Objects (cont.)

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(Adopted from my & Edward Yang's CS242 slides)

Today

- Statically-typed OO languages: C++
  - vtables
- Closer look at subtyping

Why talk about C++?

- C++ is an OO extension of C
  - Efficiency and flexibility from C
  - OO program organization from Simula
- Interesting design decisions
  - Features were and still are added incrementally
  - Backwards compatibility is a huge priority
  - “What you don’t use, you don’t pay for.”- Bjarne Stroustrup

Recall: C++ OO concepts in 1 slide

- Encapsulation
  - Public, private, protected + friend classes
- Dynamic lookup
  - Only for special functions: virtual functions
- Inheritance
  - Single and multiple inheritance!
  - Public and private base classes!
- Subtyping: tied to inheritance

Plan for C++

- Look at dynamic lookup as done in C++ (vtables)
  - Why?
- Only interesting when inheritance comes into play
  - Why?

Simple example

runtime representation of A object

```
class A {
  int a;
  void f(int);
}
```

```
int a
```

```
A* pa;
pa->f(2);
```

compiles to →

```
__A_f(pa, 2);
```

info necessary to lookup function: type of pointer

Inheritance

```
class A {
  int a;
  void f(int);
}
class B : A {
  int b;
  void g(int)
}
class C : B {
  int c;
  void h(int)
}
```

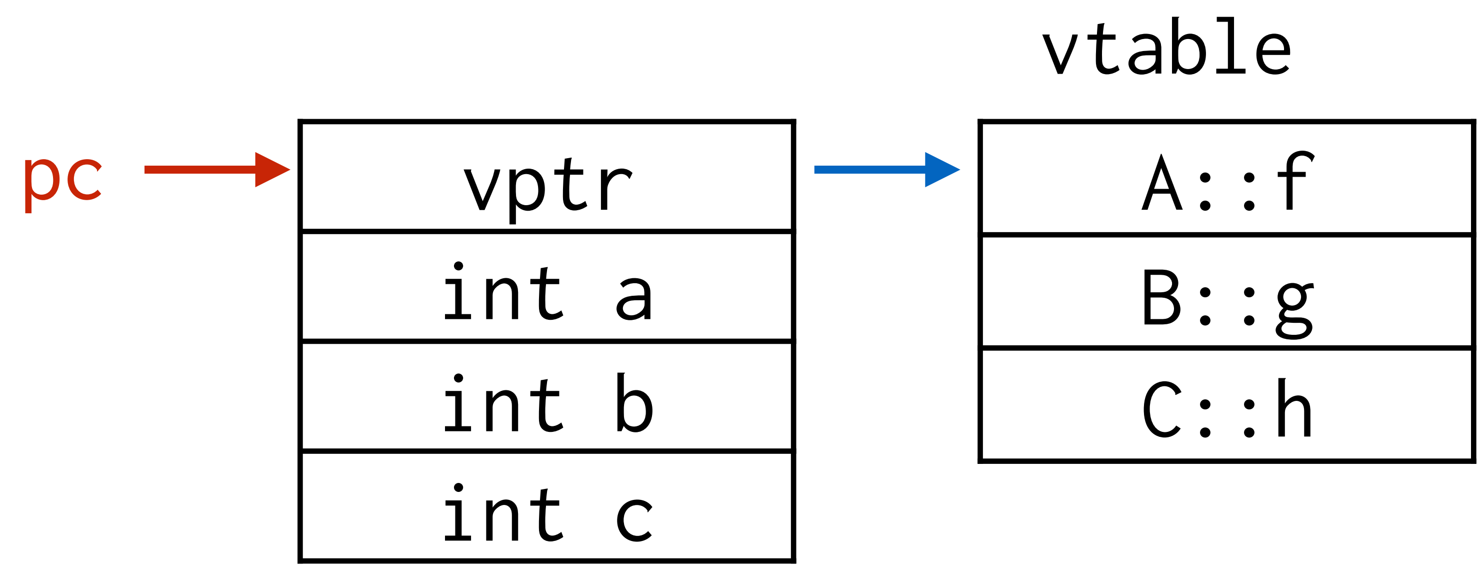
runtime representation of C object

int a
int b
int c

Inheritance + virtual methods

```
class A {
  int a;
  virtual void f(int);
  virtual void g(int)
  virtual void h(int)
}
class B : A {
  int b;
  void g(int)
}
class C : B {
  int c;
  void h(int)
}
C* pc;
pc->g(2);
```

