"A language that doesn't affect the way you think about programming, is not worth knowing."
- Unknown

CSE341
Programming Languages

Gebze Technical University Computer Engineering Department
2021-2022 Fall Semester
Object Oriented Programming

Slides are taken from J. Mitchell

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Functional Programming

- Functional programming is a style of programming:

Imperative Programming:
- Program = Data + Algorithms

OO Programming:
- Program = Object. message (object)

Functional Programming:
- Program = Functions Functions

- Computation is done by application of functions

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Object-Oriented Programming

- Object-oriented programming is a style of programming:

Imperative Programming:
- Program = Data + Algorithms

Logic Programming:
- Program = Axioms + Queries

Functional Programming:
- Program = Functions Functions

OO Programming:
- Program = Object.message (object)

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Outline

- Central concepts in object-oriented languages
  - Dynamic lookup, encapsulation, subtyping, inheritance
- Objects as activation records
  - Simula: implementation as activation records with static scope
- Pure dynamically-typed object-oriented languages
  - Object implementation and run-time lookup
  - Class-based languages (Smalltalk)
  - Prototype-based languages (Self, JavaScript)
- Statically-typed object-oriented languages
  - C++ – using static typing to eliminate search
  - C++ – problems with C++ multiple inheritance
  - Java – using Interfaces to avoid multiple inheritance

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Object-Oriented Programming

- Primary object-oriented language concepts
  - dynamic lookup
  - encapsulation
  - inheritance
  - subtyping
- Program organization
  - Work queue, geometry program, design patterns
- Comparison
  - Objects as closures?

Objects

- An object consists of
  - hidden data
    instance variables, also called fields, data members, …
    hidden functions also possible
  - public operations
    methods or member functions
    can also have public variables in some languages
- Object-oriented program:
  - Send messages to objects

hidden data	
msg_1	$method_1$
. . .	. . .
msg_n	$method_n$

What's interesting about this?

- Universal encapsulation construct
  - Data structure
  - File system
  - Database
  - Window
  - Integer
- Metaphor usefully ambiguous
  - sequential or concurrent computation
  - distributed, synchronous or asynchronous communication

Object-Orientation

- Programming methodology
  - organize concepts into objects and classes
  - build extensible systems
- Language concepts
  - dynamic lookup
  - encapsulation
  - subtyping allows extensions of concepts
  - inheritance allows reuse of implementation

Dynamic Lookup

- In object-oriented programming,
  object → message (arguments)
  code depends on object and message
- In conventional programming,
  operation (operands)
  meaning of operation is always the same

Fundamental difference between abstract data types (alone) and objects

Example

- Add two numbers x → add (y)
  different add if x is integer, string
- Conventional programming add (x, y)
  function add has fixed meaning

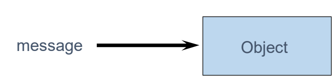
Important distinction:
Overloading is resolved at compile time
Dynamic lookup is a run time operation

Language Concepts

- “dynamic lookup”
  - different code for different objects
  - integer “+” different from string “+”
- encapsulation
- subtyping
- inheritance

Encapsulation

- Builder of a concept has detailed view
- User of a concept has “abstract” view
- Encapsulation separates these two views
  - Implementation code: operate on representation
  - Client code: operate by applying fixed set of operations provided by implementer of abstraction



Language Concepts

- "Dynamic lookup"
  - different code for different object
  - integer "+" different from real "+"
- Encapsulation
  - Implementer of a concept has detailed view
  - User has "abstract" view
  - Encapsulation separates these two views
- Subtyping
- Inheritance

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

Object Interfaces

- Interface
  - The messages understood by an object
- Example: point
  - x-coord : returns x-coordinate of a point
  - y-coord : returns y-coordinate of a point
  - move : method for changing location
- The interface of an object is its *type*

Subtyping

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

Point	Colored_point
x-coord	x-coord
y-coord	y-coord
move	color
	move
	change_color

Colored_point interface contains Point
Colored_point is a subtype of Point

Inheritance

- Implementation mechanism
- New objects may be defined by reusing implementations of other objects

Example

```
class Point
    private
        float x, y
    public
        point move (float dx, float dy);
class Colored_point
    private
        float x, y; color c
    public
        point move(float dx, float dy);
        point change_color(color newc);
```

Subtyping
- Colored points can be used in place of points
- Property used by client program

Inheritance
- Colored points can be implemented by reusing point implementation
- Technique used by implementer of classes

OO Program Structure

- Group data and functions
- Class
  - Defines behavior of all objects that are instances of the class
- Subtyping
  - Place similar data in related classes
- Inheritance
  - Avoid re-implementing functions that are already defined

Example: Geometry Library

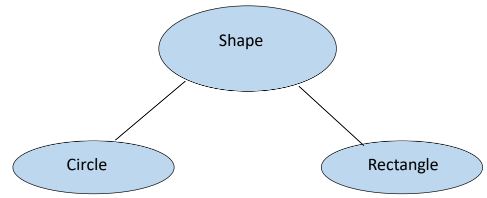
- Define general concept: shape
- Implement two shapes: circle, rectangle
- Functions on implemented shapes

  center, move, rotate, print
- Anticipate additions to library

Shapes

- Interface of every shape must include
  - center, move, rotate, print
- Different kinds of shapes are implemented differently
  - Rectangle: four points, representing corners
  - Circle: center point and radius

Subtype Hierarchy



- General interface defined in the shape class
- Implementations defined in circle, rectangle
- Extend hierarchy with additional shapes

Code Placed in Classes

	center	move	rotate	print
Circle	c_center	c_move	c_rotate	c_print
Rectangle	r_center	r_move	r_rotate	r_print

- Dynamic lookup
  - circle → move(x,y) calls function c_move
- Conventional organization
  - Place c_move, r_move in move function

Example use: Processing Loop

Remove shape from work queue
Perform action

Control loop does not know the type of each shape

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Simula: Objects as Activation Records

- Simula 67: First object-oriented language
- Designed for simulation
  - Later recognized as general-purpose programming language
- Extension of Algol 60
- Standardized as Simula (no "67") in 1977
- Inspiration to many later designers
  - Smalltalk
  - C++
  - ...

Brief history

- Norwegian Computing Center
  - Designers: Dahl, Myhrhaug, Nygaard
  - Simula-1 in 1966 (strictly a simulation language)
  - General language ideas
    - Influenced by Hoare's ideas on data types
    - Added classes and prefixing (subtyping) to Algol 60
  - Nygaard
    - Operations Research specialist and political activist
    - Wanted language to describe social and industrial systems
    - Allow "ordinary people" to understand political (?) changes
  - Dahl and Myhrhaug
    - Maintained concern for general programming

Sample Simula 67 Code

```
Begin
   Class Glyph;
      Virtual: Procedure print Is Procedure print;;
   Begin
   End;

   Glyph Class Char (c);
      Character c;
   Begin
      Procedure print;
        OutChar(c);
   End;

   Glyph Class Line (elements);
      Ref (Glyph) Array elements;
   Begin
      Procedure print;
      Begin
         Integer i;
         For i:= 1 Step 1 Until UpperBound (elements, 1) Do
            elements (i).print;
         OutImage;
      End;
   End;

   Ref (Glyph) rg;
   Ref (Glyph) Array rgs (1 : 4);

   ! Main program;
   rgs (1):- New Char ('A');
   rgs (2):- New Char ('b');
   rgs (3):- New Char ('b');
   rgs (4):- New Char ('a');
   rg:- New Line (rgs);
   rg.print;
End;
```

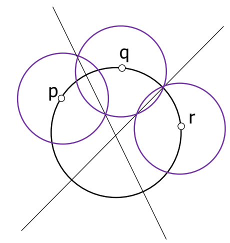
Source: https://www.quora.com/What-is-the-origin-of-common-Object-Oriented-Programming-notation

Objects in Simula

- Class
  - A procedure that returns a pointer to its activation record
- Object
  - Activation record produced by call to a class
- Object access
  - Access any local variable or procedures using dot notation: object.var
- Memory management
  - Objects are garbage collected
    - user destructors considered undesirable

