

# Object typing and subtypes

## Reading

Chapter 10, section 10.2.3

Chapter 11, sections 11.3.2 and 11.7

Chapter 12, section 12.4

Chapter 13, section 13.3

# Subtyping and Inheritance

- Interface
  - The external view of an object
- Subtyping
  - Relation between interfaces
- Implementation
  - The internal representation of an object
- Inheritance
  - Relation between implementations

# Example: Smalltalk Point class

class name	Point
super class	Object
class var	pi
instance var	x y
class messages and methods	
<...names and code for methods...>	
instance messages and methods	
<...names and code for methods...>	

# Subclass: ColorPoint

class name	ColorPoint
super class	Point
class var	
instance var	color
class messages and methods	
newX:xv Y:yv C:cv	< ... code ... >
instance messages and methods	
color	^color
draw	< ... code ... >

add instance variable

add method

override Point method

# Object Interfaces

- Interface
  - The messages understood by an object
- Example: point
  - x:y: set x,y coordinates of point
  - moveDx:Dy: method for changing location
  - x returns x-coordinate of a point
  - y returns y-coordinate of a point
  - draw display point in x,y location on screen
- The interface of an object is its *type*

# Subtyping

- If interface A contains all of interface B, then A objects can also be used B objects.

Point

x:y:

moveDx:Dy:

x

y

draw

Colored\_point

x:y:

moveDx:Dy:

x

y

color

draw

Colored\_point interface contains Point  
Colored\_point is a subtype of Point

# Implicit Object types – Smalltalk/JS

- Each object has an interface
  - Smalltalk: set of instance methods declared in class
  - Example:

```
Point      { x:y:, moveDx:Dy:, x, y, draw}
ColorPoint { x:y:, moveDx:Dy:, x, y, color, draw}
```
  - This is a form of type
    - Names of methods, does not include type/protocol of arguments
- Object expression and type
  - Send message to object

```
p draw          p x:3 y:4
q color         q moveDx: 5 Dy: 2
```
  - Expression OK if message is in interface

# Subtyping

- Relation between interfaces
  - Suppose expression makes sense

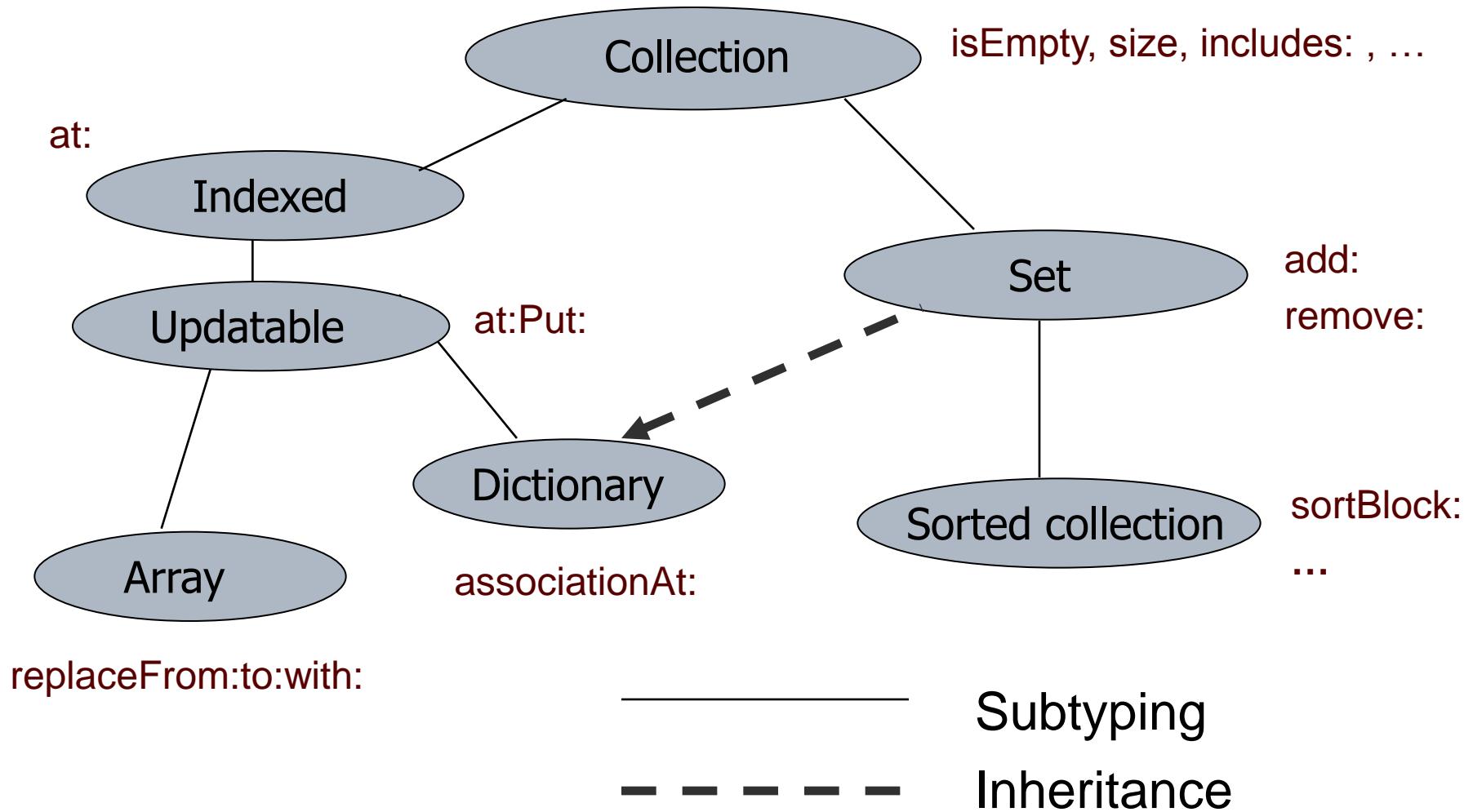
p msg:pars -- OK if msg is in interface of p
  - Replace p by q if interface of q contains interface of p
- Subtyping
  - If interface is superset, then a subtype
  - Example: ColorPoint subtype of Point
  - Sometimes called “conformance”