runtime representation of C object



compiles to

```
(*(pc->vptr[1]))(pc, 2)
```

Non-virtual vs. Virtual

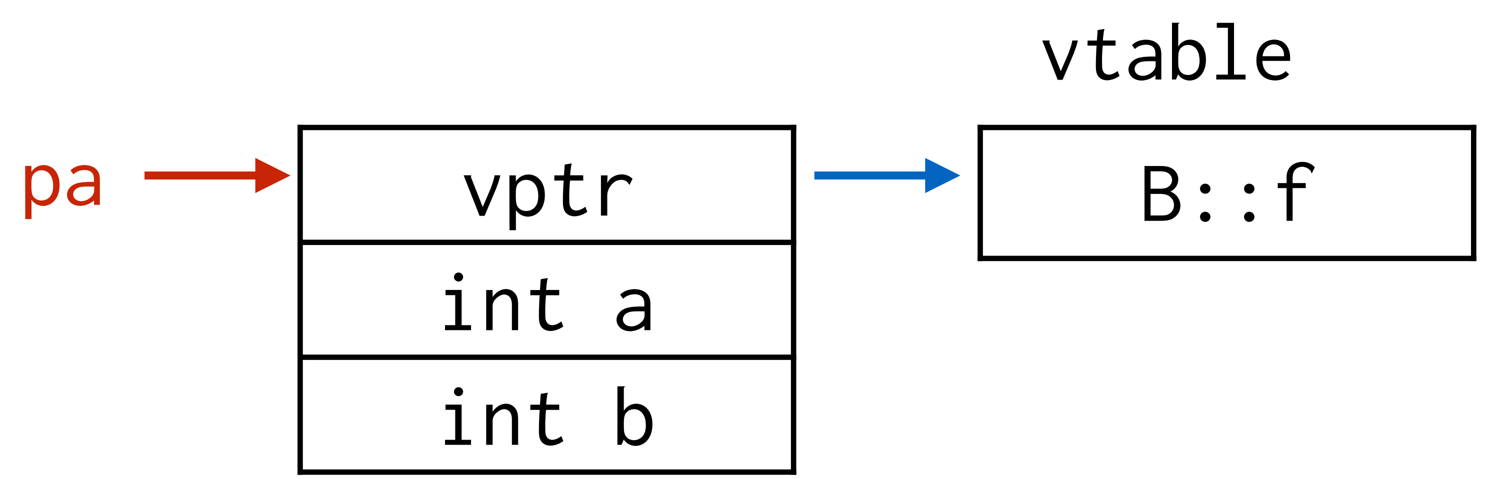
- Non-virtual functions
  - Do they get called directly? **A: yes**, B: no
- Virtual functions
  - Do they get called directly? A: yes, **B: no**
  - They go through the vtable

Non-virtual vs. Virtual

- Non-virtual functions
  - Can they be redefined? A: yes, B: no, **C: ehhhh**
  - They can be overloaded
- Virtual functions
  - Can they be redefined? **A: yes**, B: no, C: ehhhh

Virtual methods can be redefined

```
class A {
  int a;
  virtual void f() {
    printf(“parent”);
  }
}
class B : A {
  int b;
  virtual void f() {
    printf(“child”);
  }
}
A* pa = new B();
pa->f();
```