Example: Circles and lines

- Problem
  - Find the center and radius of the circle passing through three distinct points, p, q, and r
- Solution
  - Draw intersecting circles Cp, Cq around p,q and circles Cq', Cr around q, r (Picture assumes Cq = Cq')
  - Draw lines through circle intersections
  - The intersection of the lines is the center of the desired circle
  - Error if the points are colinear



Approach in Simula

- Methodology
  - Represent points, lines, and circles as objects
  - Equip objects with necessary operations
- Operations
  - Point
    equality(anotherPoint) : boolean
    distance(anotherPoint) : real (needed to construct circles)
  - Line
    parallelto(anotherLine) : boolean (to see if lines intersect)
    meets(anotherLine) : REF(Point)
  - Circle
    intersects(anotherCircle) : REF(Line)

Simula Point Class

```
class Point(x,y); real x,y;
    begin
      boolean procedure equals(p); ref(Point) p;
        if p =/= none then
          equals := abs(x - p.x) + abs(y - p.y) < 0.00001
      real procedure distance(p); ref(Point) p;
        if p == none then error else
          distance := sqrt(( x - p.x )**2 + (y - p.y) ** 2);
end ***Point***

p :- new Point(1.0, 2.5);
q :- new Point(2.0,3.5);
if p.distance(q) > 2 then ...
```

formal p is pointer to Point

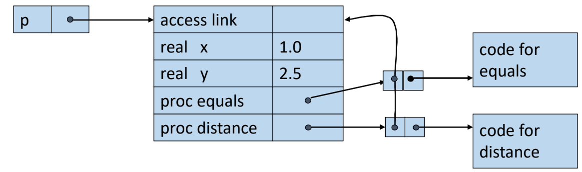
uninitialized ptr has value none

pointer assignment

Activation Records

- Modern imperative programming languages typically have local variables
  - Created upon entry to function
  - Destroyed when function returns
- Each invocation of a function has its own instantiation of local variables
  - Recursive calls to a function require several instantiations to exist simultaneously
  - Functions return only after all functions it calls have returned ➔ last-in-first-out (LIFO) behavior.
  - A LIFO structure called a stack is used to hold each instantiation
- The portion of the stack used for an invocation of a function is called the function's activation record

Representation of objects



Object is represented by activation record with access link to find global variables according to static scoping

Simula Line Class

```
class Line(a,b,c); real a,b,c;
  begin
    boolean procedure parallelto(l); ref(Line) l;
       if l =/= none then  parallelto := ...
    ref(Point) procedure meets(l); ref(Line) l;
       begin real t;
          if l =/= none and ~parallelto(l) then ...
       end;
    real d;   d := sqrt(a**2 + b**2);
    if d = 0.0 then error else
       begin
          d := 1/d;
          a := a*d;  b := b*d;  c := c*d;
       end;
 end *** Line***
```

Local variables

line determined by ax+by+c=0

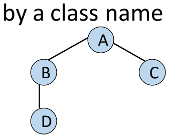
Procedures

Initialization: "normalize" a,b,c

Derived Classes in Simula

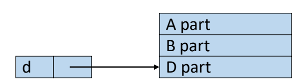
- A class declaration may be prefixed by a class name

  class A
  A class B
  A class C
  B class D



- An object of a "prefixed class" is the concatenation of objects of each class in prefix

  d :- new D(…)



Main Object-Oriented Features

- Classes
- Objects
- Inheritance ("class prefixing")
- Subtyping
- Virtual methods
  - A function can be redefined in subclass
- Inner
  - Combines code of superclass with code of subclass
- Inspect/Qua
  - run-time class/type tests

Inspect and Qua

- Following the two are the same:

```
Inspect XA do Show;
XA.Show;
```

- Or,

```
Inspect XA do Begin
  Show; ...
End
Otherwise Begin
  OutText("Sorry, XA not created"); OutImage
End;
```

- Or,

```
Current :- First;
While Current ne None do begin
  Inspect Current
    When A do Show    ! Show of A;
    When B do Show    ! Show of B;
    When C do Show    ! Show of C;
    Otherwise OutText("Not a (sub)class of A");
  OutImage;
  Current :- Current.Link
End While;
```


Inspect and Qua

```
Class A; Begin Ref(A) Link; Procedure Show; ... End;
A Class B; Begin Procedure Show; ... End;
B Class C; Begin Procedure Show; ... End;

Ref(A) XA, First, Current;
Ref(B) XB; Ref(C) XC;

XA :- New B;
XB :- New B;
XA.Show;        ! Show of A
XA Qua B.Show;  ! Show of B - it is possible to go down
XB Qua A.Show;  ! Show of A - it is possible to go up
XA :- New A;
XA Qua B.Show;  ! This is illegal - attributes of B do not exist
```


Features Absent from Simula 67

- Encapsulation
  - All data and functions accessible; no private, protected
- Self/Super mechanism of Smalltalk
  - But has an expression this⟨class⟩ to refer to object itself, regarded as object of type ⟨class⟩. Not clear how powerful this is…
- Class variables
  - But can have global variables
- Exceptions
  - Not fundamentally an OO feature ...

Simula Summary

- Class
  - ”procedure" that returns ptr to activation record
  - initialization code always run as procedure body
- Objects: closure created by a class
- Encapsulation
  - protected and private not recognized in 1967
  - added later and used as basis for C++
- Subtyping: determined by class hierarchy
- Inheritance: provided by class prefixing

A closure is a function or reference to a function together with a referencing environment. A closure allows a function to access non-local variables even when invoked outside its immediate lexical scope.

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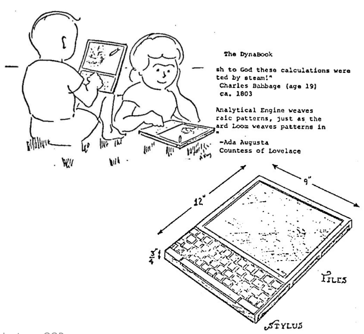
Smalltalk

Smalltalk

- Major language that popularized objects
- Developed at Xerox PARC
  - Smalltalk-76, Smalltalk-80 were important versions
- Object metaphor extended and refined
  - Used some ideas from Simula, but it is a very different language
  - Everything is an object, even a class
  - All operations are “messages to objects”
  - Very flexible and powerful language
    - Similar to “everything is a list” in Lisp, but more so
    - Example: object can detect that it has received a message it does not understand, can try to figure out how to respond

Motivating Application: Dynabook

- Concept developed by Alan Kay
- Small portable computer
  - Revolutionary idea in early 1970's
    - At the time, a *minicomputer* was shared by 10 people, stored in a machine room
  - What would you compute on an airplane?
- Influence on Smalltalk
  - Language intended to be programming language and operating system interface
  - Intended for "non-programmer"
  - Syntax presented by language-specific editor



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Smalltalk Language Terminology

- Object Instance of some class
- Class Defines behavior of its objects
- Selector Name of a message
- Message Selector together with parameter values
- Method Code used by a class to respond to message
- Instance variable Data stored in object
- Subclass Class defined by giving incremental modifications to some superclass

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Example: Point Class

- Class definition written in tabular form

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...〉	

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Smalltalk Code

```
class name      Point
super class     Object
instance var    x y
class var       pi

class messages and methods
        newX:xvalue Y:yvalue | |
        ^ self new x: xvalue
                        y: yvalue
        newOrigin | |
        ^ self new x: 0
                        y: 0
        initialize | |
                pi <- 3.14159
```

```
instance messages and methods
        x: xcoord y: ycoord | |
                x <- xcoord
                y <- ycoord
        moveDx: dx Dy: dy | |
                x <- dx + x
                y <- dy + y
        x | |
        ^x
        y | |
        ^y
        draw | |
                << code to draw point >>
```


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Class Messages and Methods

Three class methods

```
newX:xvalue Y:yvalue | |
^ self new x: xvalue
           y: yvalue

newOrigin ||
^ self new x: 0
           y: 0

initialize ||
pi <- 3.14159
```

Explanation

- selector is newX:Y:
  e.g, Point newX:3 Y:2
- symbol ^ marks return value
- new is method in all classes, inherited from Object
- || marks scope for local decl
- initialize method sets pi, called automatically
- <- is syntax for assignment

