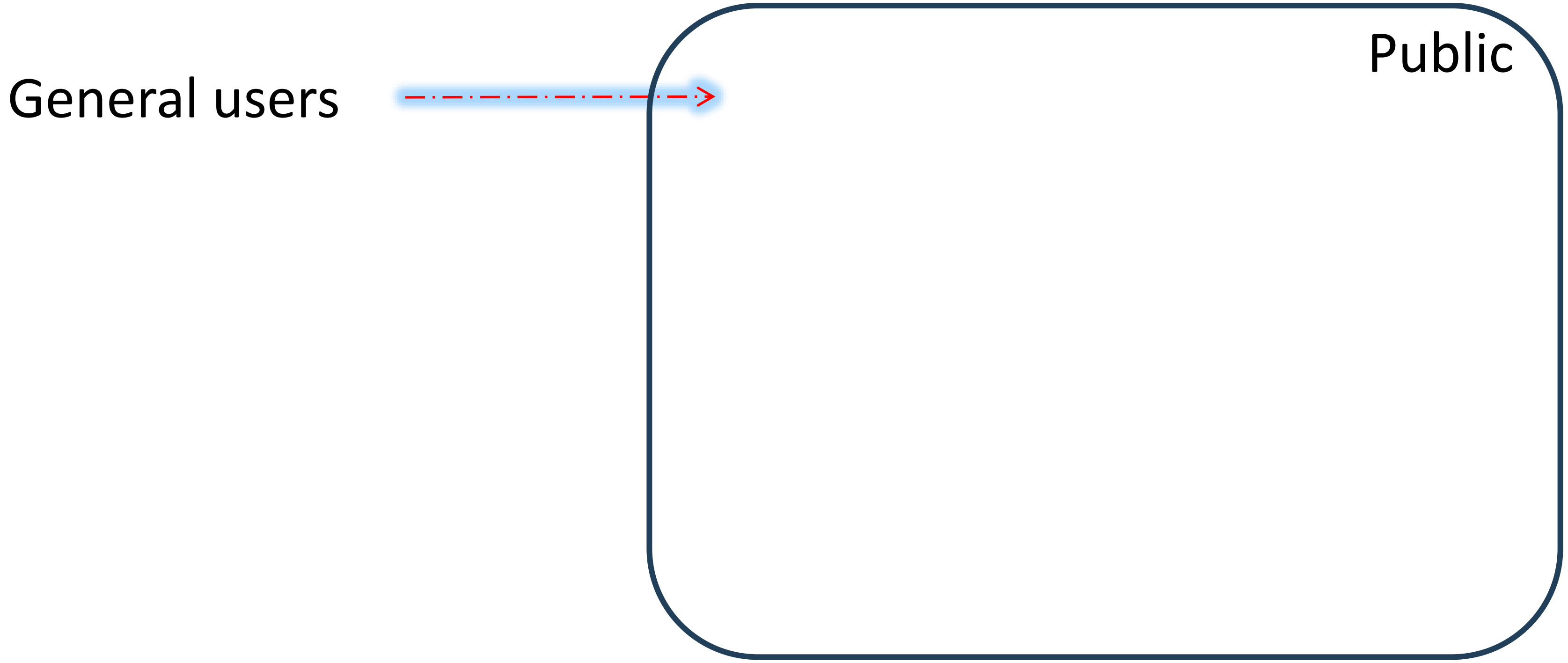

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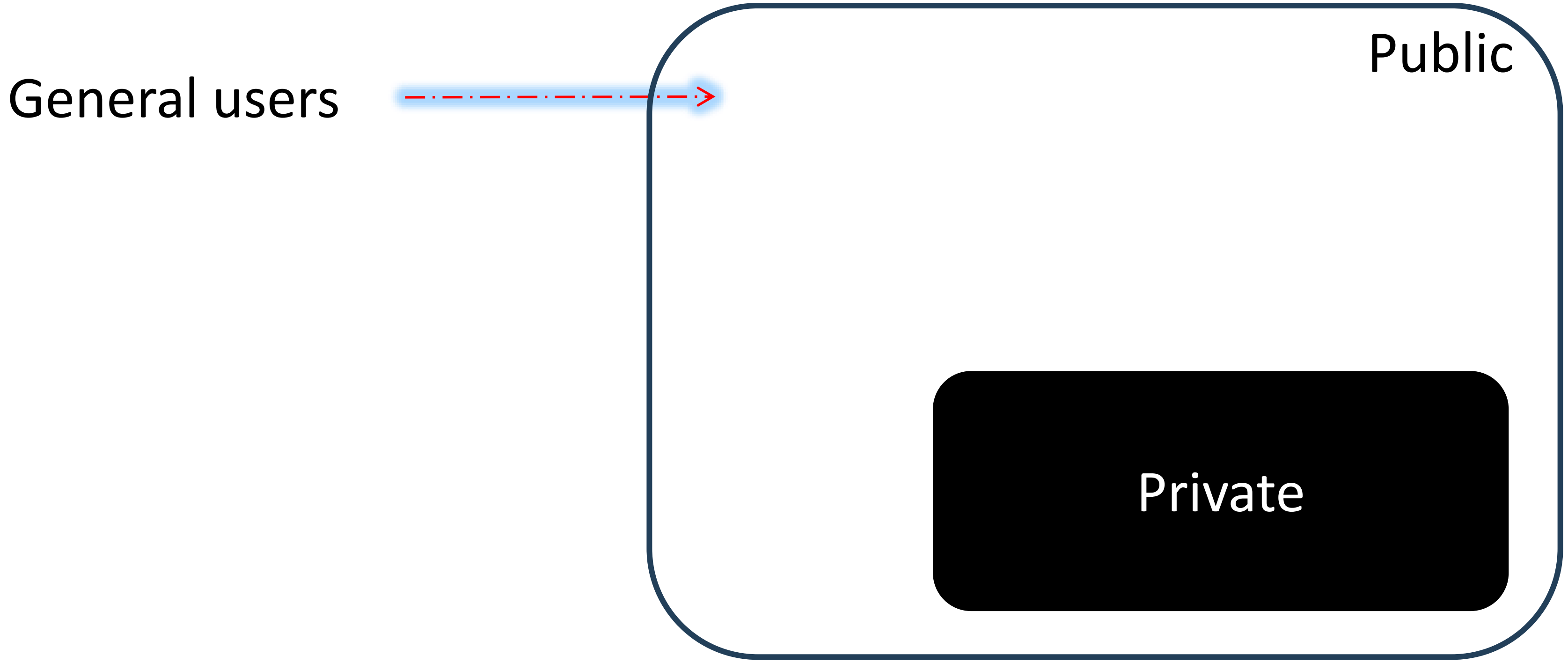

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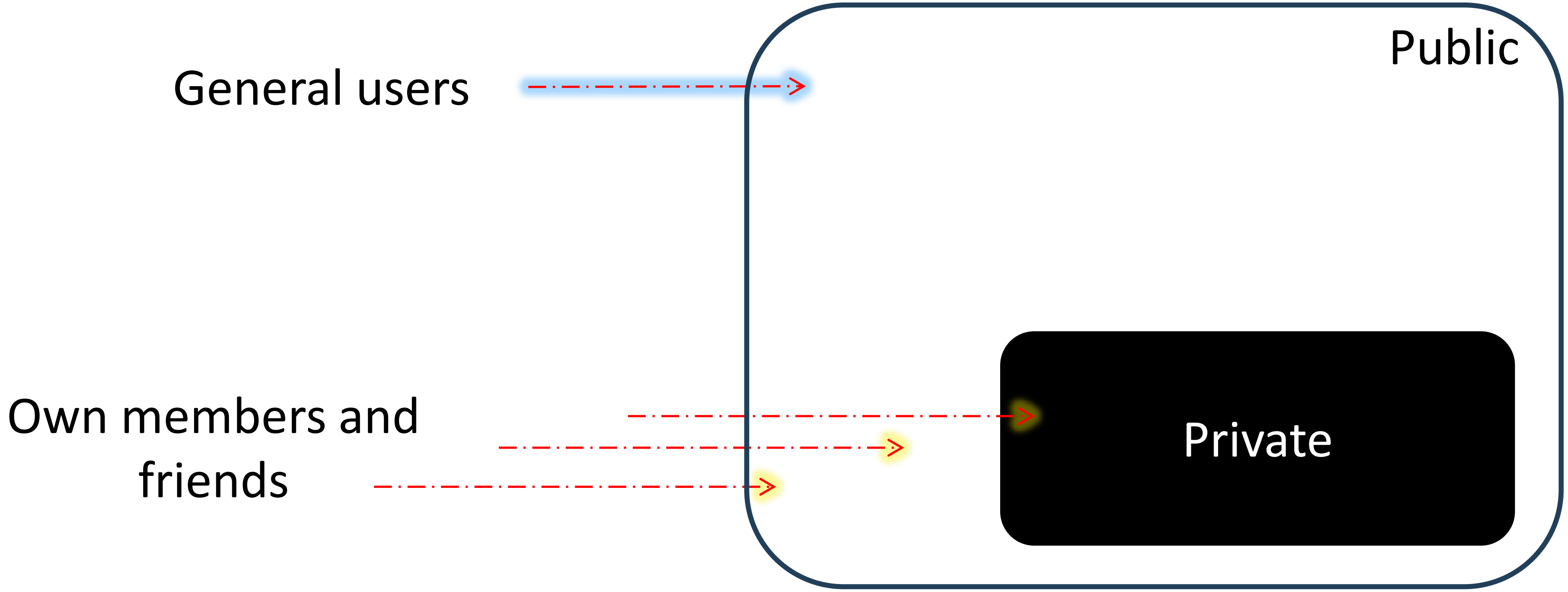