Can extend to more detailed interfaces that include types of parameters

# Subtyping and Inheritance

- Smalltalk/JavaScript subtyping is implicit
  - Not a part of the programming language
  - Important aspect of how systems are built
- Inheritance is explicit
  - Used to implement systems
  - No forced relationship to subtyping

# Smalltalk Collection Hierarchy



# C++ Subtyping

- Subtyping in principle
  - $A <: B$  if every  $A$  object can be used without type error whenever a  $B$  object is required
  - Example:

Point:	int getX(); void move(int);	{	Public members
ColorPoint:	int getX(); int getColor(); void move(int); void darken(int tint);		

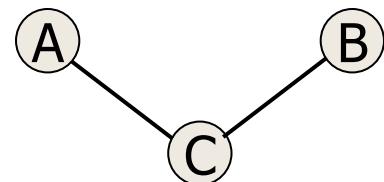
- C++:  $A <: B$  if class  $A$  has public base class  $B$

# Implementation of subtyping

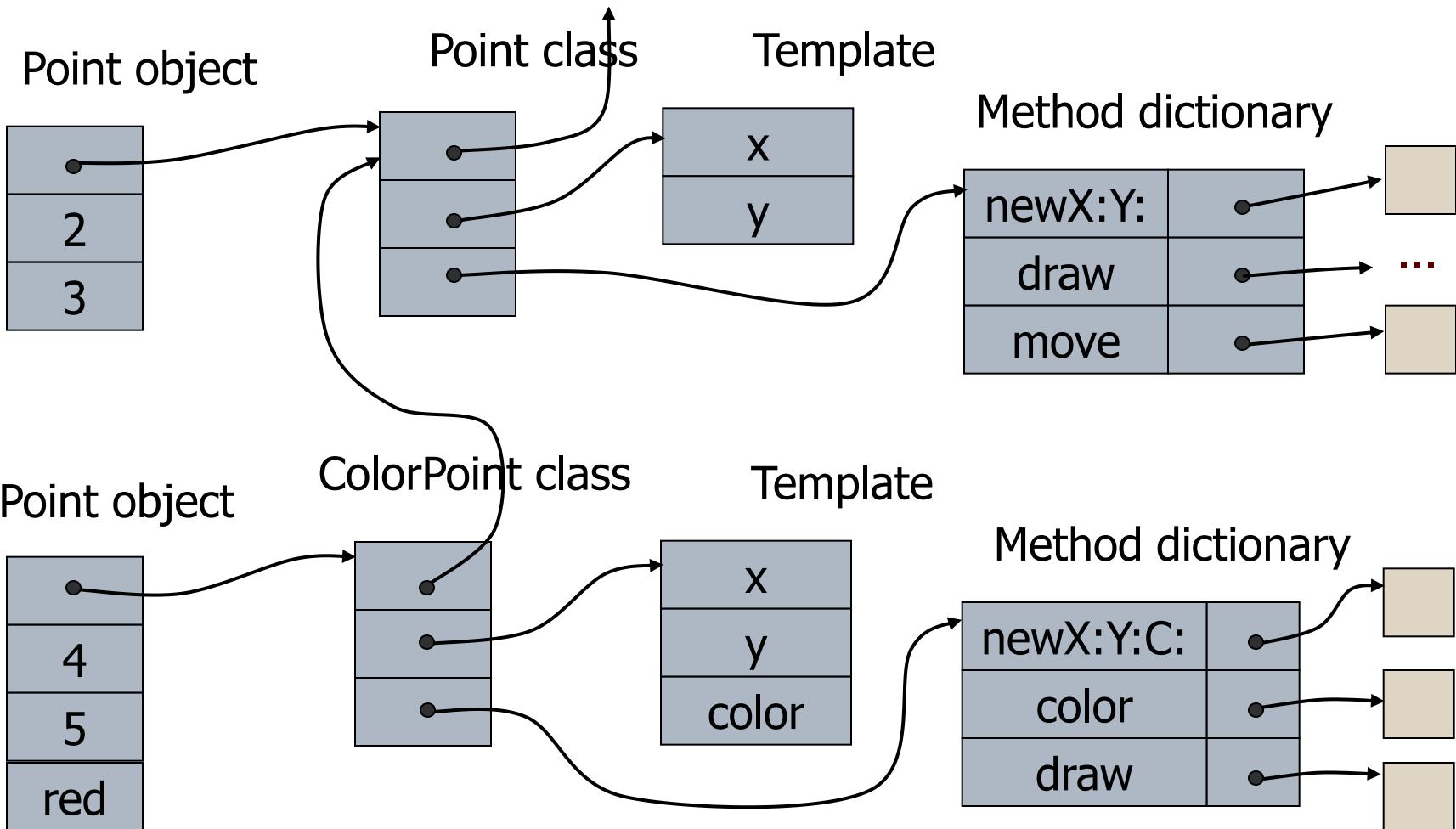
- No-op
  - Dynamically-typed languages
  - C++ object representations (single-inheritance only)

```
circle *c = new Circle(p,r);  
shape *s = c; // s points to circle c
```
- Conversion
  - C++ object representations w/multiple-inheritance

```
C *pc = new C;  
B *pb = pc;  
A *pa = pc;  
// may point to different position in object
```



