C++ & Subtyping

Week 7

- Statically-typed OO languages: C++
- 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)
}
```

Does runtime representation of A objects change? A: yes, B: no

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 B object

int a
int b

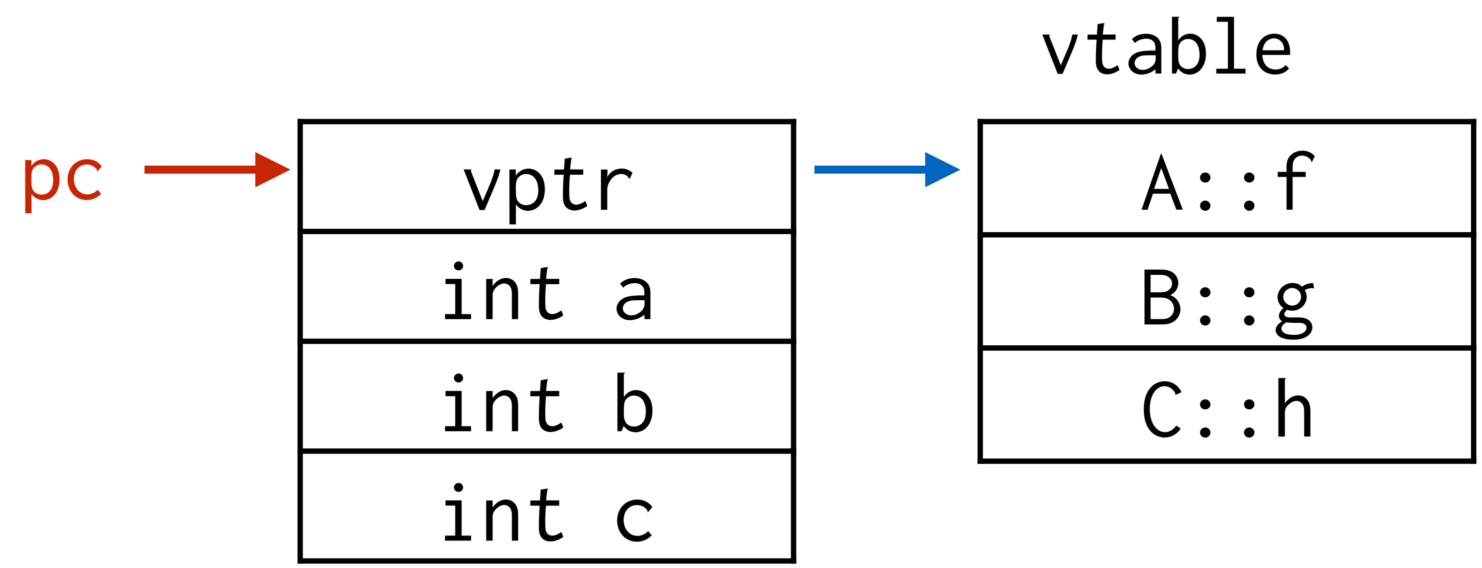
runtime representation of C object

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)
```