Instance Messages and Methods

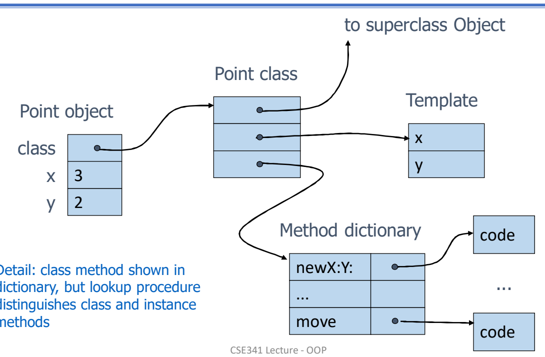
Five instance methods

```
x: xcoord y: ycoord | |
   x <- xcoord
   y <- ycoord
moveDx: dx Dy: dy | |
   x <- dx + x
   y <- dy + y
x | | ^x
y | | ^y
draw | |
  ⟨...code to draw point...⟩
```

Explanation

- set x,y coordinates,
  e.g, pt x:5 y:3
- move point by given amount
- return hidden inst var x
- return hidden inst var y
- draw point on screen

Run-time Representation of Point



Detail: class method shown in dictionary, but lookup procedure distinguishes class and instance methods

Inheritance

- Define colored points from points

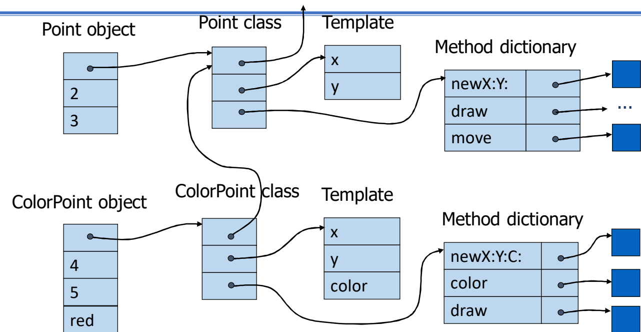
class name	ColorPoint
super class	Point
class var	
instance var	color
class messages and methods	
newX:xv Y:yv C:cv	⟨ ... code ... ⟩
instance messages and methods	
color	| | ^color
draw	⟨ ... code ... ⟩

new instance variable

new method

override Point method

Run-time Representation



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

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Encapsulation in Smalltalk

- Methods are public
- Instance variables are hidden
  - Not visible to other objects
    - pt x is not allowed unless x is a method
  - But may be manipulated by subclass methods
    - This limits ability to establish invariants
    - Example:
      - Superclass maintains sorted list of messages with some selector, say insert
      - Subclass may access this list directly, rearrange order

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Smalltalk Summary

- Class
  - creates objects that share methods
  - pointers to template, dictionary, parent class
- Objects: created by a class, contains instance variables
- Encapsulation
  - methods public, instance variables hidden
- Subtyping: implicit, no static type system
- Inheritance: subclasses, self, super

  Single inheritance in Smalltalk-76, Smalltalk-80

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Self Programming Language

- Prototype-based pure object-oriented language
- Designed by Randall Smith (Xerox PARC) and David Ungar (Stanford University)
  - Successor to Smalltalk-80
  - “Self: The power of simplicity” appeared at OOPSLA ‘87
  - Initial implementation done at Stanford; then project shifted to Sun Microsystems Labs
  - Vehicle for implementation research
- Self 4.4 available from http://selflanguage.org/

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Self Programming Language

- A dialect of Smalltalk
- Dynamically typed & just-in-time compilation & prototype-based approach to objects

Prototype-based Programming

- No classes
- Objects inherit directly from other objects through a prototype property (Self, JavaScript, Io)
- Pros:
  - Simpler language rules, e.g., is class an object?, if so what class is it an instance of?, …
  - An object can be given specialized behavior, e.g., debugging and object – override a method of the object…
  - Better control, e.g., singleton – do not give it a copy method…

Singleton Pattern

- Only one instance of a class needed throughout the system
  - Objects needed for logging, communication, database
- How to ensure a class has only one instance and can be accessed globally?
  - Global variables?
- Pros
  - More control over instance – can add additional logic to access, e.g., dynamic creation (cannot be done with globals), synchronizing access (per thread vs per process)
  - Polymorphism, e.g., single graphics card interface, many machines
- Cons
  - Still context dependent as global variables

Design Goals

- Conceptual economy
  - Everything is an object
  - Everything done using messages
  - No classes
  - No variables
- Concreteness
  - Objects should seem "real"
  - GUI to manipulate objects directly

How Successful?

- Self is a carefully designed language
- Few users: not a popular success
  - No compelling application, until JavaScript
  - Influenced development of object calculi w/o classes
- However, many research innovations
  - Very simple computational model
  - Enormous advances in compilation techniques
  - Influenced the design of Java compilers

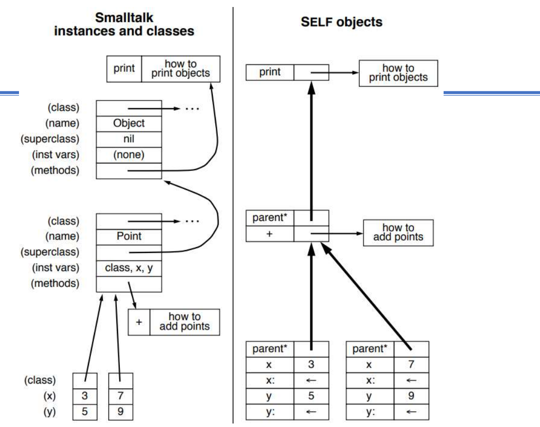
Language Overview

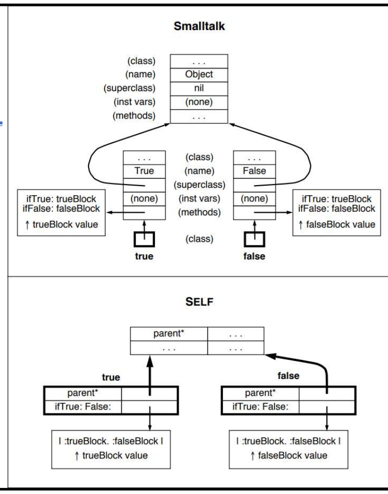
- Dynamically typed
- Everything is an object
- All computation via message passing
- Creation and initialization: clone object
- Operations on objects:
  - send messages
  - add new slots
  - replace old slots
  - remove slots

Objects and Slots

Object consists of named slots
- Data
  - Such slots return contents upon evaluation; so act like instance variables
- Assignment
  - Set the value of associated slot
- Method
  - Slot contains Self code
- Parent
  - Point to existing object to inherit slots

Ungar and Smith, 1991.





Ungar and Smith, 1991.

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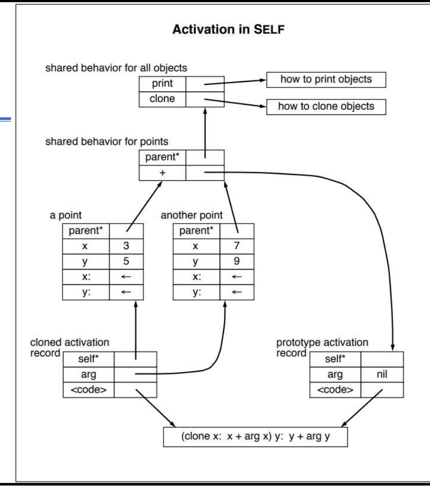

Ungar and Smith, 1991.