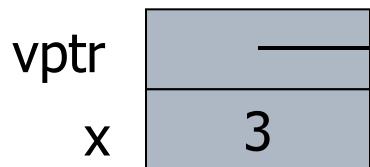
# Smalltalk/JavaScript Representation



This is a schematic diagram meant to illustrate the main idea. Actual implementations may differ.

# C++ Run-time representation

Point object



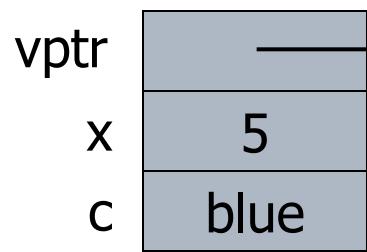
Point vtable



Code for move



ColorPoint object



ColorPoint vtable



Code for move

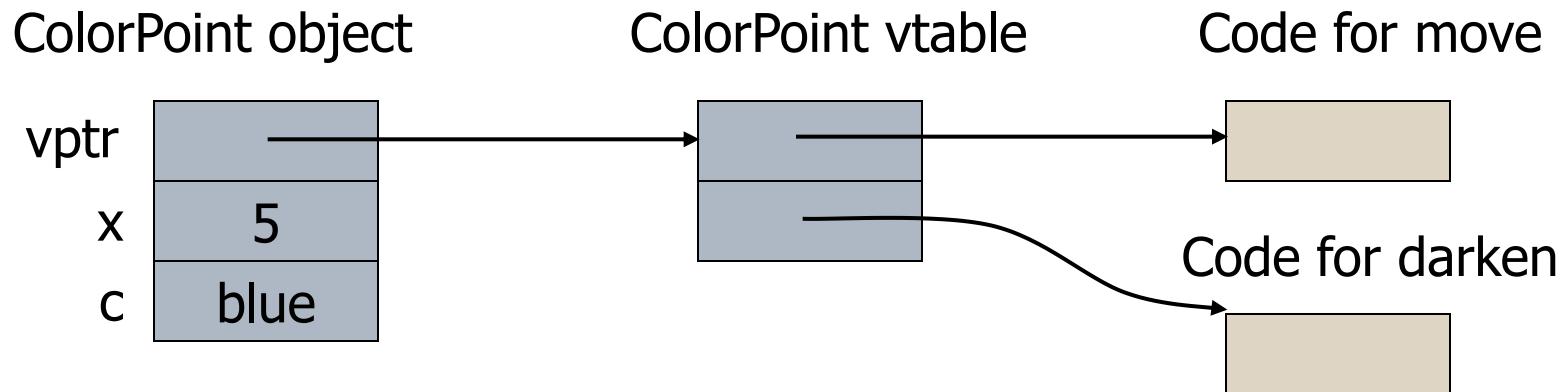
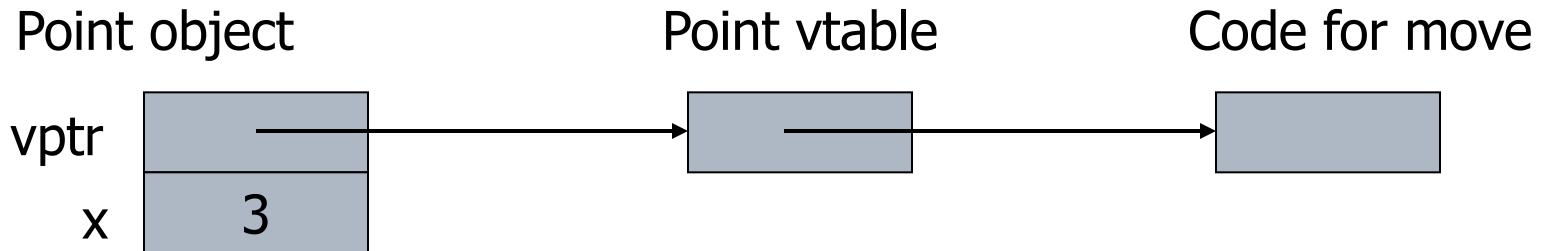
Code for darken