info necessary to lookup function: found at runtime

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

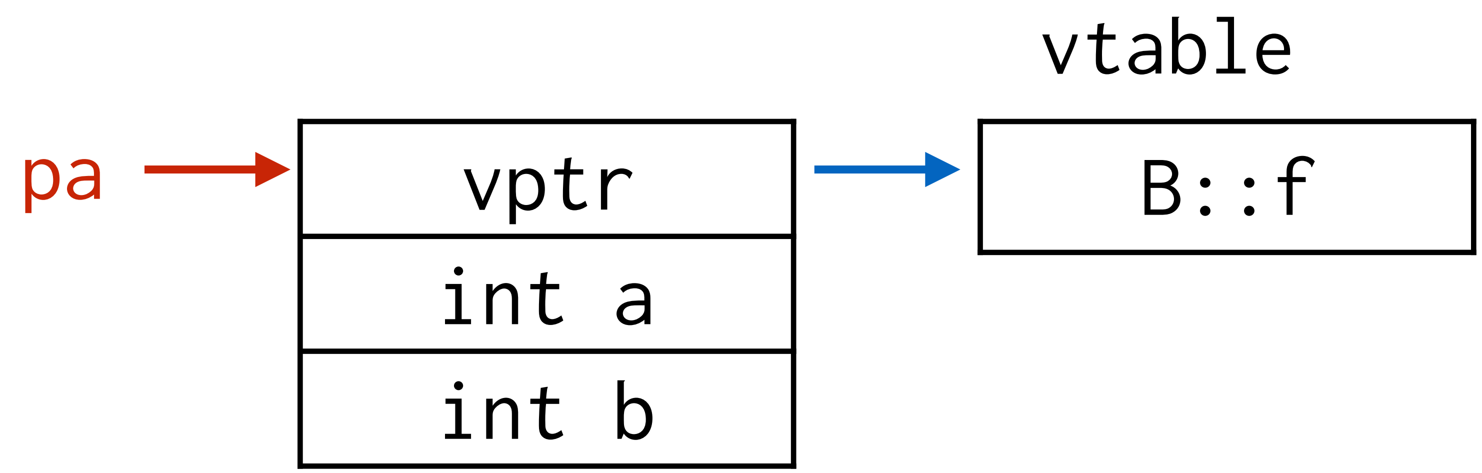
Non-virtual vs. Virtual

- 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();
```

runtime representation of B object



compiles to

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

info necessary to lookup
function: found at runtime

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();
```

runtime representation of B object

pa

`int a`
`int b`

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!

Week 7

- Statically-typed OO languages: C++
- 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, move, color}
```

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

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

Subtyping in C++

- Is implementing same functions enough?
  - A: yes, B: no

```
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

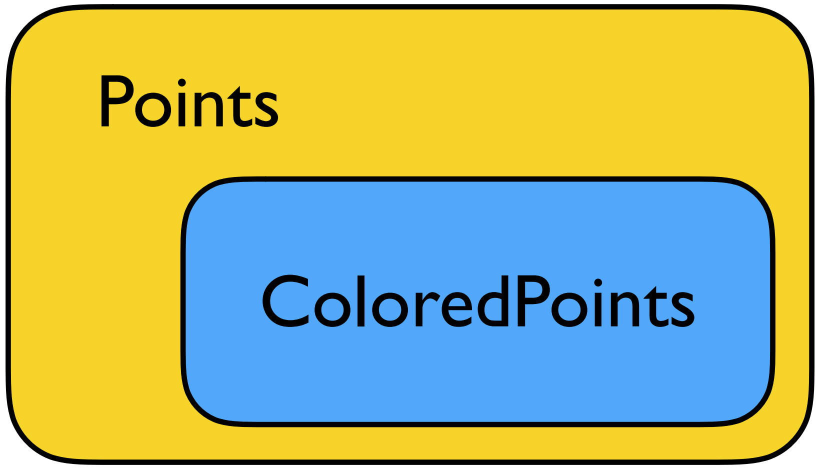
What does subtyping really mean?

Where does the name come from?

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

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

- 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

Who defines $<:$?

A: developers **B:** language designers

Who defines <: ?

- 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`.
  - Suppose `A* pa = new B();` then `pa->clone();` returns a `B*` that can always be casted to an `A*`

Argument ~~covariance~~

- Is it OK to override `equals` 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`
  - Suppose `A* pa1 = new B();` and `A* pa2 = new C();` where `C` is a subclass of `A` then `pa->equals(pa2);` should fail since we should not be allowed to cast a `C` object to a `B` object

Subtyping rule for functions

- Subtyping for function results
  - if `A <: B` then `C -> A <: C -> B` (covariance)
    - E.g., `C -> ColorPoint <: C -> Point`
  - Anywhere you expect a function that returns a `B` you can use a function that returns an `A` — `A`'s "are" `B`'s so you can upcast the return value

Subtyping rule for functions

- Subtyping for function arguments
  - if `A <: B` then `B -> C <: A -> C` (contravariance)
    - E.g., `Point -> C <: ColorPoint -> C`
  - Anywhere you expect a function that can operate `A`s you can use a more general function that operates on `B`s — you can always cast the `A` argument you were going to call the function with to a `B`

Return covariance (w/ records)

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

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

```
type A = {                          type B = {
  equals :: A -> bool;    <:          equals :: A -> bool;
  clone  :: () -> A;      <:          clone  :: () -> B;
}                                   }
```

Argument covariance (w/ records)

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

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

```
type A = {
  equals :: A -> bool;
  clone  :: () -> A;
}
```

$\cancel{<:}$

$<:$

```
type B = {
  equals :: B -> bool;
  clone  :: () -> B;
}
```

Example

`Circle <: Shape`

$$
\begin{tikzcd}
 & \texttt{Circle -> Shape} & \\
\texttt{Circle -> Circle} \arrow[ur, "<:"] & & \texttt{Shape -> Shape} \arrow[ul, "<:"'] \\
 & \texttt{Shape -> Circle} \arrow[ul, "<:"] \arrow[ur, "<:"'] &
\end{tikzcd}
$$

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 <:

Today

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