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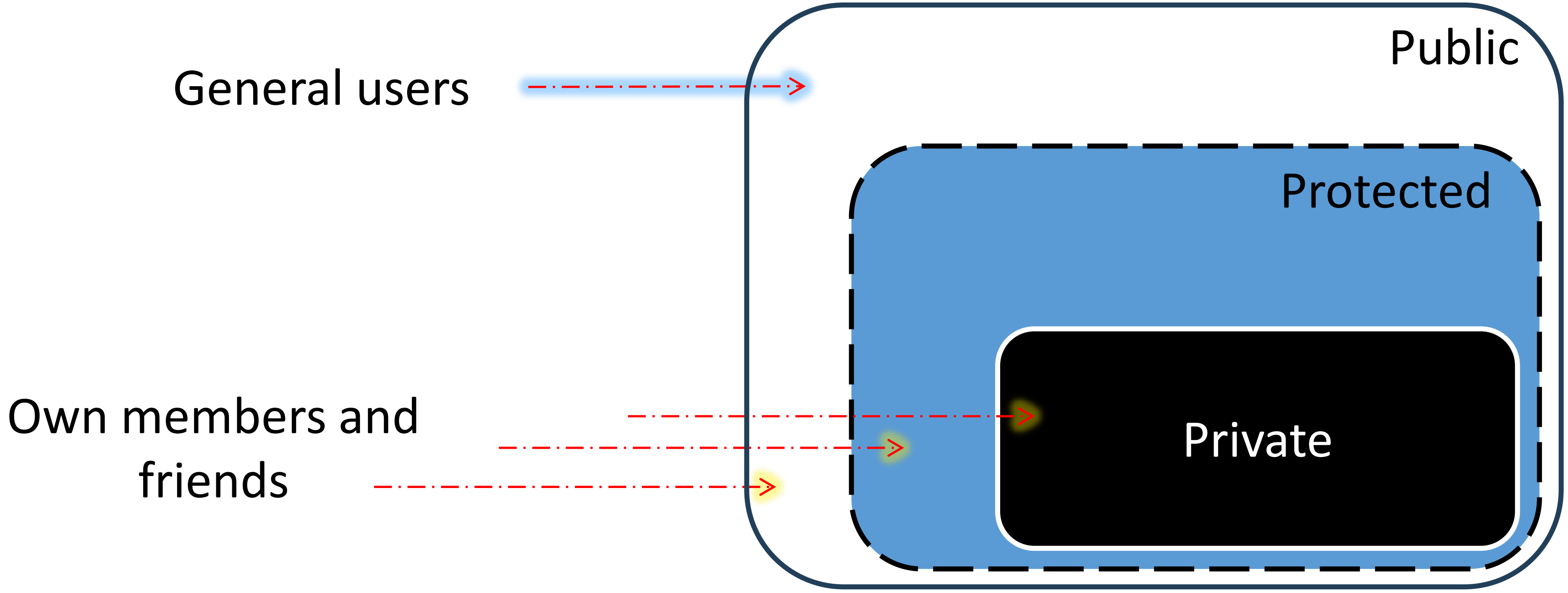

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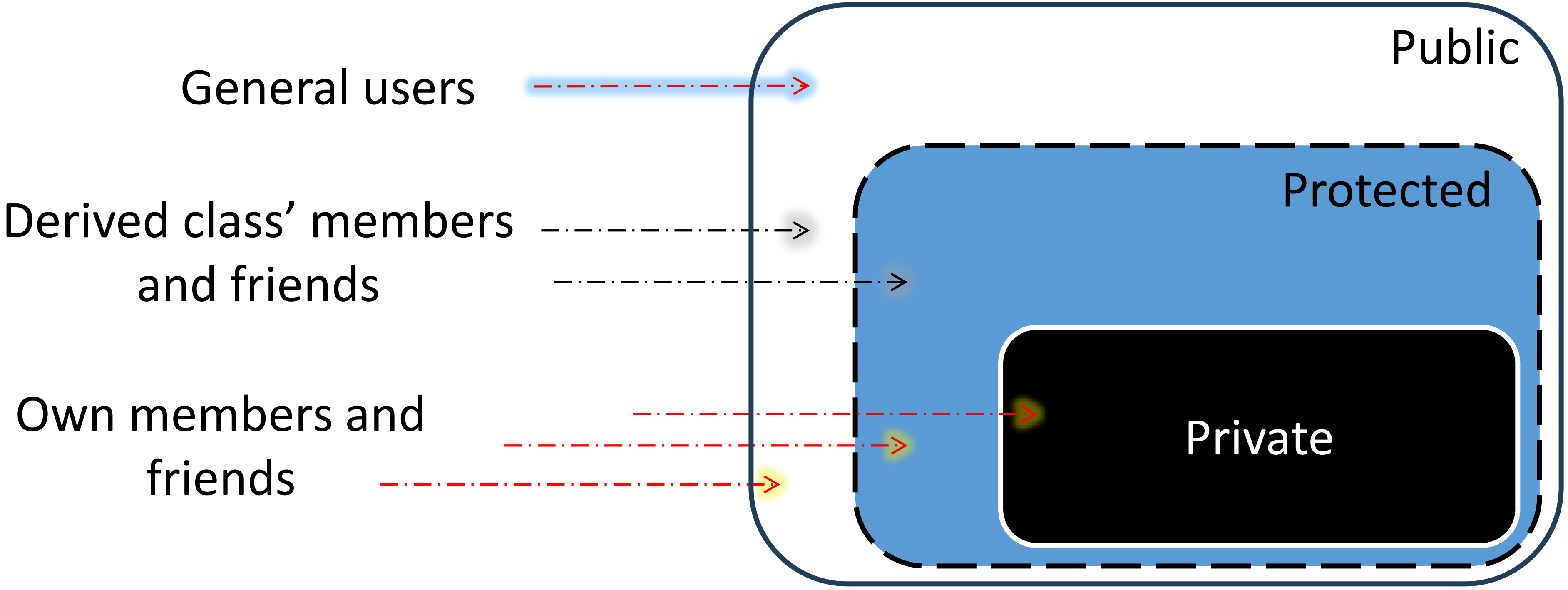

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- Recap: Access to members vs. Member visibility
- Protected members access test:

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};
```

2

```
#include "Base_and_Derived.h"
int main()
{
  Base b;
  b.f();

  Derived d;
  d.f();

  Base* pb = new Derived();
  pb->f();
  delete pb;

  return 0;
}
```

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- Example:

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Derived::f() called
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```

- Calling base or derived member function test:

Inheritance Exercise

Prog.

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Type fields

Type fields

1

```
class Point {
  // as before
};
class Color { /* … */ };
// Shape concept: version 1
enum Kind { CIRCLE, TRIANGLE, RECTANGLE };
class Shape {
  Kind k; // type field
  Point Center;
  Color c;
public:
  Shape(Kind kk, Point Cen, Color col) :
      k(kk), Center(Cen), c(col) {}
  void draw();
  void rotate(int);
};
```

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  void rotate(int);
};
```

2

```
void Shape::draw()
{
  switch (k) { // use type field
  case CIRCLE:
    // draw a circle
    break;
  case TRIANGLE:
    // draw a triangle
    break;
  case RECTANGLE:
    // draw a square
    break;
  }
}
```

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      break;
   case RECTANGLE:
      // draw a square
      break;
   }
}
```

3

```
void Shape::rotate(int deg)
{
   switch (k) { // use type field
   case CIRCLE:
      // rotate a circle: just do nothing
      break;
   case TRIANGLE:
      // rotate a triangle
      break;
   /* … */
   }
}
```

Type fields cont.

4

