CS558 Programming Languages

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Lecture 10a

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Object-oriented Programming

- Programs are structured in terms of objects: collections of variables ("fields") and functions ("methods")
  - Implicitly associates variable data with functions
- Invented to model discrete entities or processes, e.g.
  - Simulations (object = real-world object)
  - Graphical user interfaces (object = desktop item)
- But can be used for any programming task

OOP Characteristics

- OOP languages usually support
  - Dynamic dispatch
  - Encapsulation
  - Inheritance
  - Subtyping
- …but there is no precise definition of OOP

Some important OOP languages

Language	Static types?	Class-based?	All values are objects?
Simula67	✔	✔	
Smalltalk		✔	✔
C++	✔	✔	
Java/C#	✔	✔	
JavaScript			
Python		✔	
Ruby		✔	✔

Procedures vs. Methods

- Fundamental OOP control structure is method invocation
  - Similar to function call in a procedural language
  - But each method takes the object itself as an implicit argument, and this receiver object also helps resolve method name:

```
s.add(x)      ; OO style
Set.add(s,x)  ; procedural style
```

  - Change in metaphor: instead of applying functions to values, we “send messages to object.”

Dynamic Dispatch

- In most OOP languages, the receiving object itself controls how each message is processed.

- This is a form of dynamic overloading (i.e., a certain kind of polymorphism)

```
s1 = new ordered-list-set
s2 = new balanced-tree-set
if ... then s = s1 else s = s2
s.add(42)
```

- The implementation of the `add` method is completely different in `s1` and `s2`; the choice of which one runs is determined at run time.

Classes

- In OOP, we typically want to create multiple objects having the same structure (field names) and method definitions

- In most OO languages this is done by defining a class, which is a kind of template from which new objects can be created

- Different instances of the class will typically have different field values, but all will share the same method implementations

- Classes are not essential; one alternative (used by JavaScript, e.g.) is to create new objects by cloning existing prototype objects

Encapsulation

- Objects are often (though not always) designed so that their data fields can only be accessed by the object's own methods

- This kind of encapsulation is just what is needed to implement an Abstract Data Type (ADT)

  - It allows the representation or implementation of an object to change without affecting client code that interacts with the object only via method send.

- However, OO programmers often violate encapsulation. For example, object fields may be public, allowing them to be accessed from code outside the object's methods

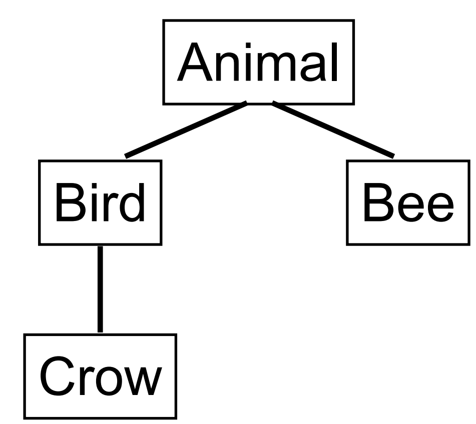
Subtyping in general

- Recall that types can often be naturally refined into subtypes
  - type = set of values supporting certain operations
  - subtype = subset of values supporting those operations and more
- Example: Type “Animal” supports operation “eat.” Subtype “Bird” supports operation “eat” and also operation “fly.”
- For type soundness, say B is a subtype of A if we can use a B value wherever an A value is expected.
- Informally, makes sense to say B is a subtype of A if every value of B “is a” value of A.

Subclasses

Name-based subtyping

- In class-based OO languages, it is common to declare immediate subtypes by defining subclasses.
    - e.g. in Scala: `class Bird extends Animal`
- The overall subtyping relation is automatically taken to be the reflexive, transitive closure of the immediate subclass declarations
    - e.g. if we also define `class Crow extends Bird` then automatically `Crow` is a subtype of `Animal`
- This leads to a subtyping hierarchy



Heterogenous Collections

- Subtyping and dynamic dispatch combine to give powerful support for manipulating heterogeneous collections:

```
abstract class Animal {
  def name() : String
  def eat() : String
}

class Bird extends Animal {
  def name() = "bird"
  def eat() = "chomp on insects"
}
```

```
class Bee extends Animal {
  def name() = "bee"
  def eat() = "suck nectar"
```

Output:

```
bird:chomp on insects
bee:suck nectar
```

```
object Main {
  val animals : List[Animal] = List(new Bird(), new Bee())
  for (animal <- animals)
      println(animal.name() + ":" + animal.eat())
}
```

Inheritance

- Classes may also be related because their implementations are similar.
- To avoid writing duplicate code, we might like to inherit most of the implementation of one class from another
  - possibly overriding some aspects of the implementation in the subclass
- This works nicely when the inheriting class is also a subtype of the providing class