Data at same offset

Function pointers at same offset

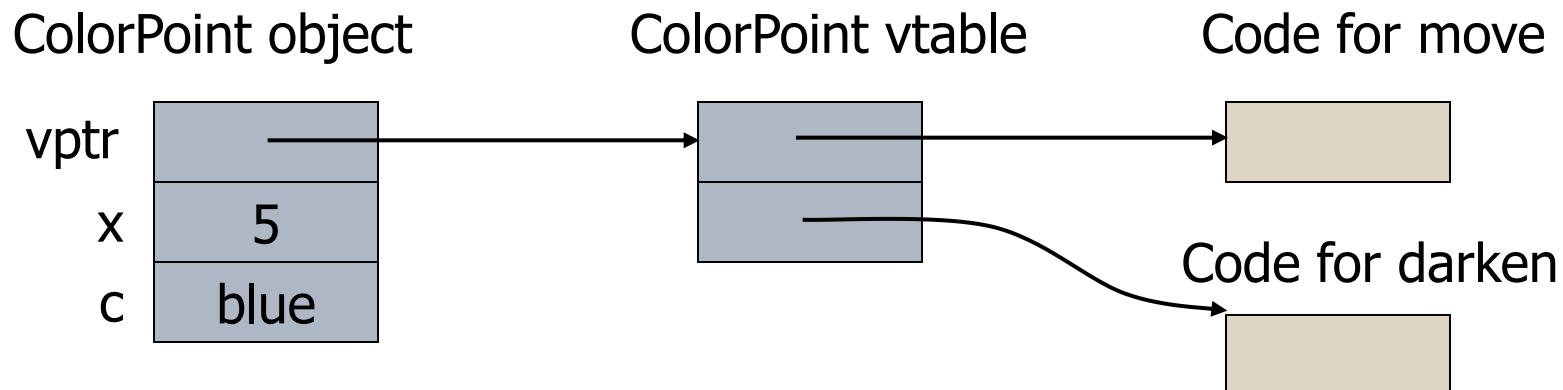
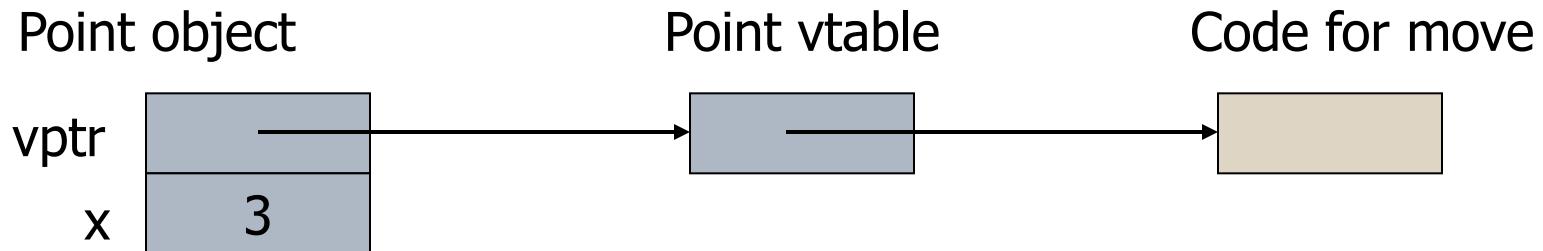
# C++: virtual function lookup



Point p = new Pt(3);

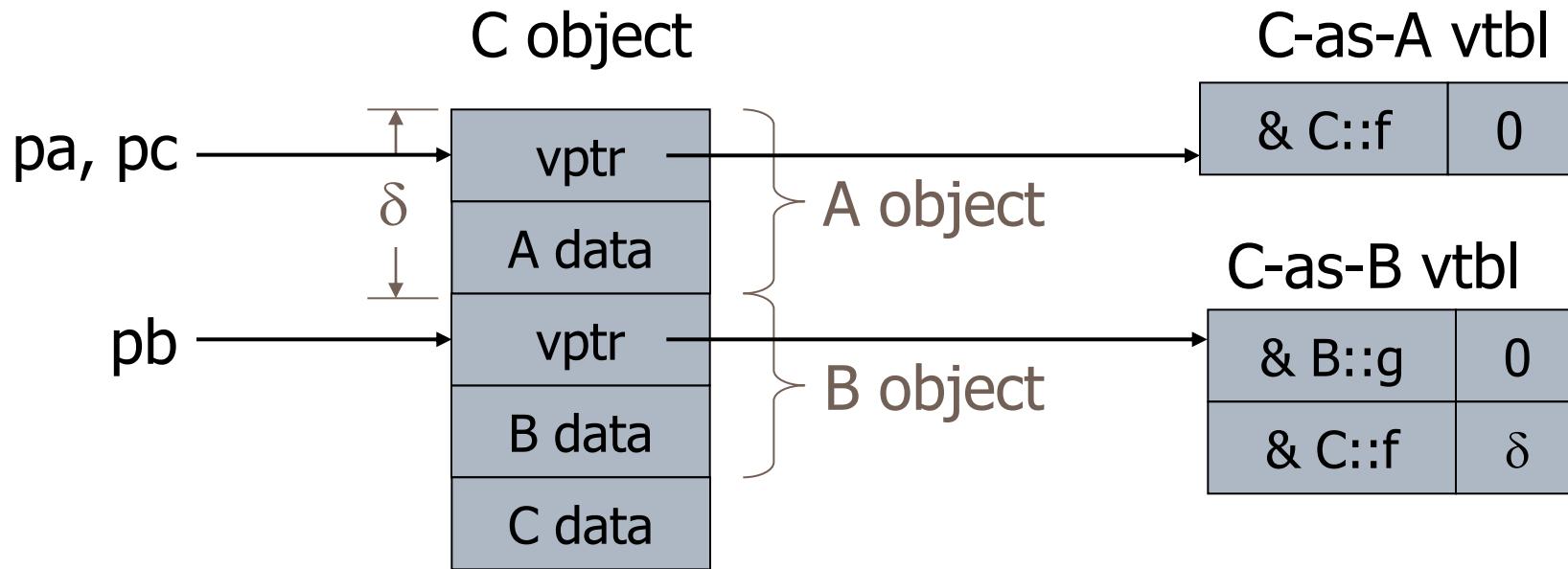
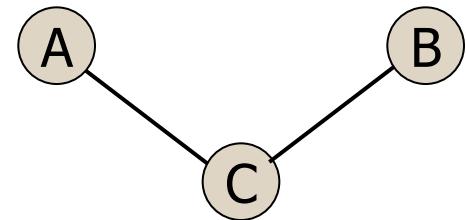
p->move(2);                  // (\*(p->vptr[0]))(p,2)