```
// use Shape
void f()
{
     Color c;
     Point p;
     Shape s1(CIRCLE, p, c);
     s1.draw(); // Call draw: execute Circle case of switch statement
     Shape s2(RECTANGLE, p, c);
     s2.rotate(30); // rotate 30 degrees
}
```

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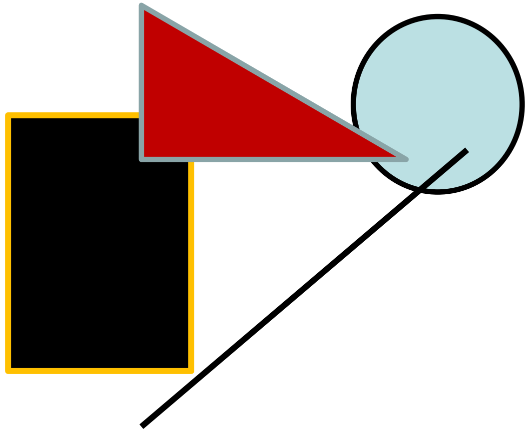

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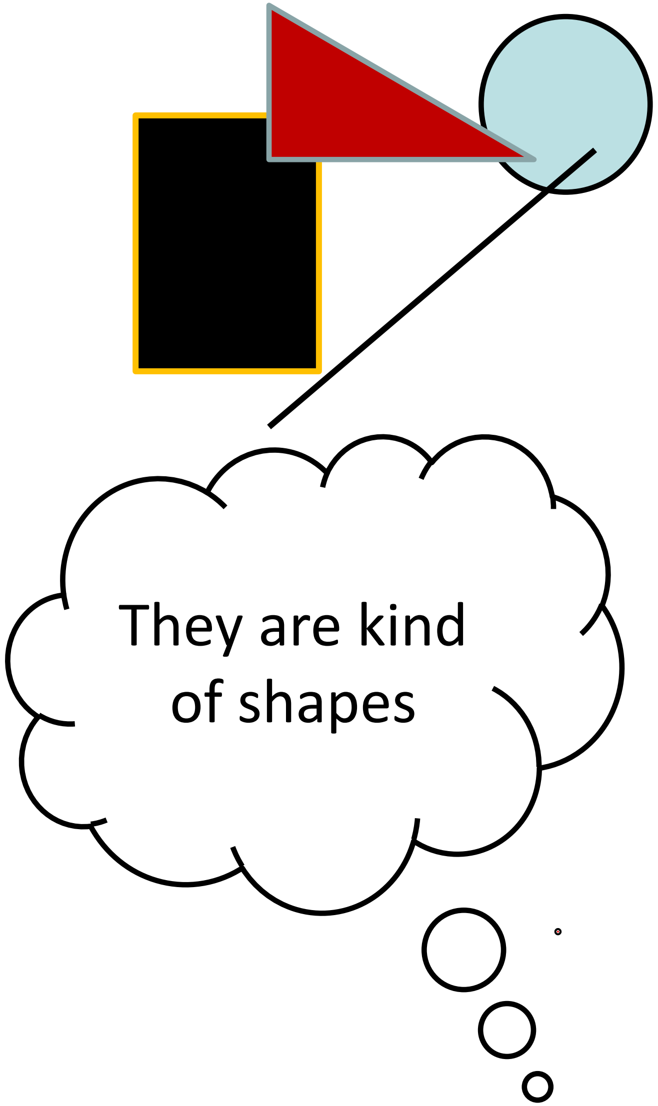

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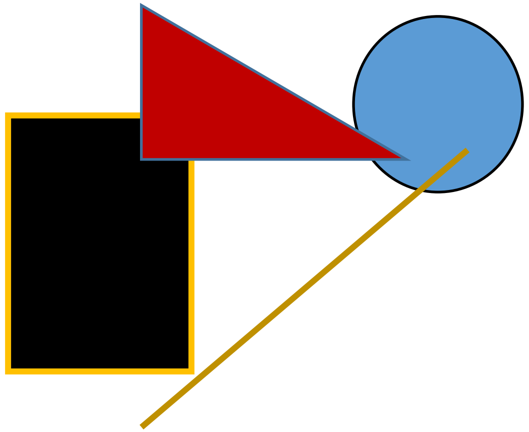
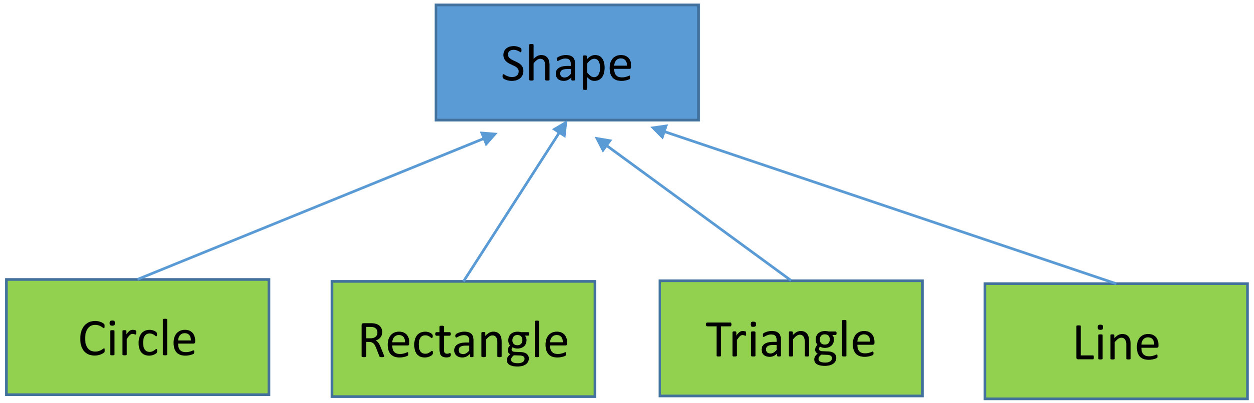
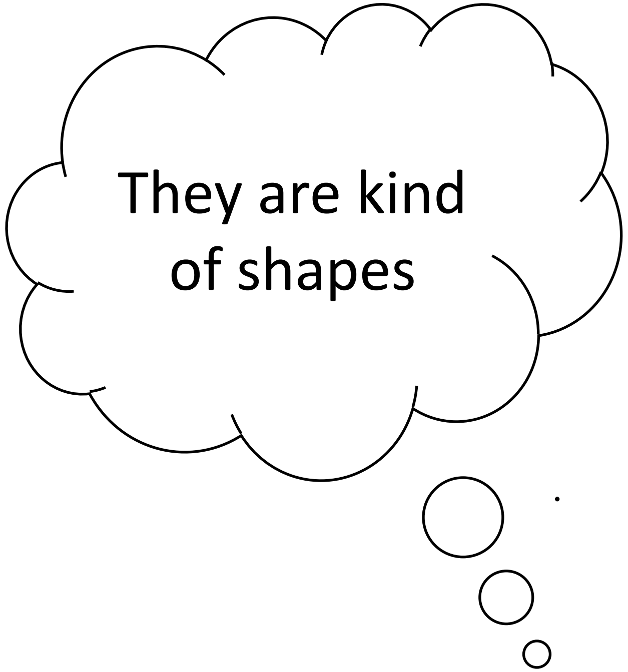






Shape class hierarchy

- Shape
  - General properties: color, general operation
  - Specific properties: How to create circle, rectangle, …

1

```
// Shape concept: version 2
enum Kind { CIRCLE, TRIANGLE, RECTANGLE };
class Color { /* … */ };
class Shape {
protected:
  Kind k;
public:
  Shape(Kind kk) : k(kk) {}
  void draw();
  void rotate(int);
};
```

2

```
class Circle : public Shape {
  Point center;
  int radious;
  Color c;
public:
  Circle(const Point& cent = Point(0, 0), int rad = 1) : Shape(CIRCLE),
  Center(cent), radious(rad) { /* set color */ }
  void draw() { /* … */ }
  void rotate(int degree) { /* do nothing */ }
};
```

Shape class hierarchy cont.

3

```
class Triangle : public Shape {
   Point p1, p2, p3;
   Color c;
public:
   Triangle(Point p = Point(0, 0), Point q = Point(1, 0), Point r = Point(0, 1)) :
            Shape(TRIANGLE), p1(p), p2(q), p3(r) { /* set color */ }
   void draw() { /* … */ }
   void rotate(int degree) { /* … */ }
};
```

4

```
void Shape::draw()
{
     switch (k) {
     case CIRCLE:
     // draw circle
          (static_cast<Circle *>(this))->draw();
          break;
     case RECTANGLE:
     // draw rectangle
          (static_cast<Rectangle *>(this))->draw();
          break;
     case TRIANGLE:
     // draw triangle
          (static_cast<Triangle *>(this))->draw();
          break;
     }
}
```

5

```
// use shape
DrawAllShapes(vector<Shape *> v)
{
     for (i = 0; i < v.size(); i++) {
          v[i]->Draw();
     }
}
```

Type fields cont.

- Functions such as draw() must ''know about'' all the kinds of shapes there are.
- The code for functions such as draw() grows each time a new shape is added to the system.
- If we define a new shape, every operation on a shape must be examined and (possibly) modified.
- Adding a new shape involves ''touching'' the code of every important operation on shapes such as draw, rotate.
- The choice of representation of particular shapes can get severely cramped by the requirement that (at least some of) their representation must fit into the typically fixed-sized framework presented by the definition of the general type Shape.

Poor maintainability

☞ Avoid type fields.

Virtual member functions- An example

1

```
// Shape concept
class Shape {
public:
   // no constructor
   virtual void draw();
   virtual void rotate(int);
};
void Shape::draw() { }
void Shape::rotate(int i) { }
```

Overridden functions

2

```
class Circle : public Shape {
public:
   void draw() { /* … */ }
   void rotate(int d) { /* … */ }
};
```

3