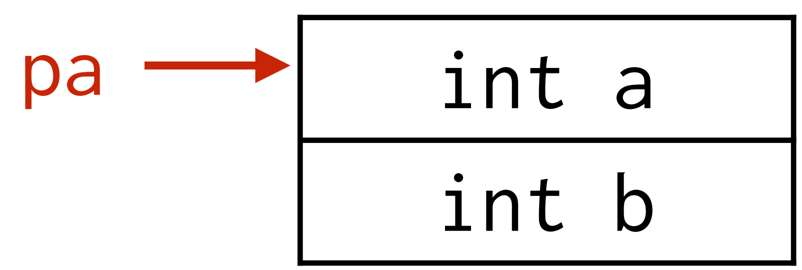


compiles to

```
(*(pa->vptr[0]))(pa)
```

Non-virtual functions are overloaded

```
class A {
  int a;
  void f() {
    printf("parent");
  }
}
class B {
  int b;
  void f() {
    printf("child");
  }
}
A* pa = new B();
pa->f();
```



compiles to →

```
__A_f(pa)
```

info necessary to lookup function: type of pointer

Dynamic vs. static OO systems

- Smalltalk and JavaScript: no static type system
  - In message `obj.method(arg)`, the `obj` can refer to anything
  - Need to find method using pointer from `obj`
  - The location in dictionary/hashtable will vary
- In C++ compiler knows the superclass for `obj`
  - Offset of data and function pointers are the same in subclass and superclass
  - Invoke function pointer at fixed offset in vtable!

Virtual method call takeaway

Invoke function pointer at fixed offset in vtable!

Today

- Statically-typed OO languages: C++
    - ➤ vtables
- Closer look at subtyping

What is subtyping?

- Relationship between interfaces
  - in contrast to inheritance: relationship between implementations
- If interface A contains all of interface B, then A <: B
  - Interface = set of messages the object understands
  - Eg., ColorPoint <: Point

Subtyping in JavaScript

- Objects implicitly have an interface
  - No recorded by some type system;

```
Point        {x, y, move}
ColoredPoint {x, y, color, move}
```

- No relationship to inheritance
  - can delete methods, etc.

```
Boo {x, y, move, boo}
```

Subtyping in C++

- Subtyping is explicit
  - A <: B if A has public base class B
- Why is this not enough?

```
class ColoredPoint {
 public:
   virtual void move();
   virtual int  color();
 private:
   ...
}
```

```
class Point {
 public:
   virtual int move();
 private:
   ...
}
```

What is an interface in C++?

- Recall: everything gets compiled down to fn call
  - memory layout of objects
  - memory layout of vtables
- From inheritance, we get:
  - compatible memory layout
  - subtype relation

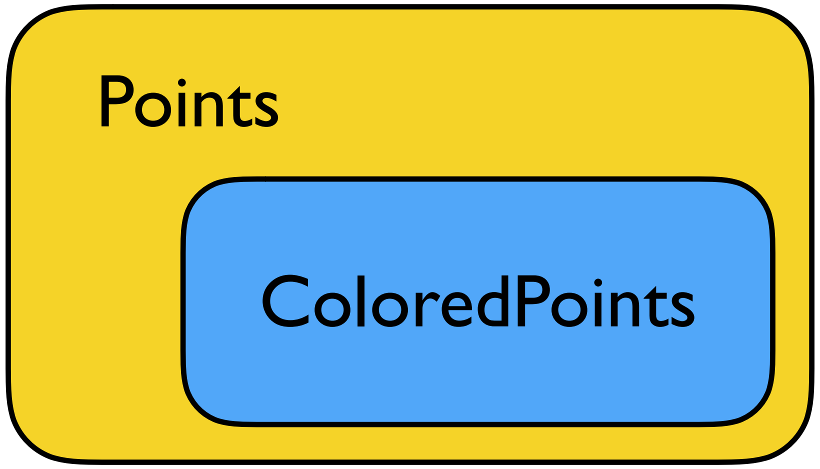
What does subtyping really mean?

Where does the name come from?

- ColoredPoint vs. Point
  - Interface is clearly bigger for Colored Point

```
Point        {x, y, move}
ColoredPoint {x, y, color, move}
```

- Why **sub**type?
  - Think: Natural <: Integer
  - Think:



What does it mean in PL?

- S is a subtype of T if any term of type S can be used* in a context where a term of type T is expected
    - This is a runtime phenomenon: when one term can be used where an object of another type is expected
    - Static type system can tell us if we got it right

What does it mean in PL?

$$\frac{e :: S \qquad S <: T}{e :: T}$$

Who defines <: ?