# C++: virtual function lookup, part 2



```
Point cp = new ColorPt(5,blue);
cp->move(2);        // (*(cp->vptr[0]))(cp,2)
```

# C++ Multiple Inheritance



- Offset  $\delta$  in vtbl is used in call to `pb->f`, since `C::f` may refer to `A` data that is above the pointer `pb`
- Call to `pc->g` can proceed through C-as-B vtbl

# Independent classes not subtypes

```
class Point {  
public:  
    int getX();  
    void move(int);  
protected: ...  
private:   ...  
};
```

```
class ColorPoint {  
public:  
    int getX();  
    void move(int);  
    int getColor();  
    void darken(int);  
protected: ...  
private:   ...  
};
```

- C++ does not treat `ColorPoint <: Point` as written
  - Need public inheritance `ColorPoint : public Point`
  - Why??

# Why C++ design?

- Client code depends only on public interface
  - In principle, if ColorPoint interface contains Point interface, then any client could use ColorPoint in place of point
  - However -- offset in virtual function table may differ
  - Lose implementation efficiency (like Smalltalk)
- Without link to inheritance
  - Subtyping leads to loss of implementation efficiency
- Also encapsulation issue:
  - Subtyping based on inheritance is preserved under modifications to base class ...

# Recurring subtype issue: downcast

- The Simula type of an object is its class
- Simula downcasts are checked at run-time
- Example:

```
class A(...); ...
```

```
A class B(...); ...
```

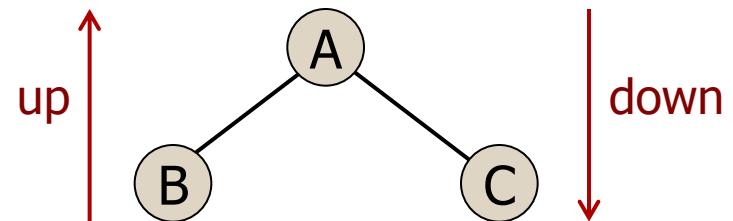
```
ref (A) a :- new A(...)
```

```
ref (B) b :- new B(...)
```

```
a := b      /* OK since B is subclass of A */
```

```
...
```

```
b := a      /* compiles, but run-time test */
```