```
class Rectangle : public Shape {
public:
   void draw() { /* … */ }
   void rotate(int d) { /* … */ }
};
```

4

```
class Triangle : public Shape {
public:
   void draw() { /* … */ }
   void rotate(int d) { /* … */ }
};
```

Overriding functions

5

```
DrawAllShapes(vector<Shape *> v)
{
   for (i = 0; i < v.size(); i++)
   {
      v[i]->Draw();
   }
}
```

- *virtual* means “may be redefined later in a class derived from this one”.
- *virtual* indicates that a member function can act as an interface to itself and the corresponding functions defined in classes derived from it.

Virtual functions- Introduction

Simula → C++

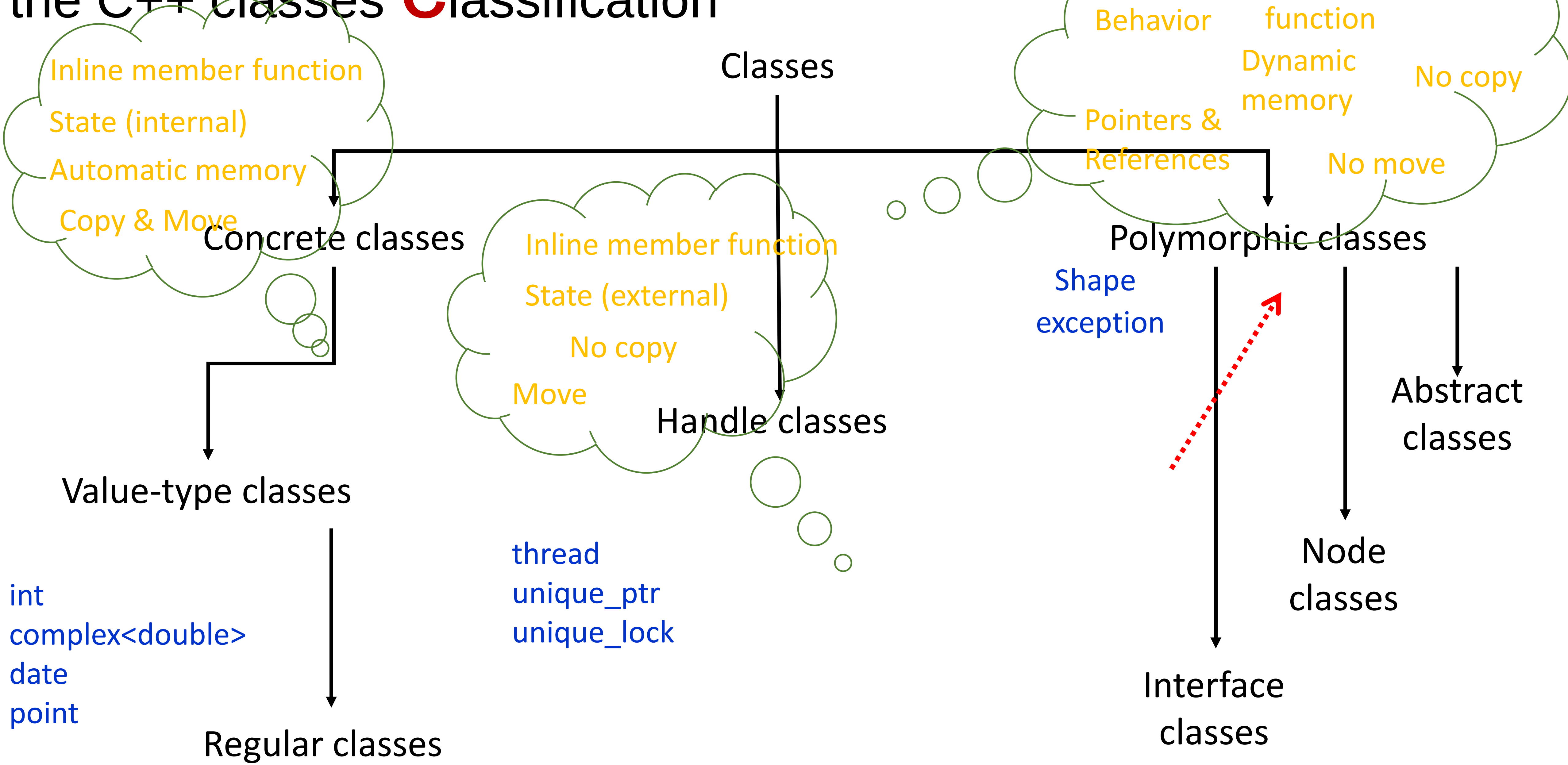
- Virtual (member) functions
- From an OO perspective, it is the single most important feature of C++.

Virtual functions

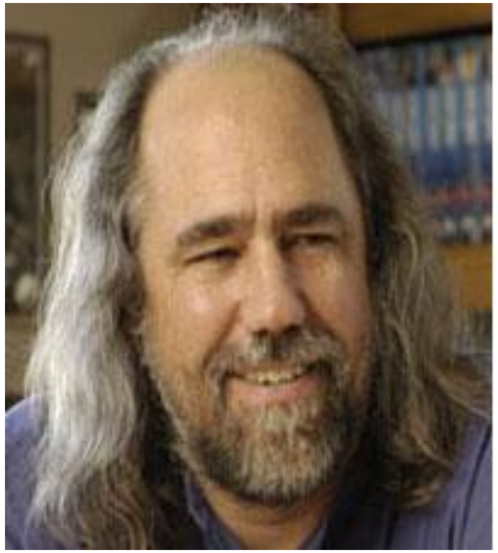
1. allow the programmer to declare functions in a base class that *can be redefined* in each derived class.
2. allow derived classes to replace the implementation provided by the base class.
3. the primary mechanism for run-time *polymorphism* in C++.

- The compiler and linker will guarantee the correct correspondence between objects and the function applied to them.
- A virtual member function is sometimes called a *method*.

the C++ classes Classification



Object-Oriented Programming



Object

Inheritance

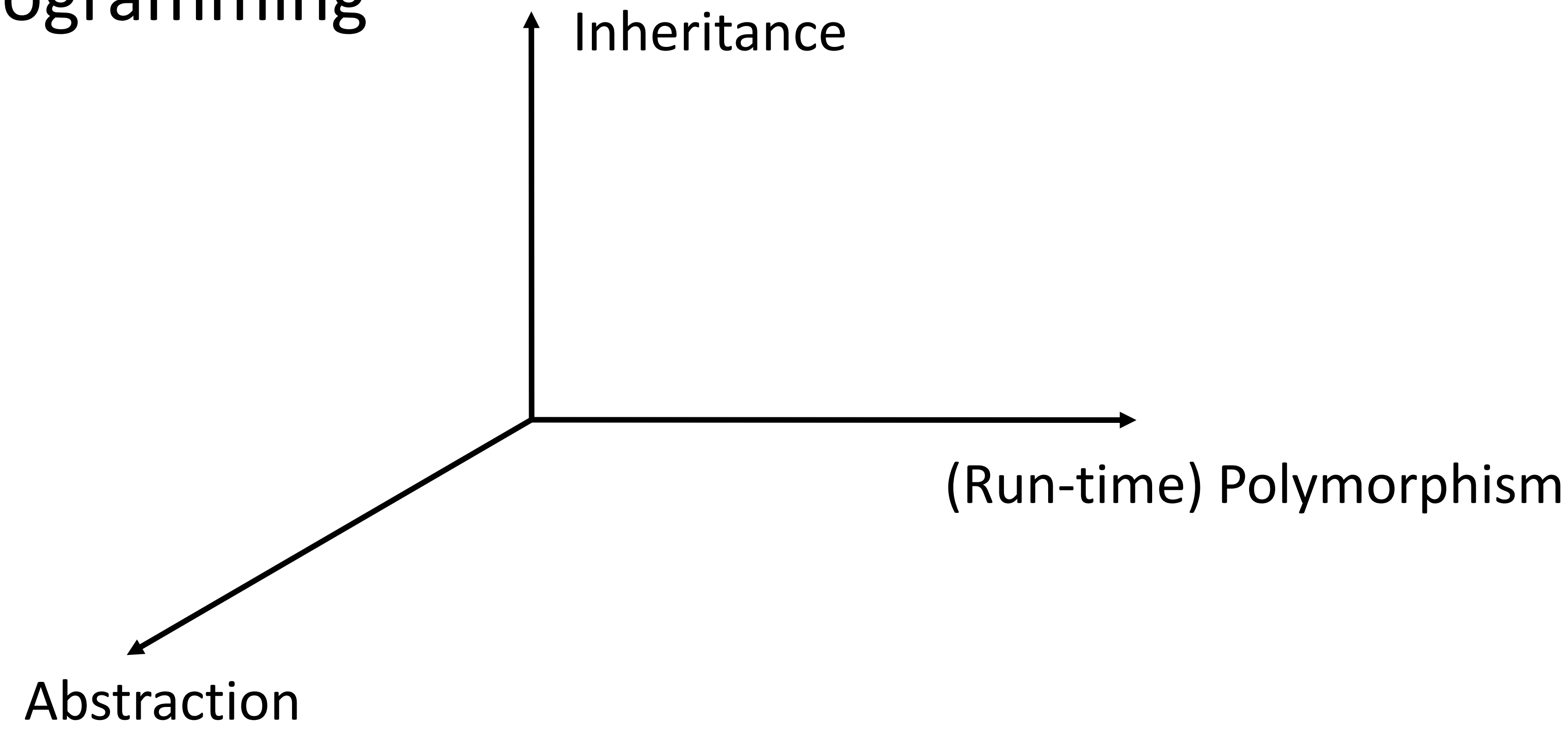
Class

Inheritance

(Run-time) Polymorphism

Abstraction

Object-Oriented Programming



- Abstraction: the ability to represent concepts directly in a program and hide incidental details behind well-defined interfaces.
- Inheritance: To build one class from another so that the new class can be used in place of the original.
- Polymorphism: the ability to provide the same interface to objects with differing implementations.

In OO context:

- Anytime you find yourself writing code of the form, “if the object is of type T1, then do something, but if it’s of type T2, then do something else, “ slap yourself. That isn’t The C++ Way. Yes, it’s reasonable strategy in C, in Pascal, even in Smalltalk, but not in C++, In C++, you use virtual functions.

  - Scott Meyers

Scott Meyers

Virtual member functions- Some rules

• the argument types specified for a virtual function in a derived class cannot differ from the argument types declared in the base.