- Language designers!
- How is `<:` defined in C++?
  - Class definition: `class B: public A { }` tells us `B <: A`
- Why is the definition important?
  - It may restrict how we can override functions in subclasses

Return covariance

- Is it OK to override `clone` as follows?

```
class A {
 public:
   virtual bool equals(A&);
   virtual A* clone();
}
```

```
class B: public A {
 public:
   bool equals(A&);
   B* clone();
}
```

  - ➤ Yes! Why? any case we need `clone` of `A`s, we can use `B`'s `clone` and upcast the `B` to an `A`.

Argument ~~covariance~~

- Is it OK to override `clone` as follows?

```
class A {
 public:
   virtual bool equals(A&);
   virtual A* clone();
}
```

```
class B: public A {
 public:
   bool equals(B&);
   B* clone();
}
```

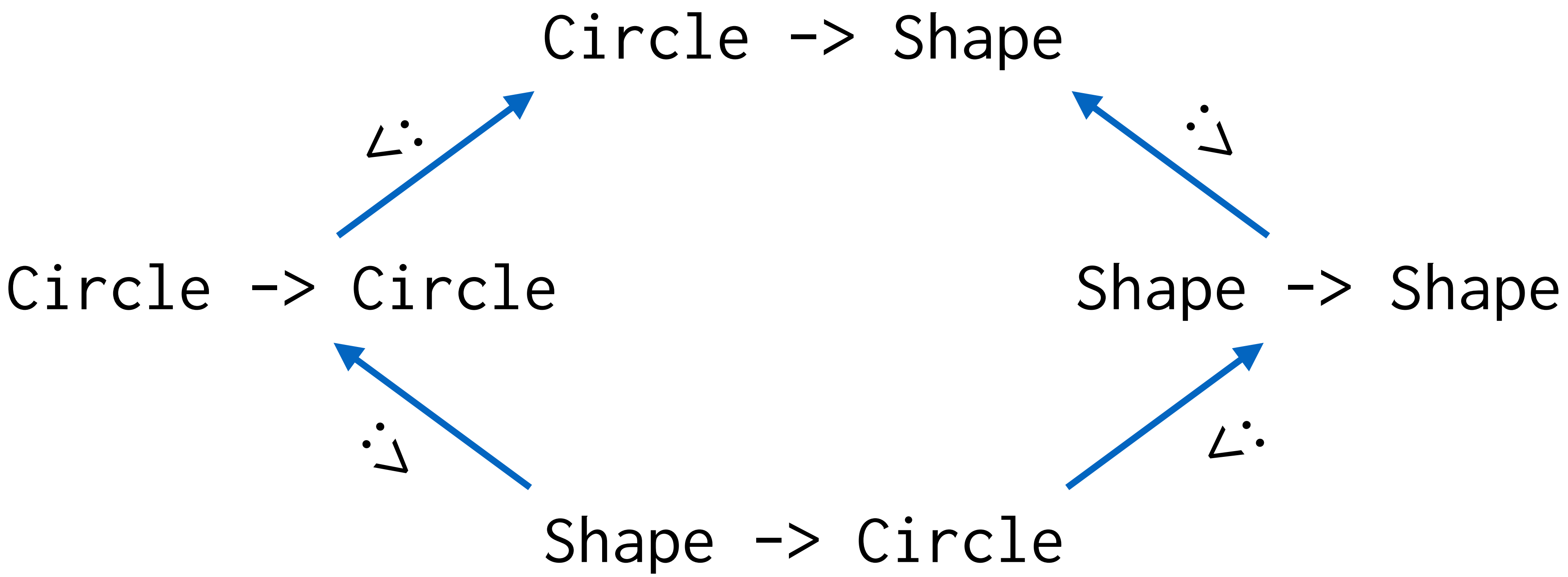
  - No! Why? the implementation of equals must be prepared for any object of type `A` to be passed in; `B` is one kind of `A`

Subtyping rule for functions

- Subtyping for function results
  - if `A <: B` then `C -> A <: C -> B` (covariance)
- Subtyping for function arguments
  - if `A <: B` then `B -> C <: A -> C` (contravariance)