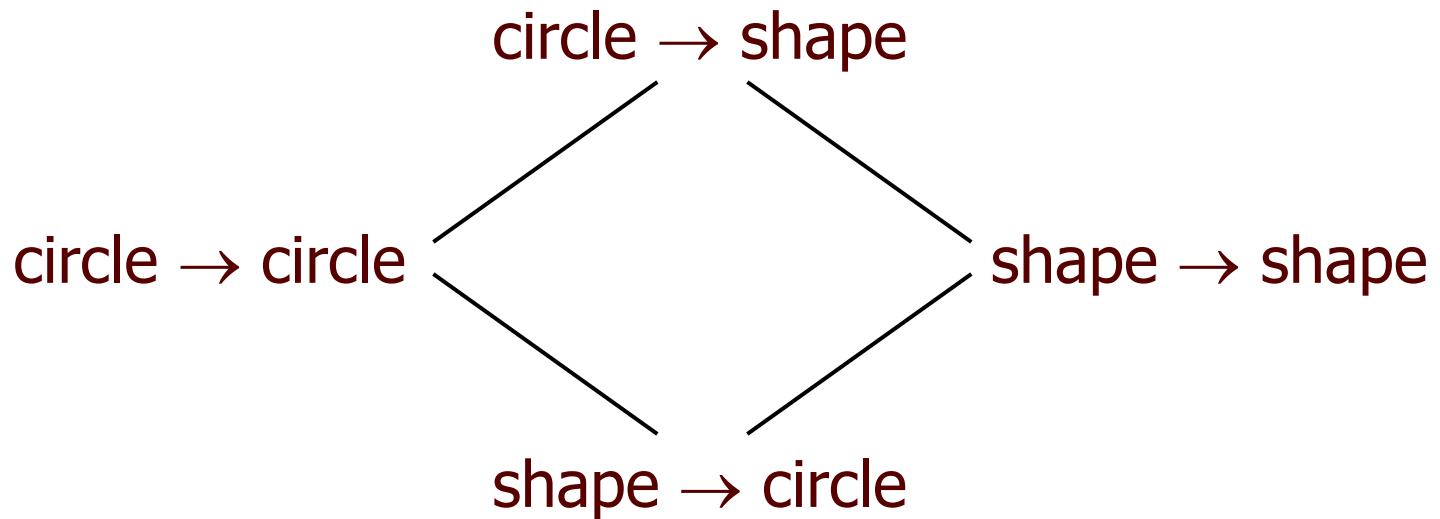


# Function subtyping

- Subtyping principle
  - $A <: B$  if an  $A$  expression can be safely used in any context where a  $B$  expression is required
- Subtyping for function results
  - If  $A <: B$ , then  $C \rightarrow A <: C \rightarrow B$
- Subtyping for function arguments
  - If  $A <: B$ , then  $B \rightarrow C <: A \rightarrow C$
- Terminology
  - Covariance:  $A <: B$  implies  $F(A) <: F(B)$
  - Contravariance:  $A <: B$  implies  $F(B) <: F(A)$

# Examples

- If  $\text{circle} <: \text{shape}$ , then



C++ compilers recognize limited forms of function subtyping

# Subtyping with functions

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

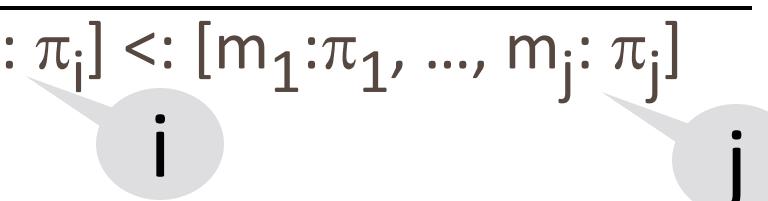
```
class ColorPoint: public Point {  
public:  
    int getX();  
    int getColor();  
    ColorPoint * move(int);  
    void darken(int);  
protected: ...  
private: ...  
};
```

Inherited, but repeated here for clarity

- In principle:  $\text{ColorPoint} <: \text{Point}$
- In practice: This is covariant case; contravariance is another story

# Subtyping principles (recap)

- “Width” subtyping for object types

$$\frac{i > j}{[m_1:\pi_1, \dots, m_i:\pi_i] <: [m_1:\pi_1, \dots, m_j:\pi_j]}$$


- “Depth” subtyping for object types

$$\frac{\sigma_i <: \pi_i}{[m_1:\sigma_1, \dots, m_i:\sigma_i] <: [m_1:\pi_1, \dots, m_j:\pi_j]}$$

- Function subtyping

$$\frac{\sigma' <: \sigma \quad \pi <: \pi'}{\sigma \rightarrow \pi <: \sigma' \rightarrow \pi'}$$

# Subtyping recursive types

- Principle

$$\frac{s <: t \Rightarrow \sigma(s) <: \pi(t)}{\text{type } s = \sigma(s) <: \text{type } t = \pi(t)}$$

s not in  $\pi(t)$   
t not in  $\sigma(s)$

- Example

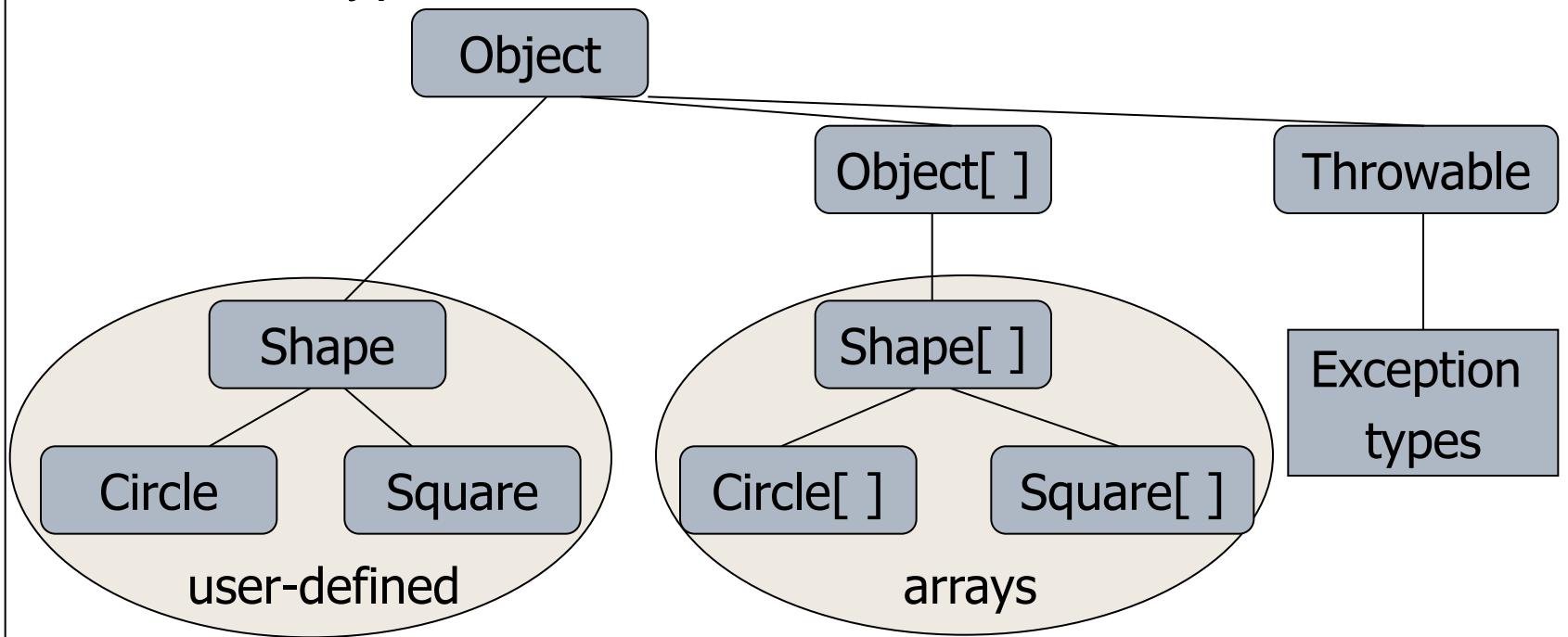
$$\frac{cp <: p \Rightarrow \{ \dots mv: \text{int} \rightarrow cp \} <: \{ \dots mv: \text{int} \rightarrow p \}}{\text{type } cp = \{ \dots mv: \text{int} \rightarrow cp \} <: \text{type } p = \{ \dots mv: \text{int} \rightarrow p \}}$$