```
class B {
public:
   virtual void f();
   virtual int g();
}
```

```
class D : public B {
public:
   void f();
   int g(double); // error
}
```

• A virtual function must be defined for the class in which it is first declared (unless it is declared to be a pure virtual function).

• A virtual function can be used even if no class is derived from its class, and a derived class that does not need its own version of a virtual function need not provide one.

Virtual vs. Non-virtual Member functions

- Non-virtual member functions are resolved:
  - statically (static binding)
  - at compile-time
  - based on type of pointer or reference to the object.

vs.

- Virtual member functions are resolved:
  - dynamically (dynamic binding)
  - at run-time
  - based on type of the object.

Pure virtual member functions

- All objects are represented by a class.
- All classes *do not necessarily* represent objects.

```
class Shape {
public:
  virtual void rotate(int);
  virtual void draw();
};
void Shape::draw() { error << "Shape::Draw\n"; }
void rotate(int i) {error << "Shape::Rotate\n"; }
```

Shape vs. Rectangle

Abstract concept — Concrete class/ object

```
Shape s; // silly: shapeless shape
s.draw(); // print error message
s.rotate(20); // print error message
```

- A better alternative is to declare the virtual functions of class Shape to be *pure virtual functions*.

```
// Shape concept
class Shape { // abstract class
public:
  virtual void rotate(int) =0; // pure virtual function
  virtual void draw() =0; // pure virtual function
  // ...
};
```

Abstract classes

- pure virtual function: virtual function that must be overridden in a derived class. Indicated by the curious *=0 syntax*.
- A class with one or more pure virtual functions is an abstract class.
- Decoupling Interface from Implementation
- An abstract class represents an interface. Direct support for abstract classes:

  - helps catch errors that arise from confusion of classes' role as interfaces and their role in representing objects;

  - supports a style of design based on separating the specification of interfaces and implementations.

- Examples:
  - Chess game: Piece
  - Portfolio Management: Asset
  - Operating system: File
  - Tehran Securities Exchange: Index
  - Nuclear Physics: Particle
  - Banking system: Account
  - Operating system: Character device
  - Hardware design: Logic gates

Interface inheritance vs. Implementation inheritance

- From the point of OO, C++ supports two kind of inheritance:
  - *Implementation inheritance*: to save implementation effort by sharing facilities provides by a base class
  - *Interface inheritance*: to allow different derived classes to be used interchangeably through the interface provided by a common base class
- The benefits of class hierarchy:

Implementation inheritance

A base class provides functions or data that simplifies the implementation of derived classes

vs.

An object of a derived class can be used wherever an object of a base class is required

Interface inheritance

Virtual destructor

```cpp
// Shape concept
class Shape {
public:
  // no constructor
  virtual void draw();
  virtual ~Shape() {}
};
void Shape::draw() { }
```

```cpp
class Circle : public Shape {
public:
  void draw() { /* … */ }
  ~Circle() { /* … */ } // overrides ~Shape()
};
```

```cpp
void user(Shape* p)
{
    p->draw();
    // …
    delete p; // invoke the appropriate dtor
}
```

override controls: Override

```
struct B {
    virtual void f();
    virtual void g() const;
    virtual void h(char);
    void k();    // not virtual
};

struct D : B {
    void f();    // overrides B::f()
    void g();    // doesn't override B::g() (wrong type)
    virtual void h(char); // overrides B::h()
    void k();    // doesn't override B::k() (B::k() is not virtual)
};
```

- To allow the programmer to be more explicit about overriding, we now have the "contextual keyword" override:

override controls: Override

```
struct B {
    virtual void f();
    virtual void g() const;
    virtual void h(char);
    void k();
};

struct D : B {
    void f() override;
    void g() override;
    virtual void h(char) override;
    void k() override;
};
```

- override is not an ordinary keyword but it is a *contextual* keyword, so you can still use it as an identifier:

```
int override = 7; // not recommended
```

override controls: final

- final specifier: Stopping inheritance
- Specifies that
  - a virtual function cannot be overridden in a derived class and
  - a class cannot be inherited from.

```
struct base {
    virtual void f();
    // …
};

struct derived: base {
    void f() final;
    // …
};
```

```
struct not_a_base final {
// …
};
```

- final is not an ordinary keyword but it is a *contextual* keyword, so you can still use it as an identifier:

```
int final = 7; // not recommended
```

final- more details

- If it is performance (in-lining) you want or you simply never want to override, it is typically better not to define a function to be virtual in the first place.

override Specifiers- virtual, pure virtual, final and override

- virtual: The function may be overridden.
- =0: The function must be virtual and must be overridden.
- override: The function is meant to override a virtual function in a base class.
- final: The function is not meant to be overridden.

- Language rule:

In the absence of any of these controls, a non-static member function is virtual if and only if it overrides a virtual function in a base class.

Covariant return types

- The return type of an overriding function shall be either identical to the return type of the overridden function or *covariant* with the classes of the functions. **from *Committee Draft***
- Return type relaxation rule:
- If the original return type was B*, then the return type of the overriding function may be D*, provided B is a public base of D. Similarly, a return type of B& may be relaxed to D&

```
class B {
public:
  virtual B* f();
  virtual B* g(int);
};

class D : public B {
public:
    D* f();
    D* g(int);
};
```

Covariant return type- an example

```
class Shape {
public:
    virtual ~Shape() { }
    virtual void draw() = 0;
    virtual void move() = 0;
    // ...
    virtual Shape* clone()  const = 0; // Uses the copy ctor
    virtual Shape* create() const = 0; // Uses the default ctor
};
```

```
class Circle : public Shape {
public:
    Circle* clone() const
    {
        return new Circle(*this); // make copy
    }
    Circle* create() const
    {
        return new Circle(); // make new object
    };
    // …
};
```

Virtual constructor

- There is no *direct support* for virtual constructor in C++.
- An idiom that allows you to do something that C++ doesn't directly support.
- Base facility to implement Abstract Factory pattern.

```
class Point {
public:
	virtual Point(); // error
};
```

1

```
class Shape {
public:
	virtual ~Shape() { }
	virtual void draw() = 0;
	virtual void move() = 0;
	// ...
	virtual Shape* clone()  const = 0; // Uses the copy ctor
	virtual Shape* create() const = 0; // Uses the default ctor
};
```

2

```
class Circle : public Shape {
public:
	Circle* clone() const
	{
		return new Circle(*this); // make copy
	}
	Circle* create() const
	{
		return new Circle(); // make new object
	};
	// …
};
```

3