Example

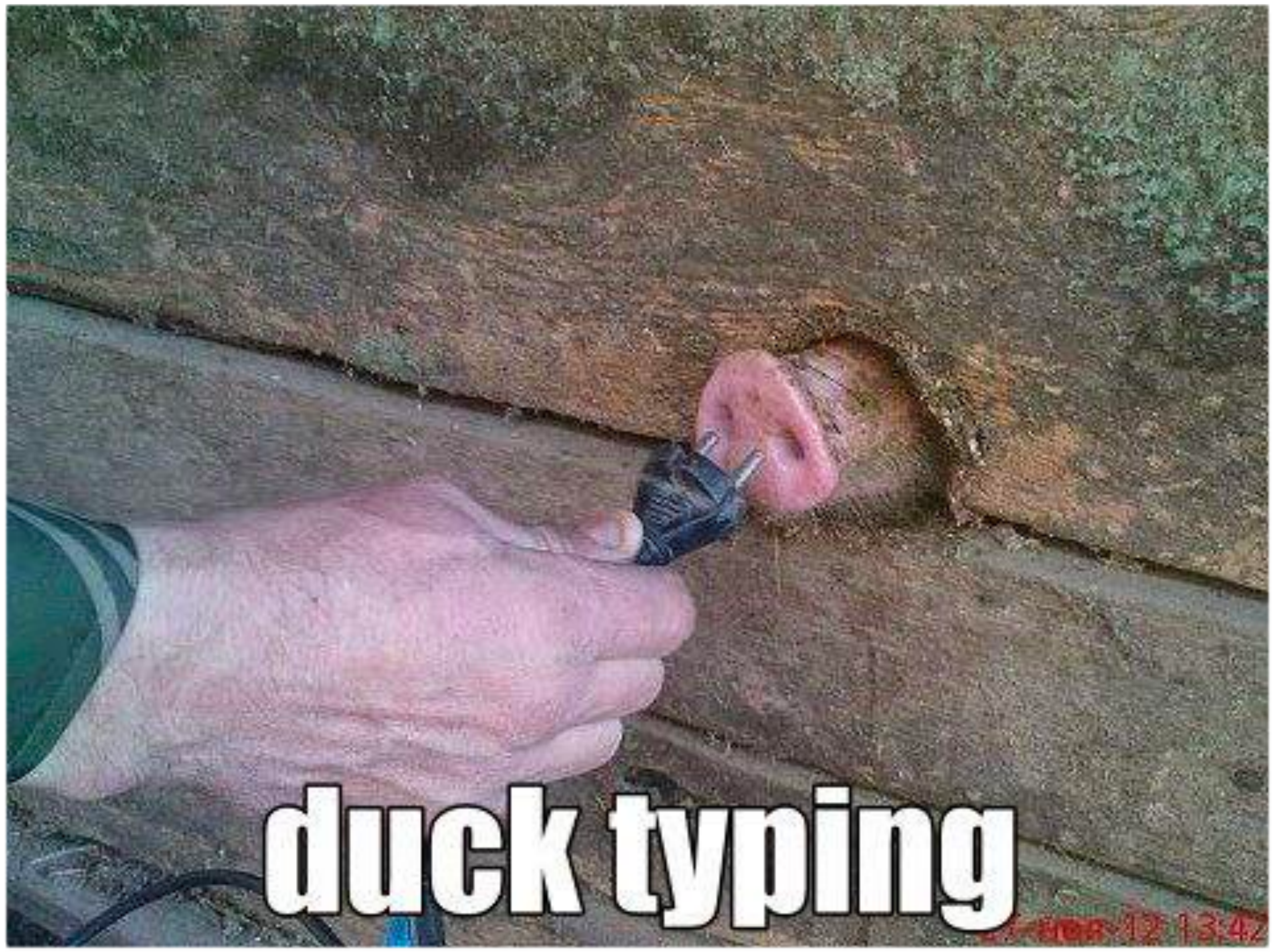
`Circle <: Shape`



For other data types: can be tricky!

- E.g., Java screwed up <: definition for Arrays
  - Generic arrays are covariant
  - Breaks type and memory safety!

We are placing trust in <:


duck typing

Can we do better?

Behavioral subtyping (Liskov substitution principle)

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