Using Inheritance

```
abstract class Animal {
  def name() : String
  def eat() : String
}

class Bird extends Animal {
  def name() = "bird"
  def eat() = "chomp on insects"
}

class Bee extends Animal {
  def name() = "bee"
  def eat() = "suck nectar"
}
object Main {
  val animals : List[Animal] = List(new Bird(), new Crow(), new Bee())
  for (animal <- animals)
    println(animal.name() + ":" + animal.eat())
}
```

definition of `eat()` is inherited from `Bird`

```
class Crow extends Bird {
  override def name() = "crow"
}
```

definition of `name()` from `Bird` is overridden

Output:

```
bird:chomp on insects
crow:chomp on insects
bee:suck nectar
```

Flexibility of Dynamic Dispatch

- Method calls are always dispatched to the original receiving object, so superclass code can access functionality in subclasses.

```
abstract class Animal {
  def name() : String
  def eat() : String
}

class Bird extends Animal {
  def name() = "bird"
  def eat() = "chomp on " + food()
  def food() = "insects"
}
```

```
class Crow extends Bird {
  override def name() = "crow"
  override def food() = "anything"
}

class Robin extends Bird {
  override def name() = "robin"
  override def food() = "worms"
}
```

```
object Main {
  val animals : List[Animal] = List(new Bird(), new Crow(), new Robin())
  for (animal <- animals)
    println(animal.name() + ":" + animal.eat())
}
```

Output:

```
bird:chomp on insects
crow:chomp on anything
robin:chomp on worms
```

Subtyping vs. Inheritance

- Sometimes we'd like to use inheritance even when subtyping is not appropriate, e.g.:
  - Suppose we add `bat` as a new kind of `animal`. Since bats also eat insects, we might be tempted to make `bat` a subclass of `bird` so that it would inherit the implementation of `eat()`.
  - But it is not the case that a bat "is a" bird! That is, it does not suffice to provide a bat when a bird is expected. (E.g. if `bird` had a method `lay_eggs()`, we would not be able to give an appropriate implementation of that method for `bat`.)
- Inheritance concerns can warp design of subtyping hierarchy

Beyond Single Inheritance

- More flexible inheritance mechanisms can help.
  - Some languages (e.g. C++) let a class inherit from multiple super-classes. (Semantics of field inheritance can be messy.)
  - Java supports subtyping through multiple interfaces, which are like classes without fields.
  - Scala supports both inheritance and subtyping through traits, which are like partial class definitions that can be "mixed in" together.

Using Traits for Subtyping

```
abstract class Named {
  def name() : String
}

trait Flies extends Named {
  def fly() : String
}

trait Eats extends Named {
  def eat() : String
}
```

```
class Airplane extends Flies {
  def name() = "plane"
  def fly() = "using jets"
}

class Lion extends Eats {
  def name() = "lion"
  def eat() = "chomps on red meat"
}

class Bird extends Flies with Eats {
  def name() = "bird"
  def fly() = "by flapping wings"
  def eat() = "chomps on insects"
}
```

Output:

```
bird:by flapping wings
plane:using jets
bird:chomps on insects
lion:chomps on red meat
```

```
object Main {
  val fliers : List[Flies] = List(new Bird(), new Airplane())
  val eaters: List[Eats] = List(new Bird(), new Lion())
  for (flier <- fliers) println(flier.name() + ":" + flier.fly())
  for (eater <- eaters) println(eater.name() + ":" + eater.eat())
}
```

Using Traits for Inheritance

```
abstract class Animal {
  def name() : String
  def eat() : String
  def reproduce() : String
}

trait Insectivorous {
  def eat() = "chomp on insects"
}

trait Oviparous {
  def reproduce() = "lay eggs"
}
```

```
class Bat extends Animal
          with Insectivorous {
  def name() = "bat"
  def reproduce() = "bear live young"
}

class Bee extends Animal
          with Oviparous {
  def name() = "bee"
  def eat() = "suck nectar"
}
```

```
class Bird extends Animal with Insectivorous with Oviparous {
  def name() = "bird"
}

object Main {
  val animals : List[Animal] = List(new Bird(), new Bat(), new Bee())
  for (animal <- animals)
    println(animal.name() + ":" + animal.eat() + ":" + animal.reproduce())
}
```

Output:

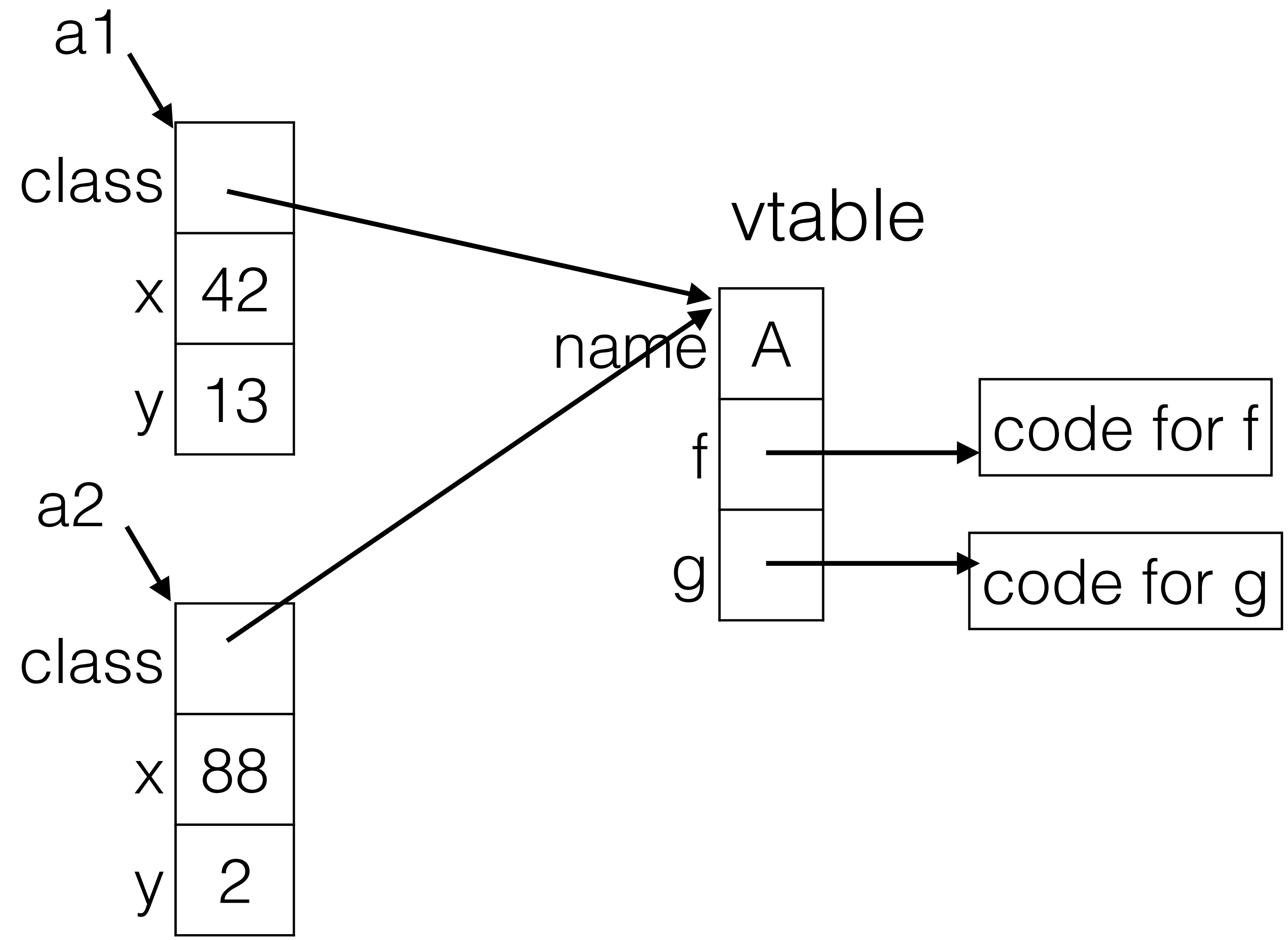
```
bird:chomp on insects:lay eggs
bat:chomp on insects:bear live young
bee:suck nectar:lay eggs
```

Representation of Objects

- An object is essentially a record (usually heap-allocated to support unlimited lifetime) containing values for the fields and code pointers for methods
- In a dynamically-typed language, the object record fields/methods have labels that can be searched at run time (at least in a naive implementation)
- In a statically-typed language, we can (usually) compute the offset of each field/method statically, avoiding run-time search
- In a class-based language, we usually factor the representation so that method pointers are stored in a separate class record

Example without inheritance

```
class A {
  int x;
  int y;
  f() = x+y;
  g(z) = f()+z;
}
val a1:A = …
val a2:A = …
val w = a1.g(10)
```