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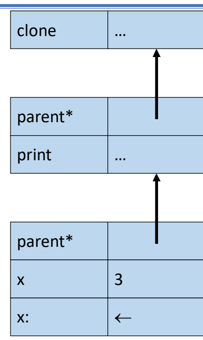
Messages and Methods

- When message is sent, object searched for slot with name
- If none found, all parents are searched
  - Runtime error if more than one parent has a slot with the same name
- If slot is found, its contents evaluated and returned
  - Runtime error if no slot found



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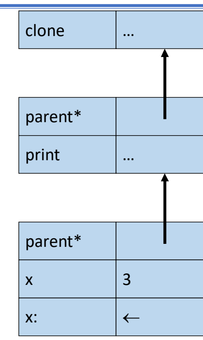
Messages and Methods

obj x	3
obj print	*print point object*
obj x: 4	obj *after setting x to 4*



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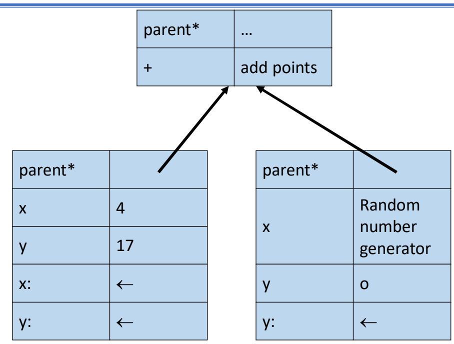
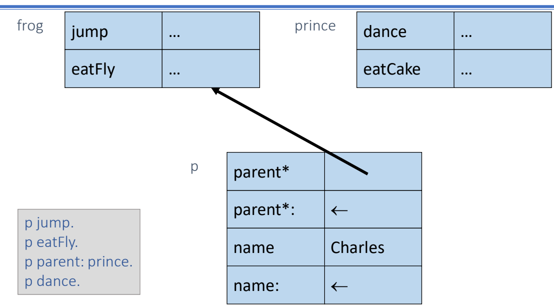
Mixing State and Behavior



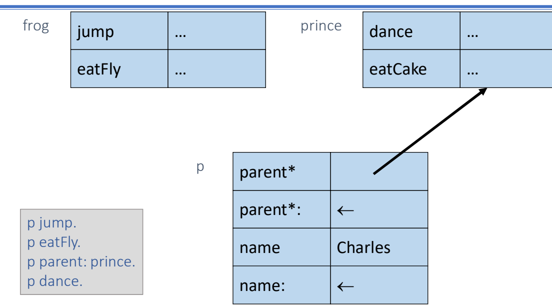
Object Creation

- To create an object, we copy an old one
- We can add new methods, override existing ones, or even remove methods
- These operations also apply to parent slots

Changing Parent Pointers



Changing Parent Pointers



Disadvantages of classes?

- Classes require programmers to understand a more complex model
  - To make a new kind of object, we have to create a new class first
  - To change an object, we have to change the class
  - Infinite meta-class regression
- But: Does Self require programmer to reinvent structure?
  - Common to structure Self programs with *traits*: objects that simply collect behavior for sharing

JavaScript Prototype

- Object prototypes can be created using an object constructor function…
- "new" to create objets…
- Can add properties to objects…
- Can add methods to objects…

```
function Point(x, y) {
    this.xc = x;
    this.yc = y;
}

var p1 = new Point(50,60);

p1.color = "green";

p1.distancetoorigin =
 function () {
   return sqrt(this.x*this.x
          + this.y*this.y);
};
```


JavaScript Prototypes

- Every JavaScript object has a prototype
  - Object literals linked to Object.prototype
  - Otherwise, prototype based on constructor

```
function Foo() {
   this.x = 1;
}
obj = new Foo;
```

- Changing the JavaScript prototype
  - The prototype property is immutable
  - Changes to prototype property inherited immediately

Outline

- Central concepts in object-oriented languages
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  - Object implementation and run-time lookup
  - Class-based languages (Smalltalk)
  - Prototype-based languages (Self, JavaScript)
- Statically-typed object-oriented languages
  - C++ – using static typing to eliminate search
  - C++ – problems with C++ multiple inheritance
  - Java – using Interfaces to avoid multiple inheritance

C++ Background

- C++ is an object-oriented extension of C
- C was designed by Dennis Ritchie at Bell Labs
  - used to write Unix, based on BCPL
- C++ designed by Bjarne Stroustrup at Bell Labs
  - His original interest at Bell was research on simulation
  - Early extensions to C are based primarily on Simula
  - Called “C with classes” in early 1980’s
  - Popularity increased in late 1980’s and early 1990’s
  - Features were added incrementally

    Classes, templates, exceptions, multiple inheritance, type tests...

C++ Design Goals

- Provide object-oriented features in C-based language, without compromising efficiency
  - Backwards compatibility with C
  - Better static type checking
  - Data abstraction
  - Objects and classes
  - Prefer efficiency of compiled code where possible
- Important principle
  - If you do not use a feature, your compiled code should be as efficient as if the language did not include the feature. (compare to Smalltalk)

How successful?

- Given the design goals and constraints,
  - this is a very well-designed language
- Many users -- tremendous popular success
- However, very complicated design
  - Many features with complex interactions
  - Difficult to predict from basic principles
  - Most users chose a subset of language
    - Full language is complex and unpredictable
  - Many implementation-dependent properties

Significant Constraints

- C has specific machine model
  - Access to underlying architecture
- No garbage collection
  - Consistent with goal of efficiency
  - Need to manage object memory explicitly
- Local variables stored in activation records
  - Objects treated as generalization of structs
    - Objects may be allocated on stack and treated as L-values
    - Stack/heap difference is visible to programmer

C++ Object System

- Object-oriented features
  - Classes
  - Objects, with dynamic lookup of virtual functions
  - Inheritance
    - Single and multiple inheritance
    - Public and private base classes
  - Subtyping
    - Tied to inheritance mechanism
  - Encapsulation
    - Public, private, protected visibility

Some Good Decisions

- Public, private, protected levels of visibility
  - Public: visible everywhere
  - Protected: within class and subclass declarations
  - Private: visible only in class where declared
- Friend functions and classes
  - Careful attention to visibility and data abstraction
- Allow inheritance without subtyping
  - Better control of subtyping than without private base classes

Some Problem Areas

- Casts
  - Sometimes no-op, sometimes not (e.g., multiple inheritance)
- Lack of garbage collection
  - Memory management is error prone
    - Constructors, destructors are helpful // smart pointers?
- Objects allocated on stack
  - Better efficiency, interaction with exceptions
  - But assignment works badly, possible dangling ptrs
- Overloading
  - Too many code selection mechanisms?
- Multiple inheritance
  - Emphasis on efficiency leads to complicated behavior

Sample Class: 1D Points

```
class Pt {
  public:
     Pt(int xv);          } Overloaded constructor
     Pt(Pt* pv);
     int getX();            Public read access to private data
     virtual void move(int dx);    Virtual function
   protected:
     void setX(int xv);    Protected write access
   private:
     int x;                 Private data
 };
```

Virtual Functions

- Member functions are either
  - Virtual, if explicitly declared or inherited as virtual
  - Non-virtual otherwise
- Virtual functions
  - Accessed by indirection through ptr in object
  - May be redefined in derived (sub) classes
- Non-virtual functions
  - Are called in the usual way. *Just ordinary functions*.
  - Cannot redefine in derived classes (except overloading)
- Pay overhead only if you use virtual functions

Sample Derived Class

```
class ColorPt: public Pt {
  public:
     ColorPt(int xv,int cv);
     ColorPt(Pt* pv,int cv);
     ColorPt(ColorPt* cp);
     int getColor();
     virtual void move(int dx);
     virtual void darken(int tint);
  protected:
     void setColor(int cv);
  private:
     int color;
  };
```

Public base class gives supertype

Overloaded constructor

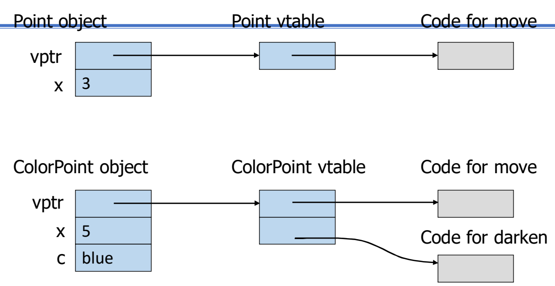
Non-virtual function

Virtual functions

Protected write access

Private data

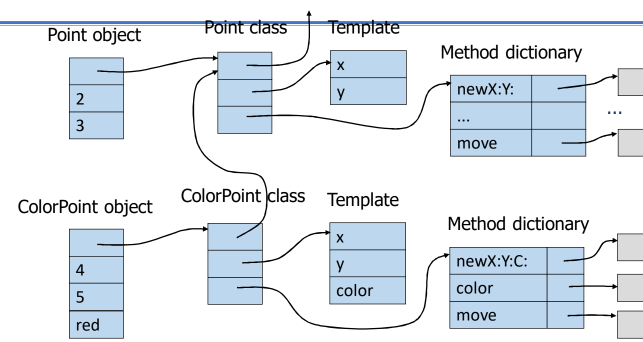
Run-time Representation



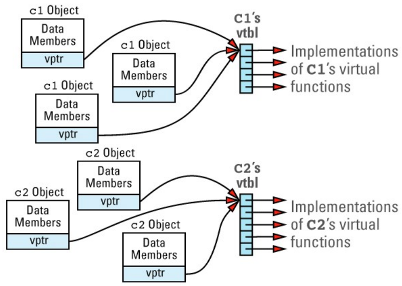
Data at same offset

Function pointers at same offset

Compare to Smalltalk/JavaScript



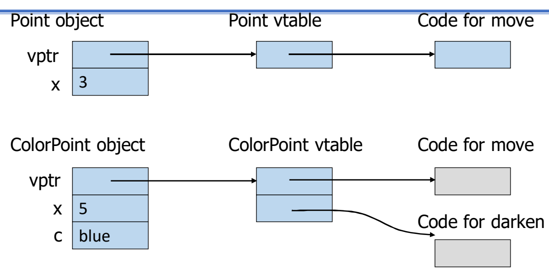
Run-time Representation



Why is C++ lookup simpler?