```
void user_code(Shape& s)
{
	Shape* s2 = s.clone();
	Shape* s3 = s.create();
	// ...
	delete s2;
	delete s3;
}
```

Virtual Constructor Test

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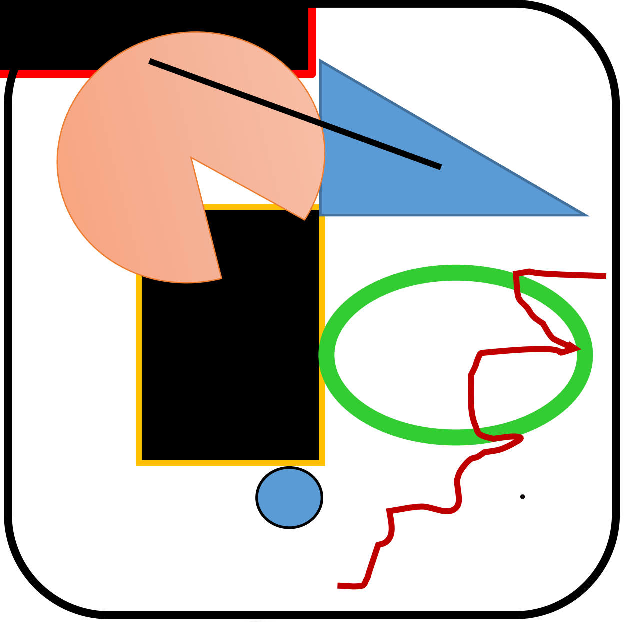
Object-oriented and other programming styles together

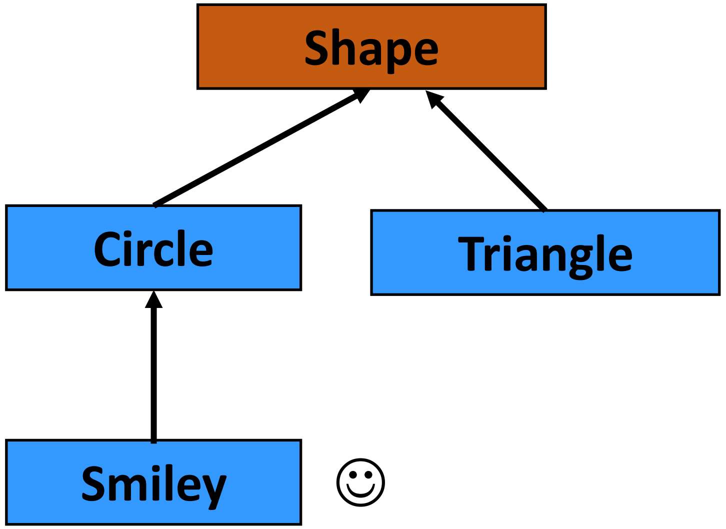
```
void rotate_and_draw(vector<Shape*>& vs, int r)
{
     // method #1
     for_each(vs.begin(),vs.end(), [](Shape* p) { p->rotate(r); }); // rotate all elements of vs
     // method #2
     for (Shape* p : vs) p->draw(); // draw all elements of vs
}
```



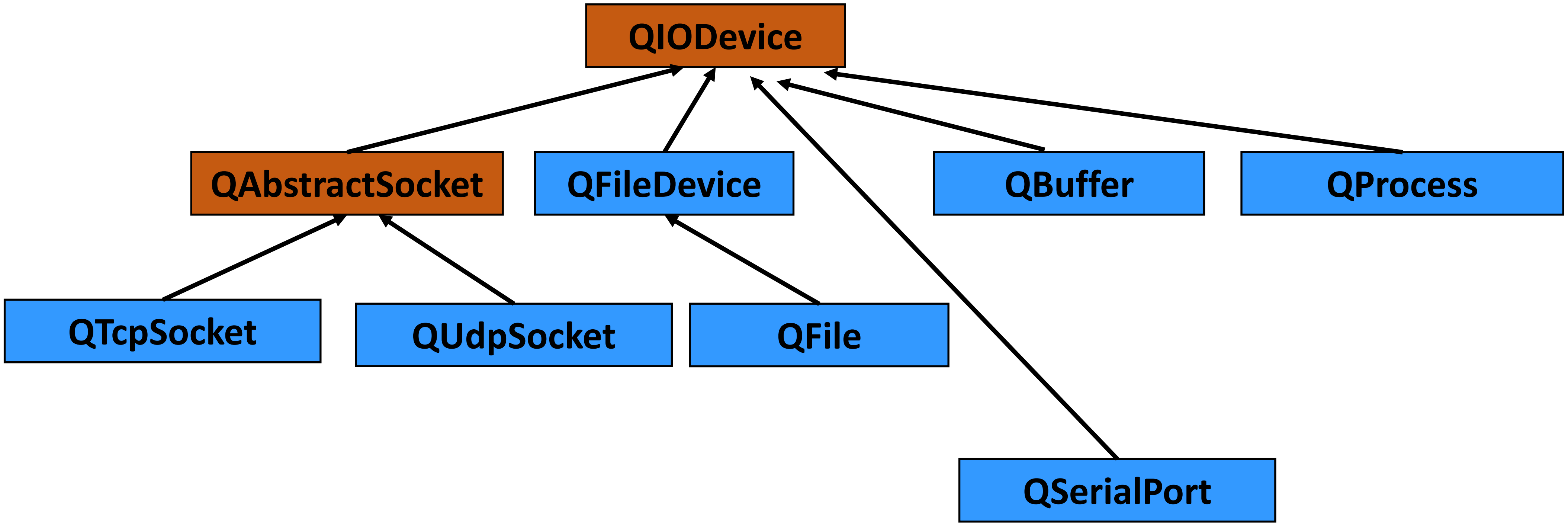
- Is this *object-oriented*? Of course it is; it relies critically on a class hierarchy with virtual functions.
- It is *generic*? Of course it is; it relies critically on a parameterized container (**vector**) and the generic function **for_each**.
- Is this *functional*? Sort of; it uses a lambda (the **[]** construct).
- Is this *Procedural*? Of course it is, the function rotate_and_draw.
- It is modern C++!

Class hierarchy

- A class hierarchy is a set of classes ordered in a lattice created by derivation. We use class hierarchy to represent concepts that have hierarchical relationship.
- A rose is a kind of flower and a flower is a kind of plant.
- A smiley face is a kind of a circle which is a kind of a shape.



Class hierarchy- An example from Qt



Accessibility of base classes and base class members

 # class member access specifier = 3
 # Base class member access specifier = 3
3 * 3 = 9 different states

```
class B {
private:
  int i;
protected:
  char c;
public:
  double d;
};
```

```
class D1 :public B {
};

class D2 :protected B {
};

class D3 :private B {
};
```

Derivation

Base class member Access Specifier

	public	protected	private
private	*private*	*private*	*private*
protected	*protected*	*protected*	*private*
public	*public*	*protected*	*private*

Inheritance　　Protected interface　　Composition

Private inheritance

```
class Foo : private Bar {
public:
    // …
};
```

- private inheritance is a syntactic variant of composition (AKA aggregation and/or has-a).

- Composition

```
class Engine {
public:
    Engine(int num_cylinders);
    void start();
};

class Car {
public:
    Car() : e_(8) { }
    void start() { e_.start(); }
private:
    Engine e_; // Car has-a Engine
};
```

- Private inheritance

```
class Car : private Engine { // Car has-a Engine
public:
    Car() : Engine(8) { }
    using Engine::start; // Start this Car by starting its Engine
};
```

Private inheritance vs. Simple composition

```
class Engine {
    // …
};

class Car {
    Engine e_; // Car has-a Engine
    // …
};
```

vs.

```
class Car : private Engine {
public:
    using Engine::start;
};
```

- Similarities

- In both cases there is exactly one Engine member object contained in every Car object
- In neither case can users (outsiders) convert a Car* to an Engine*

- Distinctions

- The simple-composition variant is needed if you want to contain several Engines per Car
- The private-inheritance variant can introduce unnecessary multiple inheritance
- The private-inheritance variant allows access to the protected members of the base class
- The private-inheritance variant allows Car to override Engine's virtual functions

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Protected inheritance

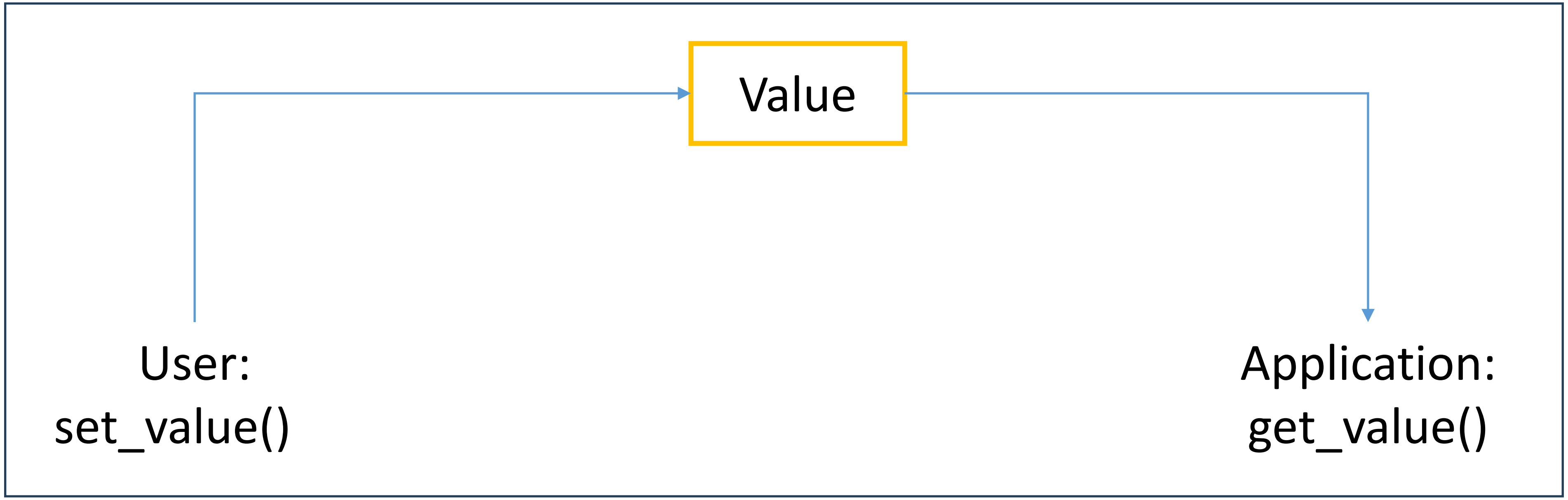
```
class Foo : protected Bar {
public:
    // …
};
```

Protected interface

- A class has two distinct interfaces for two distinct sets of clients:
  - It has a public: interface that serves unrelated classes
  - It has a protected: interface that serves derived classes

Design of Class Hierarchies: An example

- Problem: Provide a way for a program (“an application”) to get an integer value from a user.
- Invariant: Low <= Val < High
- Solution: Virtual user-interface system



- Graphical User Interface terminology: Controls or Widgets: Edit box, Text box, and …

IntValBox class

- Round 0

1