Generated code in C-like notation

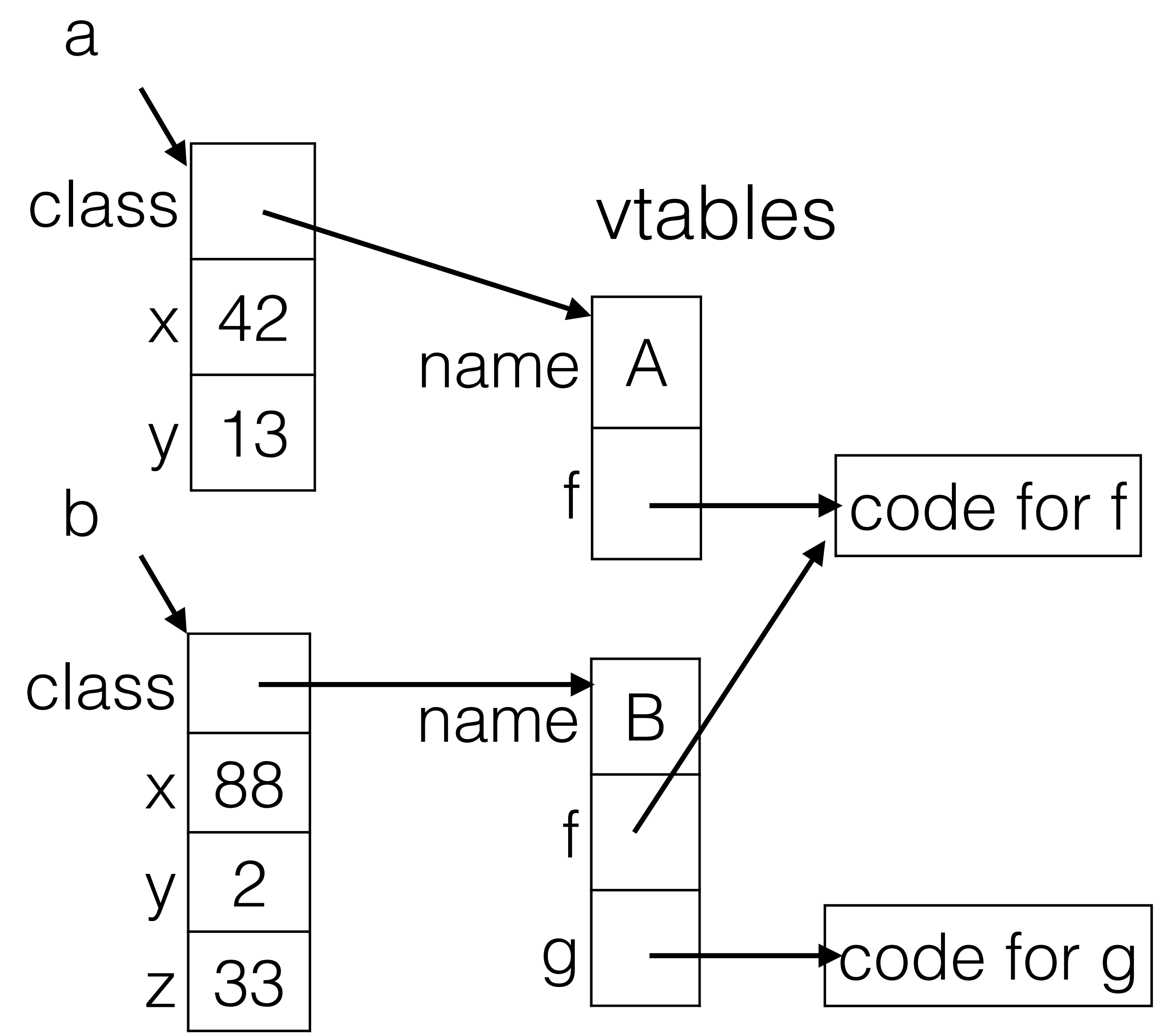
```
f(a) = a->x + a->y
g(a,z) = a->class->f(a) + z
w = a1->class->g(a1,10)
```

Implementing Sub-classes

- A key observation is that sub-classes only add (or override) fields and methods to the super-class.
- So the list of contents for super-class representation is always a prefix of list for sub-class representation
- All classes in the hierarchy can share the same offsets for the fields and methods they have in common, making run-time search unnecessary
- (This is just an implementation trick, but the resulting efficiency was historically important for the adoption of OOP.)
- Only works for single inheritance; multiple inheritance, interfaces, or traits require more work.

Example with inheritance

```
class A {
  int x;
  int y;
  f() = x+y;
}
class B extends A {
  int z;
  g() = x+z;
}
val a:A = …
val b:B = …
val w = b.f()+b.g()
```




```
f(a) = a->x + a->y
g(b) = b->x + b->z
w = b->class->f(b) +
      b->class->g(b)
```