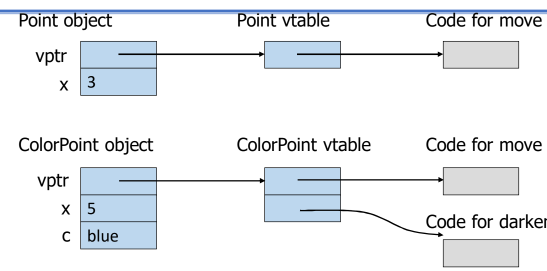
- Smalltalk/JavaScript have no static type system
  - Code obj.operation(pars) could refer to any object
  - Need to find method using pointer from object
  - Different classes will put methods at different place in method dictionary
- C++ type gives compiler some superclass
  - Offset of data, fctn ptr same in subclass and superclass
  - Offset of data and function ptr known at compile time
  - Code p->move(x) compiles to equivalent of (*(p->vptr[0]))(p,x) if move is first function in vtable

Looking Up Methods



Point p = new Pt(3);
p->move(2); // (*(p->vptr[0]))(p,2)

Looking Up Methods 2



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

Calls to Virtual Functions

- One member function may call another

```
class A {
   public:
      virtual  int  f (int x);
      virtual  int  g(int y);
};
int A::f(int x) { … g(i) …;}
int A::g(int y) { … f(j) …;}
```

- How does body of f call the right g?
  - If g is redefined in derived class B, then inherited f must call B::g

"This" Pointer (*self* in Smalltalk)

- Code is compiled so that member function takes "object itself" as first argument

  Code `int A::f(int x) { … g(i) …;}`

  compiled as `int A::f(A *this, int x) { … this->g(i) …;}`

- "this" pointer may be used in member function
  - Can be used to return pointer to object itself, pass pointer to object itself to another function, …

Non-virtual Functions

- How is code for non-virtual function found?
- Same way as ordinary "non-member" functions:
  - Compiler generates function code and assigns address
  - Address of code is placed in symbol table
  - At call site, address is taken from symbol table and placed in compiled code
- Overloading
  - Remember: overloading is resolved at compile time
  - This is different from run-time lookup of virtual function

Virtual vs Overloaded Functions

```
class parent { public:
   void printclass() {printf("p ");};
   virtual void printvirtual() {printf("p ");};   };
class child : public parent { public:
   void printclass() {printf("c ");};
   virtual void printvirtual() {printf("c ");};    };
main() {
   parent p;  child c; parent *q;
   p.printclass(); p.printvirtual(); c.printclass(); c.printvirtual();
   q = &p;  q->printclass(); q->printvirtual();
   q = &c;  q->printclass(); q->printvirtual();
}
```

Output: p p c c p p ? ?

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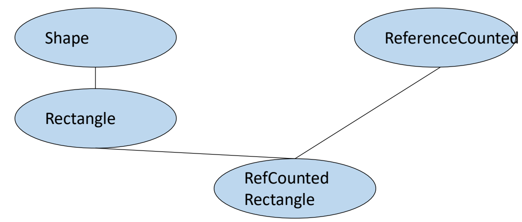
Multiple Inheritance



Inherit independent functionality from independent classes

Problem: Name Clashes

```
class A {
   public:
   virtual void f() { … }
};
class B {
   public:
   virtual void f() { … }
};
class C : public A, public B { … };
…
   C* p;
   p->f();    // error
```

same name in 2 base classes

Possible Solutions to Name Clash

- Three general approaches
  - Implicit resolution
    - Language resolves name conflicts with arbitrary rule
  - Explicit resolution
    - Programmer must explicitly resolve name conflicts
  - Disallow name clashes
    - Programs are not allowed to contain name clashes
- No solution is always best
- C++ uses explicit resolution

Repair to Previous Example

- Rewrite class C to call A::f explicitly

```
class C : public A, public B {
    public:
        void virtual f( ) {
                A::f( );    // Call A::f(), not B::f();
        }
```

- Reasonable solution
  - This eliminates ambiguity
  - Preserves dependence on A
    - Changes to A::f will change C::f

vtable for Multiple Inheritance

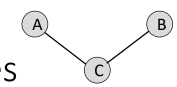
```
class A {
  public:
    int x;
    virtual void f();
};
class B {
  public:
    int y;
    virtual void g();
    virtual void f();
};
```

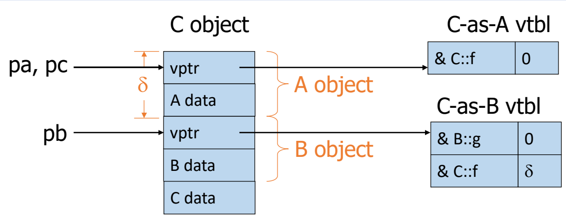
```
class C: public A, public B {
   public:
      int z;
      virtual void f();
};

C *pc = new C;
B *pb = pc;
A *pa = pc;
```

Three pointers to same object, but different static types.

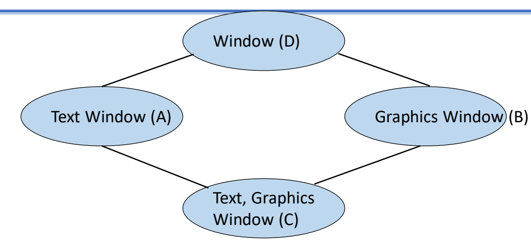
Object and Classes





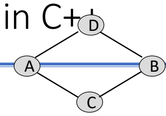
- Offset δ in vtbl is used in call to pb->f, since C::f may refer to A data that is above the pointer pb
- Call to pc->g can proceed through C-as-B vtbl

Multiple Inheritance "Diamond"



- Is interface or implementation inherited twice?
- What if definitions conflict?

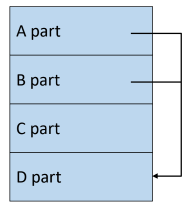
Diamond Inheritance in C++



- Standard base classes
  – D members appear twice in C
- Virtual base classes

  class A : public virtual D { … }

  – Avoid duplication of base class members
  – Require additional pointers so that D part of A, B parts of object can be shared



C++ multiple inheritance is complicated because of desire to maintain efficient lookup

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Java Language Background

- James Gosling and others at Sun, 1990 - 95
- Oak language for “set-top box”
  - small networked device with television display
    - graphics
    - execution of simple programs
    - communication between local program and remote site
    - no “expert programmer” to deal with crash, etc.
- Internet applications
  - simple language for writing programs that can be transmitted over network
  - not an integrated web scripting language like JavaScript

Design Goals

- Portability
  - Internet-wide distribution: PC, Unix, Mac
- Reliability
  - Avoid program crashes and error messages
- Safety
  - Programmer may be malicious
- Simplicity and familiarity
  - Appeal to average programmer; less complex than C++
- Efficiency
  - Important but secondary

General Design Decisions

- Simplicity
  - Almost everything is an object
  - All objects on heap, accessed through pointers
  - No functions, no multiple inheritance, no go to, no operator overloading, few automatic coercions
- Portability and network transfer
  - Bytecode interpreter on many platforms
- Reliability and Safety
  - Typed source and typed bytecode language
  - Run-time type and bounds checks
  - Garbage collection