# Java Types

- Two general kinds of types
  - Primitive types – *not* objects
    - Integers, Booleans, etc
  - Reference types
    - Classes, interfaces, arrays
    - No syntax distinguishing Object \* from Object
- Static type checking
  - Every expression has type, determined from its parts
  - Some auto conversions, many casts are checked at run time
  - Example, assuming A <: B
    - If A x, then can use x as argument to method that requires B
    - If B x, then can try to cast x to A
    - Downcast checked at run-time, may raise exception

# Classification of Java types

## Reference Types



## Primitive Types



# Subtyping

- Primitive types
  - Conversions: int -> long, double -> long, ...
- Class subtyping similar to C++
  - Subclass produces subtype
  - Single inheritance => subclasses form tree
- Interfaces
  - Completely abstract classes
    - no implementation
  - Multiple subtyping
    - Interface can have multiple subtypes (implements, extends)
- Arrays
  - Covariant subtyping – not consistent with semantic principles

# Java class subtyping

- Signature Conformance
  - Subclass method signatures must conform to superclass
- Three ways signature could vary
  - Argument types
  - Return type
  - Exceptions
  - How much conformance is needed in principle?
- Java rule
  - Java 1.1: Arguments and returns must have identical types, may remove exceptions
  - Java 1.5: covariant return type specialization

# Interface subtyping: example

```
interface Shape {  
    public float center();  
    public void rotate(float degrees);  
}  
  
interface Drawable {  
    public void setColor(Color c);  
    public void draw();  
}  
  
class Circle implements Shape, Drawable {  
    // does not inherit any implementation  
    // but must define Shape, Drawable methods  
}
```

Q: can interfaces be recursive?

# Properties of interfaces

- **Flexibility**
  - Allows subtype graph instead of tree
  - Avoids problems with multiple inheritance of implementations (remember C++ “diamond”)
- **Cost**
  - Offset in method lookup table not known at compile
  - Different bytecodes for method lookup
    - one when class is known
    - one when only interface is known
      - search for location of method
      - cache for use next time this call is made (from this line)

More about this later ...

# Array types

- Automatically defined
  - Array type  $T[ ]$  exists for each class, interface type  $T$
  - Cannot extend array types (array types are final)
  - Multi-dimensional arrays are arrays of arrays:  $T[ ] [ ]$
- Treated as reference type
  - An array variable is a pointer to an array, can be null
  - Example: `Circle[] x = new Circle[array_size]`
  - Anonymous array expression: `new int[] {1,2,3, ... 10}`
- Every array type is a subtype of `Object[ ]`, `Object`
  - Length of array is not part of its static type

# Array subtyping

- Covariance
  - if  $S <: T$  then  $S[ ] <: T[ ]$

- Standard type error

```
class A {...}
```

```
class B extends A {...}
```

```
B[ ] bArray = new B[10]
```

```
A[ ] aArray = bArray // considered OK since B[] <: A[]
```

```
aArray[0] = new A() // compiles, but run-time error  
// raises ArrayStoreException
```

# Covariance problem again ...

- Simula problem
  - If  $A <: B$ , then  $A \text{ ref} <: B \text{ ref}$
  - Needed run-time test to prevent bad assignment
  - Covariance for assignable cells is not right in principle
- Explanation
  - interface of “T reference cell” is
    - put :  $T \rightarrow T \text{ ref}$
    - get :  $T \text{ ref} \rightarrow T$
  - Remember covariance/contravariance of functions

# Afterthought on Java arrays

Date: Fri, 09 Oct 1998 09:41:05 -0600

From: bill joy

Subject: ...[discussion about java genericity]

actually, java array covariance was done for less noble reasons ...: it made some generic "bcopy" (memory copy) and like operations much easier to write...