```
class IntValBox {
	int val;
	int low, high;
	bool changed{false}; // in-class member initialization
public:
	IntValBox(int ll, int hh) : val{ll}, low{ll}, high{hh} {}
	int get_value() { changed = false; return val; }
	void set_value(int i) { changed = true; val = i; }
	void reset_value(int i) { changed = false; val = i; }
	void prompt() { /* … */ }
	bool was_changed() const { return changed; }
	// other member functions
};
```

2

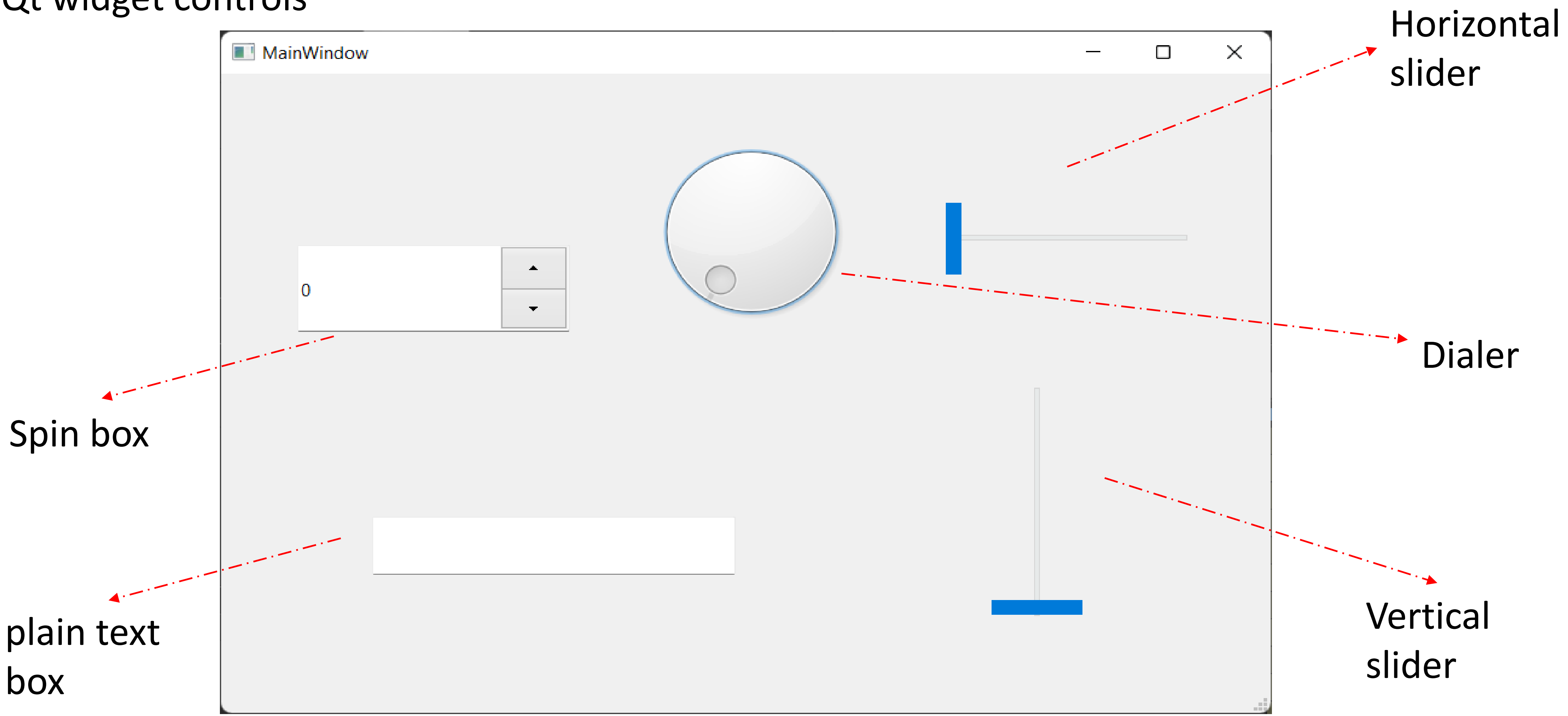
```
void interact(IntValBox b)
{
	b.prompt(); // alert user
	int i = b.get_value();
	if (b.was_changed()) {
		// new value: do something
	} else {
		// do something else
	}
}

void user()
{
	IntValBox b;
	interact(b);
}
```

- Problems: There are a lot of value box like widgets: Text box, Slider box, Dial box, Spin box

different kind of Input Values classes

- Qt widget controls



IntValBox classes

- Round 1

1

```
class IntValBox {
protected:
    int val;
    int low, high;
    bool changed{false}; // in-class member initialization
public:
    IntValBox(int ll, int hh) : val{ll}, low{ll}, high{hh} {}
    virtual int get_value() { changed = false; return val; }
    virtual void set_value(int i) { changed = true; val = i; }
    virtual void reset_value(int i) { changed = false; val = i; }
    virtual void prompt() { /* … */ }
    virtual bool was_changed() const { return changed; }
    virtual ~IntValBox() {}
    // other member functions
};
```

2

```
class IntValBoxSlider :public IntValBox {
    // private part
public:
    IntValBoxSlider(int ll, int hh);
    virtual int get_value() override;
    virtual void set_value(int) override;
    virtual void reset_value(int) override;
    virtual void prompt() override;
    virtual bool was_changed() const override;
    virtual ~IntValBox() {}
    // other member functions
};
```

3

```
void interact(IntValBox* pb)
{
    pb->prompt(); // alert user
    int i = pb->get_value();
    if (pb->was_changed()) {
        // new value: do something
    } else {
        // do something else
    }
}