Language Terminology

- Class, object – as in other languages
- Field – data member
- Method – member function
- Static members – class fields and methods
- this – self
- Package – set of classes in shared namespace
- Native method – method compiled from in another language, often C

Java Classes and Objects

- Syntax similar to C++
- Object
  - has fields and methods
  - is allocated on heap, not run-time stack
  - accessible through reference (only ptr assignment)
  - garbage collected
- Dynamic lookup
  - Similar in behavior to other languages
  - Static typing => more efficient than Smalltalk
  - Dynamic linking, interfaces => slower than C++

Point Class

```
class Point {
   private int x;
   protected void setX (int y)  {x = y;}
   public int  getX()     {return x;}
   Point(int xval) {x = xval;}      // constructor
};
```

- Visibility similar to C++, but not exactly (later slide)

Object Initialization

- Java guarantees constructor call for each object
  - Memory allocated
  - Constructor called to initialize memory
  - Some interesting issues related to inheritance
- Cannot do this (would be bad C++ style anyway):
  - Obj* obj = (Obj*)malloc(sizeof(Obj));
- Static fields of class initialized at class load time

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Garbage Collection and Finalize

- Objects are garbage collected
  - No explicit *free*
  - Avoids dangling pointers and resulting type errors
- Problem
  - What if object has opened file or holds lock?
- Solution
  - *finalize* method, called by the garbage collector
    - Before space is reclaimed, or when virtual machine exits
    - Space overflow is not really the right condition to trigger finalization when an object holds a lock...)
  - Important convention: call super.finalize

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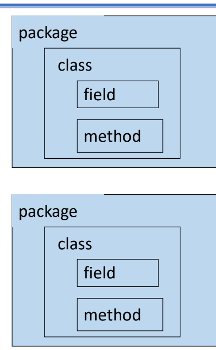
Encapsulation and Packages

- Every field, method belongs to a class
- Every class is part of some package
  - Can be unnamed default package
  - File declares which package code belongs to



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Visibility and Access

- Four visibility distinctions
  - public, private, protected, package
- Method can refer to
  - private members of class it belongs to
  - non-private members of all classes in same package
  - protected members of superclasses (in diff package)
  - public members of classes in visible packages

    Visibility determined by files system, etc. (outside language)
- Qualified names (or use import)
  - java.lang.String.substring()

$$\underbrace{\text{java.lang}}_{\text{package}}.\underbrace{\text{String}}_{\text{class}}.\underbrace{\text{substring()}}_{\text{method}}$$

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Inheritance

- Similar to Smalltalk, C++
- Subclass inherits from superclass
  - Single inheritance only (but Java has interfaces)
- Some additional features
  - Conventions regarding *super* in constructor and *finalize* methods
  - Final classes and methods

Example Subclass

```
class ColorPoint extends Point {
  // Additional fields and methods
   private Color c;
   protected void setC (Color d)  {c = d;}
   public Color  getC()     {return c;}
  // Define constructor
   ColorPoint(int xval, Color cval) {
       super(xval);    // call Point constructor
       c = cval;  }     // initialize ColorPoint field
};
```


Class *Object*

- Every class extends another class
  - Superclass is *Object* if no other class named
- Methods of class *Object*
  - GetClass – return the Class object representing class of the object
  - ToString – returns string representation of object
  - equals – default object equality (not ptr equality)
  - hashCode
  - Clone – makes a duplicate of an object
  - wait, notify, notifyAll – used with concurrency
  - finalize

Constructors and Super

- Java guarantees constructor call for each object
- This must be preserved by inheritance
  - Subclass constructor must call super constructor
    - If first statement is not call to super, then call super() inserted automatically by compiler
    - If superclass does not have a constructor with no args, then this causes compiler error
    - Exception to rule: if one constructor invokes another, then it is responsibility of second constructor to call super, e.g.,

      `ColorPoint() { ColorPoint(0,blue);}`

      is compiled without inserting call to super
- Different conventions for finalize and super
    - Compiler does not force call to super finalize

Final Classes and Methods

- Restrict inheritance
  - Final classes and methods cannot be redefined
- Example
  java.lang.String
- Reasons for this feature
  - Important for security
    - Programmer controls behavior of all subclasses
    - Critical because subclasses produce subtypes
  - Compare to C++ virtual/non-virtual
    - Method is "virtual" until it becomes final

Java Interfaces (by 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
}
```


Interfaces vs Multiple Inheritance

- C++ multiple inheritance
  - A single class may inherit from two base classes
  - Constraints of C++ require derived class representation to resemble *all* base classes
- Java interfaces
  - A single class may implement two interfaces
  - No inheritance (of implementation) involved
  - Java implementation does not require similarity between class representations
    - For now, think of Java implementation as Smalltalk/JavaScript implementation, although the Java type system supports some optimizations

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	Colored_point
x:y: moveDx:Dy: x y draw	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

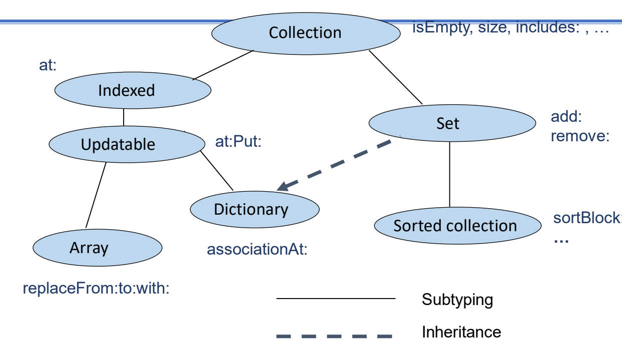
    p msg:pars -- OK if msg is in interface of p
  - Replace p by q if interface of q contains interface of p
- Subtyping
  - If interface is superset, then a subtype
  - Example: ColorPoint subtype of Point
  - Sometimes called "conformance"

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);
		Public members

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

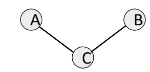
Implementation of Subtyping

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

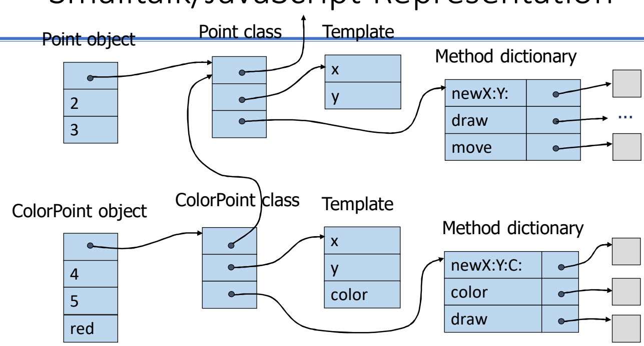
```
circle *c = new Circle(p,r);
shape *s = c;                // s points to circle c
```

- Conversion
  - C++ object representations w/multiple-inheritance

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

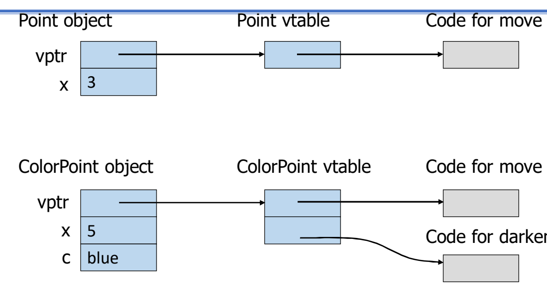


Smalltalk/JavaScript Representation



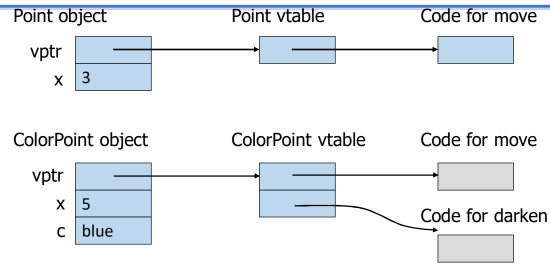
This is a schematic diagram meant to illustrate the main idea. Actual implementations may differ.

C++ Run-time Representation



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)
```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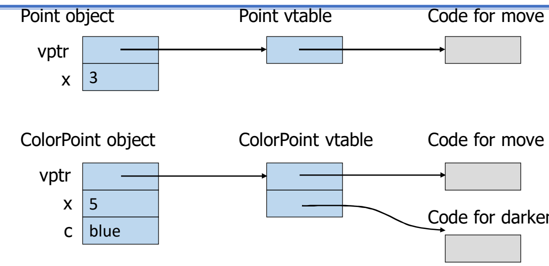
C++: Virtual Function Lookup 2




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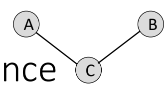
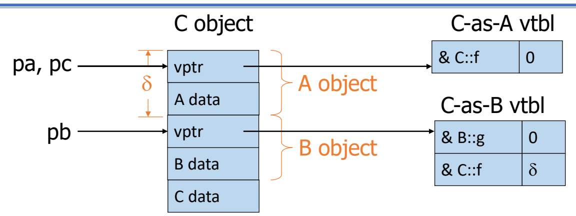
C++ Multiple Inheritance





- Offset δ 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

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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
- Recall: All public and protected members of base become private members of derived. However, derived can re-declare all to be public or protected (except originally protected).