I proposed to take this out in 95, but it was too late (...).

i think it is unfortunate that it wasn't taken out...

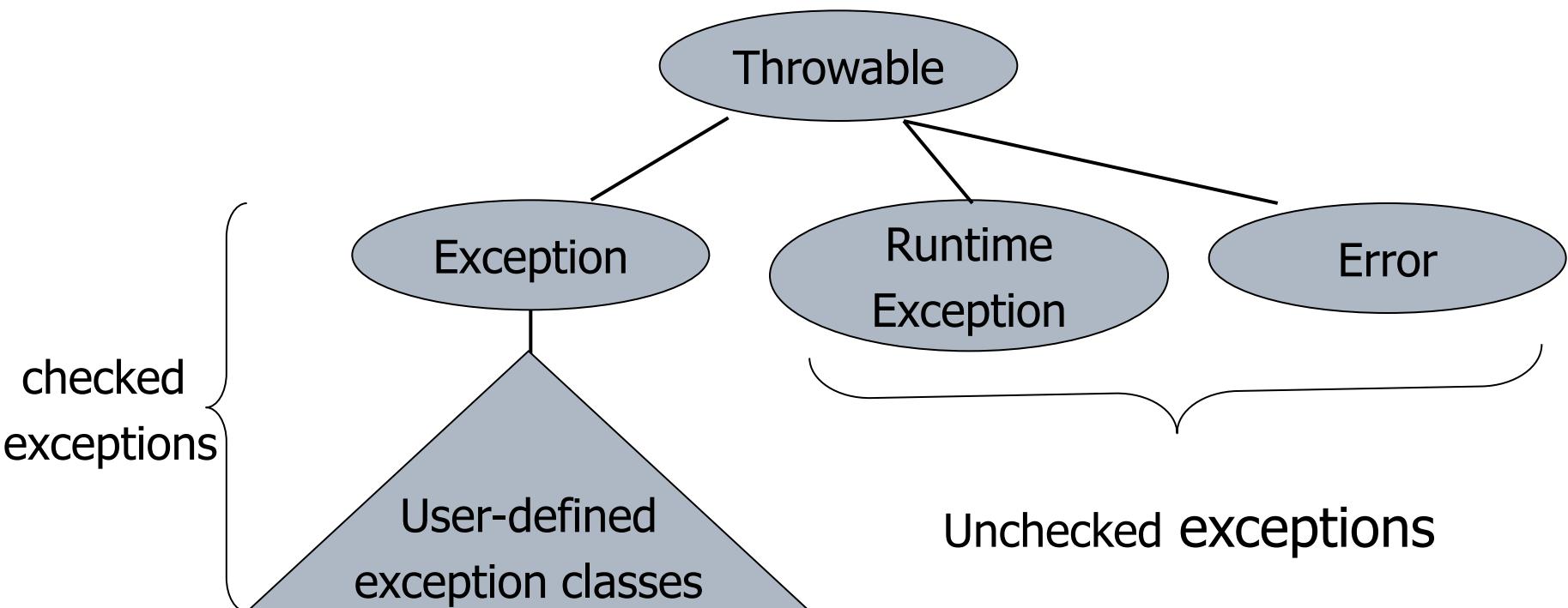
it would have made adding genericity later much cleaner, and [array covariance] doesn't pay for its complexity today.

wnj

# Java Exceptions

- Similar basic functionality to other languages
  - Constructs to *throw* and *catch* exceptions
  - Dynamic scoping of handler
- Some differences
  - An exception is an object from an exception class
  - Subtyping between exception classes
    - Use subtyping to match type of exception or pass it on ...
    - Similar functionality to ML pattern matching in handler
  - Type of method includes exceptions it can throw
    - Actually, only subclasses of Exception (see next slide)

# Exception Classes



If a method may throw a checked exception, then exception must be in the type of the method

# Why define new exception types?

- Exception may contain data
  - Class Throwable includes a string field so that cause of exception can be described
  - Pass other data by declaring additional fields or methods
- Subtype hierarchy used to catch exceptions
  - catch <exception-type> <identifier> { ... }
  - will catch any exception from any subtype of exception-type and bind object to identifier

# Subtyping concepts

- Type of an object represents its interface
- Subtyping has associated substitution principle
  - If  $A <: B$ , then A objects can be used in place of B objects
- Implicit subtyping in dynamically typed lang
  - Relation between interfaces determines substitutivity
- Explicit subtyping in statically typed languages
  - Type checker may recognize some subtyping
  - Issues: programming style, implementation efficiency
- Covariance and contravariance
  - Function argument types *reverse* order
  - Problems with Java array covariance

# Principles

- Object “width” subtyping
- Function covariance, contravariance
- Object type “depth” subtyping
- Subtyping recursive types

# Applications of principles

- Dynamically typed languages
  - If  $A <: B$  in principle, then can use A objects in place of B objects
- C++
  - Class subtyping only when public base class
  - Compiler allows width subtyping, covariant depth subtyping.  
(Think about why...)
- Java
  - Class subtyping only when declared using “extends”
  - Class and interface subtyping when declared
  - Compiler allows width subtyping, covariant depth subtyping
  - Additional typing issues related to generics