void user()
{
    unique_ptr<IntValBox> bp = new {IntValSliderBox{0, 100}};
    interact(bp);
}
```

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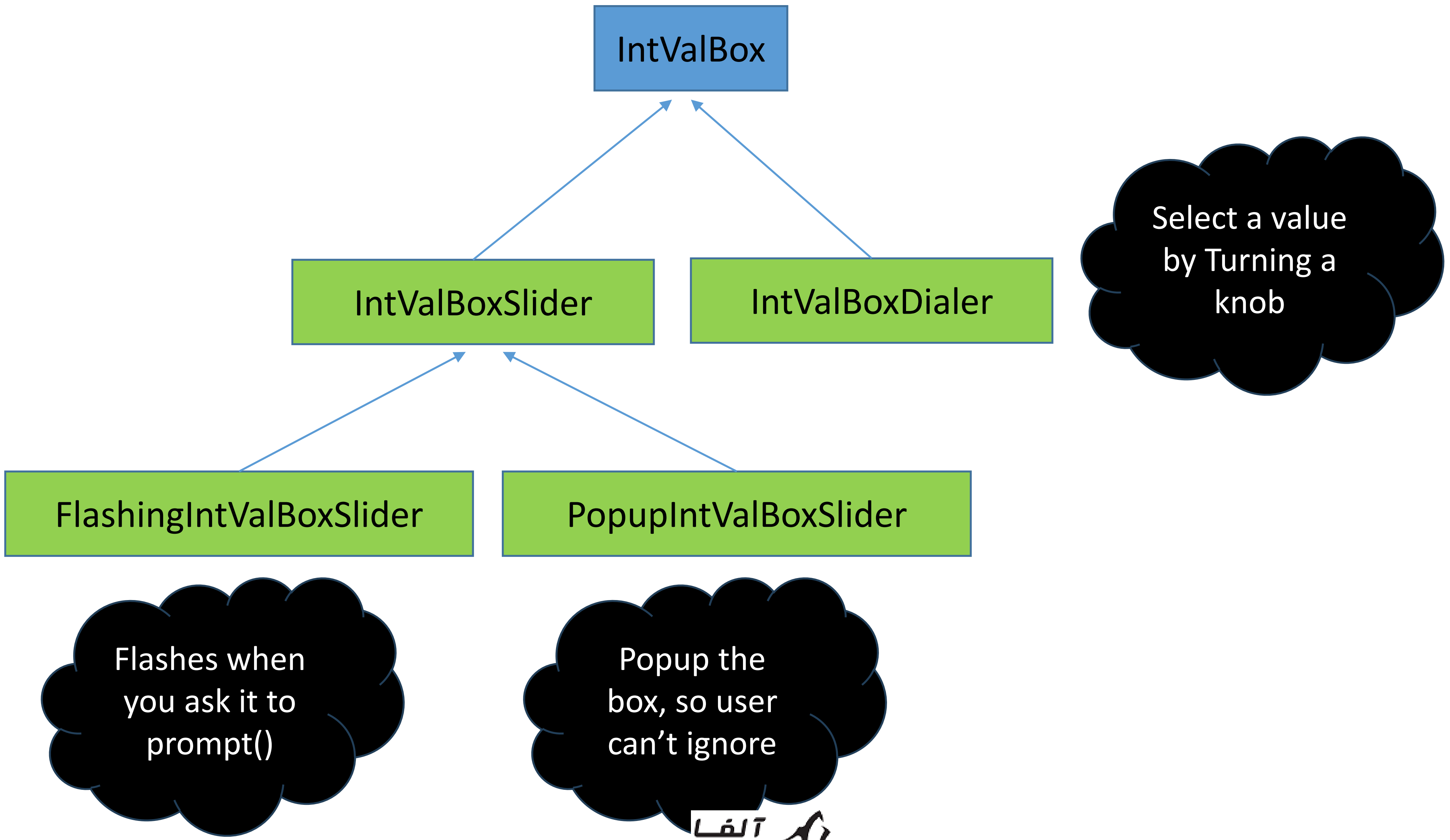
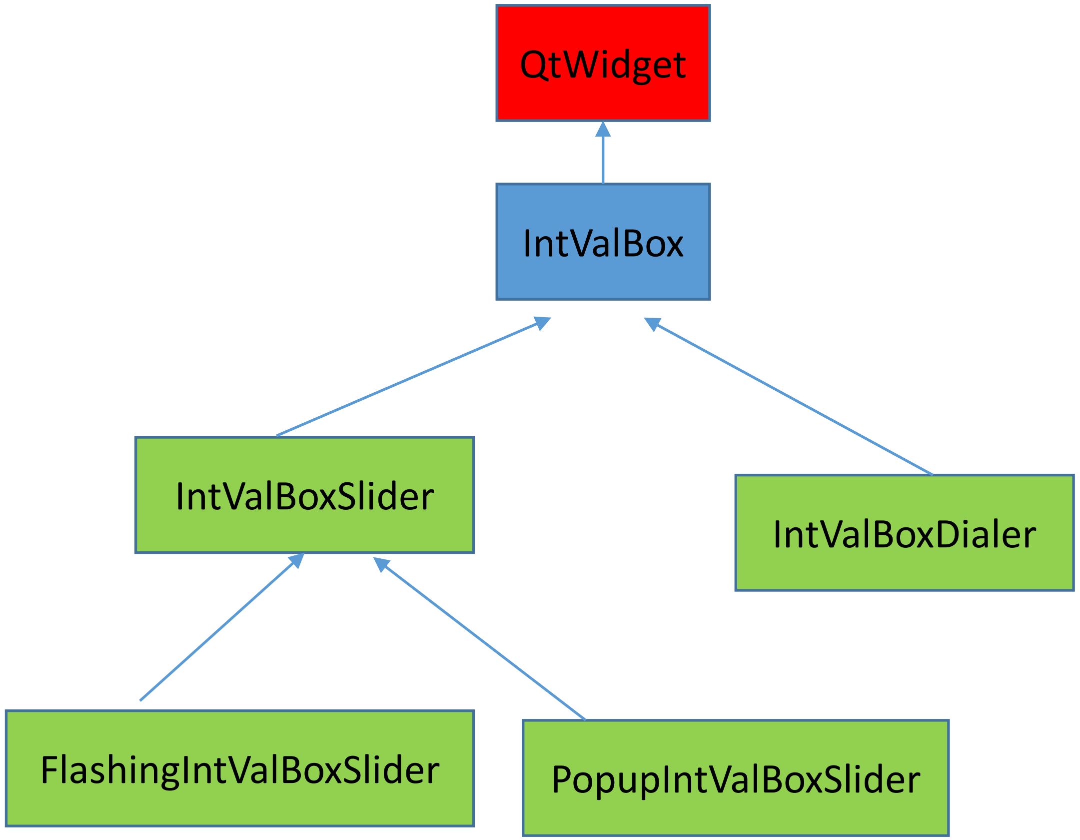
IntValBox class hierarchy

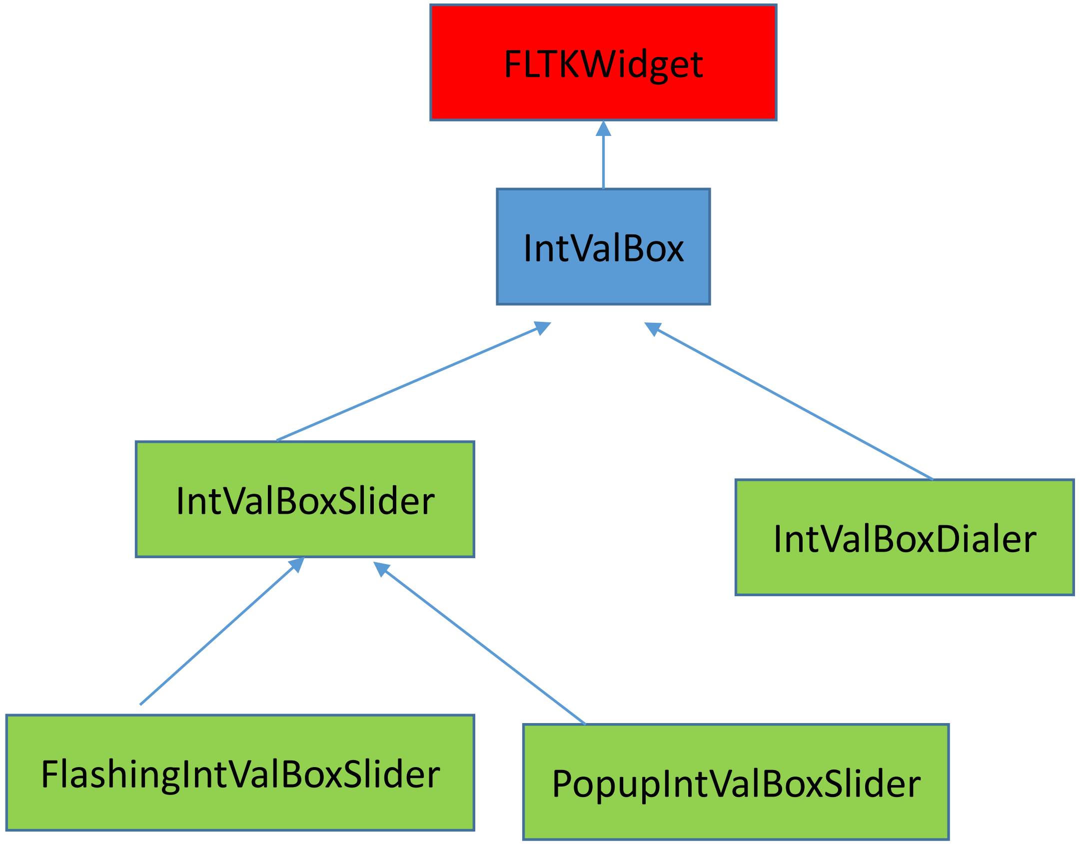


Graphics stuff

- The implementation of Widgets: OpenGL, .NET Framework, Qt, wxWidgets, FLTK, …
- Qt



- FLTK



Implementation

```
class IntValBox :public QtWidget { /* … */ };
class IntValBox :public FLTKWidget { /* … */ };
class IntValBox :public wxWidgetWidget { /* … */ }
// …
```

- The implementation detail leakage.
- Having many versions: maintenance nightmare.
- Every derived class shares the basic data declared in IntValBox.
- Changes to class QtWidget may force users to recompile or even rewrite their code.

Abstract IntValBox

```
class IntValBox {
public:
     virtual int get_value() =0;
     virtual void set_value(int i) =0;
     virtual void reset_value(int i) =0;
     virtual void prompt() =0;
     virtual bool was_changed() const =0;
     virtual ~IntValBox() {}
     // other member functions
};
```

```
class IntValBoxSlider :public IntValBox, :protected QtWidget {
public:
     IntValBoxSlider(int, int);
     virtual int get_value() =0;
     virtual void set_value(int i) =0;
     virtual void reset_value(int i) =0;
     virtual void prompt() =0;
     virtual bool was_changed() const =0;
     virtual ~IntValBox() {}
     // other member functions
};
```

...

Thanks for your patience …

A man who asks a question is a fool for minute,
The man who does not ask, is a fool for a life.
- Confucius

Learning to ask the right (often hard) questions is an essential part of learning to think as a programmer.
- Bjarne Stroustrup *programming Principles and Practice Using C++, page 4.*

There is no stupid question, but there is stupid answer.
- Howard Hinnant

Q & A