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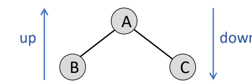
Why C++ design?

- 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:



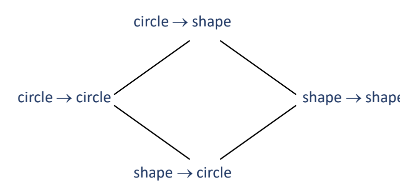

```
class A(…); ...
A class B(…); …
ref (A) a :- new A(…)
ref (B) b :- new B(…)
a := b        /* OK since B is subclass of A */
...
b := a        /* compiles, but run-time test */
```


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 $C \to A$ <: $C \to B$
- Subtyping for function arguments
  - If A <: B, then $B \to C$ <: $A \to C$
- Terminology
  - Covariance: A <: B implies F(A) <: F(B)
  - Contravariance: A <: B implies F(B) <: F(A)

Examples

- If circle <: 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: ColorPoint <: Point
- In practice: This is covariant case; contravariance is another story

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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

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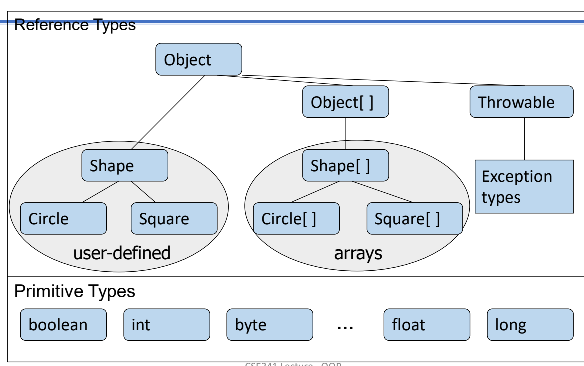
Classification of Java Types



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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

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Java Class Subtyping

- Signature Conformance
  - Subclass method signatures must conform to superclass
- Three ways signature could vary
  - Argument types
  - Return type
  - Exceptions
- 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)

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
```

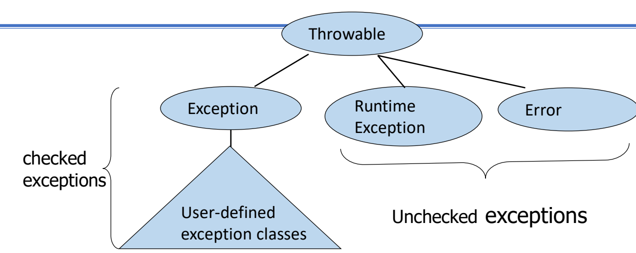

Covariance problem again …

- Simula problem
  - If A <: B, then A ref <: B 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 : $T \rightarrow T$ ref
    - get : T ref $\rightarrow T$
  - Remember covariance/contravariance of functions

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

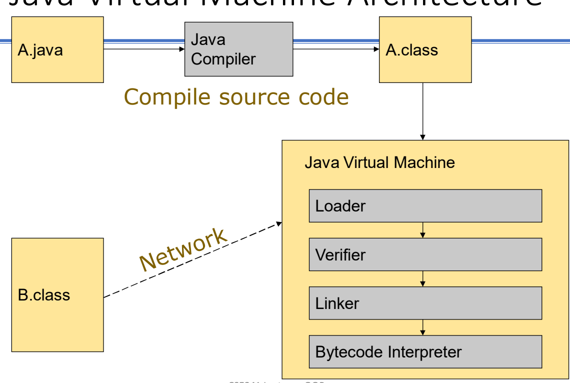
Java Language Implementation: Outline

- Java virtual machine overview
  - Loader and initialization
  - Linker and verifier
  - Bytecode interpreter
- JVM Method lookup
  - four different bytecodes
- Verifier analysis
- Method lookup optimizations (beyond Java)
- Java security
  - Buffer overflow
  - Java “sandbox”
  - Stack inspection

Java Implementation

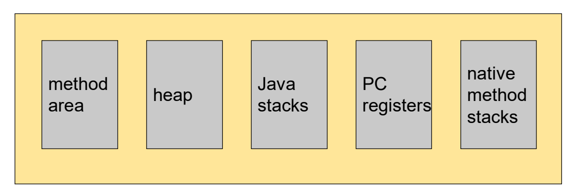
- Compiler and Virtual Machine
  - Compiler produces bytecode
  - Virtual machine loads classes on demand, verifies bytecode properties, interprets bytecode
- Why this design?
  - Bytecode interpreter/compilers used before
    - Pascal “pcode”; Smalltalk compilers use bytecode
  - Minimize machine-dependent part of implementation
    - Do optimization on bytecode when possible
    - Keep bytecode interpreter simple
  - For Java, this gives portability
    - Transmit bytecode across network

Java Virtual Machine Architecture



JVM Memory Areas

- Java program has one or more threads
- Each thread has its own stack
- All threads share same heap



Class Loader

- Runtime system loads classes as needed
  - When class is referenced, loader searches for file of compiled bytecode instructions
- Default loading mechanism can be replaced
  - Define alternate ClassLoader object
    - Extend the abstract ClassLoader class and implementation
    - ClassLoader does not implement abstract method loadClass, but has methods that can be used to implement loadClass
  - Can obtain bytecodes from alternate source
    - VM restricts applet communication to site that supplied applet

Example issue in class loading and linking:

Static members and initialization

```
class ... {
  /*  static variable with initial value */
  static int x = initial_value
  /* ---- static initialization block      --- */
  static {  /* code executed once, when loaded */  }
}
```

- Initialization is important
  - Cannot initialize class fields until loaded
- Static block cannot raise an exception
  - Handler may not be installed at class loading time

JVM Linker and Verifier

- Linker
  - Adds compiled class or interface to runtime system
  - Creates static fields and initializes them
  - Resolves names
    - Checks symbolic names and replaces with direct references
- Verifier
  - Check bytecode of a class or interface before loaded
  - Throw VerifyError exception if error occurs

Verifier

- Bytecode may not come from standard compiler
  - Evil hacker may write dangerous bytecode
- Verifier checks correctness of bytecode
  - Every instruction must have a valid operation code
  - Every branch instruction must branch to the start of some other instruction, not middle of instruction
  - Every method must have a structurally correct signature
  - Every instruction obeys the Java type discipline

Last condition is complicated.

Bytecode Interpreter

- Standard virtual machine interprets instructions
  - Perform run-time checks such as array bounds
  - Possible to compile bytecode class file to native code
- Java programs can call native methods
  - Typically functions written in C
- Multiple bytecodes for method lookup
  - invokevirtual - when class of object known
  - invokeinterface - when interface of object known
  - invokestatic - static methods
  - invokespecial - some special cases

Type Safety of JVM

- Run-time type checking
  - All casts are checked to make sure type safe
  - All array references are checked to make sure the array index is within the array bounds
  - References are tested to make sure they are not null before they are dereferenced
- Additional features
  - Automatic garbage collection
  - No pointer arithmetic

If program accesses memory, that memory is allocated to the program and declared with correct type

JVM Uses Stack Machine

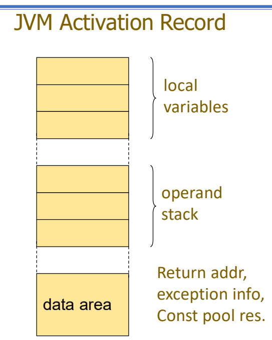
- Java

```
Class A extends Object {
    int i
    void f(int val) { i = val + 1;}
}
```

- Bytecode

```
Method void f(int)
    aload 0    ; object ref this
    iload 1    ; int val
    iconst 1
    iadd       ; add val +1
    putfield #4 <Field int i>
    return
```

refers to constant pool



Field and Method Access

- Instruction includes index into constant pool
  - Constant pool stores symbolic names
  - Store once, instead of each instruction, to save space
- First execution
  - Use symbolic name to find field or method
- Second execution
  - Use modified “quick” instruction to simplify search

Outline

- Java virtual machine overview
  - Loader and initialization
  - Linker and verifier
  - Bytecode interpreter
- JVM Method lookup
  - four different bytecodes
- Verifier analysis
- Method lookup optimizations (beyond Java)
- Java security
  - Buffer overflow
  - Java “sandbox”
  - Stack inspection

Java Security

- Security
  - Prevent unauthorized use of computational resources
- Java security
  - Java code can read input from careless user or malicious attacker
  - Java code can be transmitted over network – code may be *written* by careless friend or malicious attacker

Java is designed to reduce many security risks

Java Security Mechanisms

- Sandboxing
  - Run program in restricted environment
    - Analogy: child’s sandbox with only safe toys
  - This term refers to
    - Features of loader, verifier, interpreter that restrict program
    - Java Security Manager, a special object that acts as access control “gatekeeper”
- Code signing
  - Use cryptography to establish origin of class file
    - This info can be used by security manager

Buffer Overflow Attack

- Most prevalent *general* security problem today
  - Large number of CERT advisories are related to buffer overflow vulnerabilities in OS, other code
- General network-based attack
  - Attacker sends carefully designed network msgs
  - Input causes privileged program (e.g., Sendmail) to do something it was not designed to do
- Does not work in Java
  - Illustrates what Java was designed to prevent

Sample C code to illustrate attack

```
void f (char *str) {
   char buffer[16];
   …
   strcpy(buffer,str);
}
void main() {
   char large_string[256];
   int i;
   for( i = 0; i < 255; i++)
      large_string[i] = 'A';
   f(large_string);
}
```

- Function
  - Copies str into buffer until null character found
  - Could write past end of buffer, *over function retun addr*
- Calling program
  - Writes 'A' over f activation record
  - Function f "returns" to location 0x4141414141
  - This causes segmentation fault
- Variations
  - Put meaningful address in string
  - Put *code* in string and jump to it !!

Java Sandbox

- Four complementary mechanisms
  - Class loader
    - Separate namespaces for separate class loaders
    - Associates *protection domain* with each class
  - Verifier and JVM run-time tests
    - NO unchecked casts or other type errors, NO array overflow
    - Preserves private, protected visibility levels
  - Security Manager
    - Called by library functions to decide if request is allowed
    - Uses protection domain associated with code, user policy
    - Coming up in a few slides: stack inspection

Security Manager

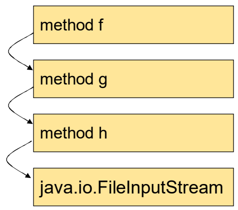
- Java library functions call security manager
- Security manager object answers at run time
  - Decide if calling code is allowed to do operation
  - Examine protection domain of calling class
    - Signer: organization that signed code before loading
    - Location: URL where the Java classes came from
  - Uses the system policy to decide access permission

Sample SecurityManager methods

checkExec	Checks if the system commands can be executed.
checkRead	Checks if a file can be read from.
checkWrite	Checks if a file can be written to.
checkListen	Checks if a certain network port can be listened to for connections.
checkConnect	Checks if a network connection can be created.
checkCreate ClassLoader	Check to prevent the installation of additional ClassLoaders.

Stack Inspection

- Permission depends on
  - Permission of calling method
  - Permission of all methods above it on stack
    - Up to method that is trusted and asserts this trust

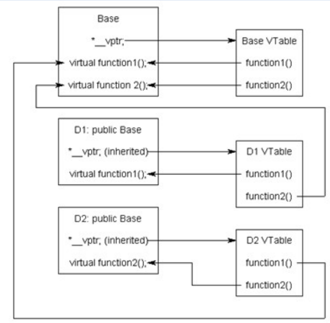


Example: privileged printing

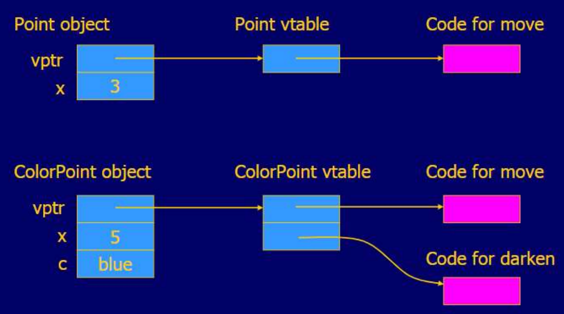
```
privPrint(f) =  (* owned by system *)
{
 checkPrivilege(PrintPriv);
 print(f);
}

foreignProg() = (* owned by Joe *)
{
 …; privPrint(file); …;
}
```


Stack Inspection

- Stack frames are annotated with names of owners and any enabled privileges
- During inspection, stack frames are searched from most to least recent:
  - fail if a frame belonging to someone not authorized for privilege is encountered
  - succeed if activated privilege is found in frame



Run-time representation



Data at same offset Function pointers at same offset

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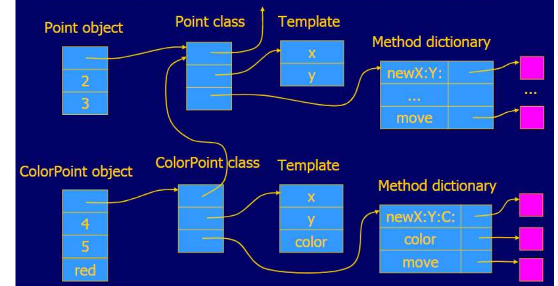
Compare to Smalltalk



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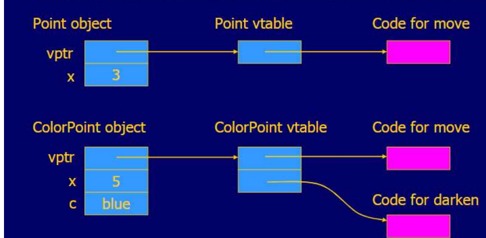
Looking up methods



Point p = new Pt(3);

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

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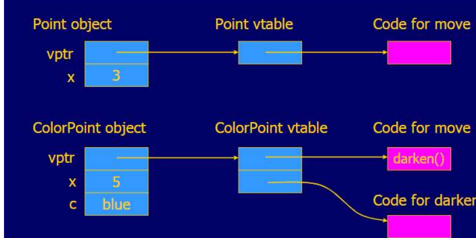
Looking up methods, part 2



Point cp = new ColorPt(5,blue);

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

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Calls to virtual functions

- One member function may call another

```
class A {
    public:
        virtual  int  f (int x);
        virtual  int  g(int y);
};
int A::f(int x) { … g(i) …;}
int A::g(int y) { … f(j) …;}
```

- How does body of f call the right g?
  - If g is redefined in derived class B, then inherited f must call B::g

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"This" pointer (analogous to *self* in Smalltalk)

- Code is compiled so that member function takes "object itself" as first argument

  Code `int A::f(int x) { … g(i) …;}`

  compiled as `int A::f(A *this, int x) { … this->g(i) …;}`

- "this" pointer may be used in member function
  - Can be used to return pointer to object itself, pass pointer to object itself to another function, ...

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Non-virtual functions

- How is code for non-virtual function found?
- Same way as ordinary "non-member" functions:
  - Compiler generates function code and assigns address
  - Address of code is placed in symbol table
  - At call site, address is taken from symbol table and placed in compiled code
  - *But* some special scoping rules for classes
- Overloading
  - Remember: overloading is resolved at compile time
  - This is different from run-time lookup of virtual function

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Thank you for listening!

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