# Lecture #17: More Special Effects—Exceptions and OOP



## Exceptions and Continuations

- Exception-handling in programming languages is a very limited form of continuation.
- Execution continues after a function call that is still active when exception raised.
- Java provides mechanism to return a value with the exception, but this adds no new complexity.



## Approach I: Do Nothing

- Some say keep it simple; don't bother with exceptions.
- Use return code convention:

  Example: C library functions often return either 0 for OK or non-zero for various degrees of badness.
- Problems:
  - Forgetting to check.
  - Code clutter.
  - Clumsiness: makes value-returning functions less useful.
  - Slight cost in always checking return codes.



## Approach II: Non-Standard Return

- First idea is to modify calls so that they look like this:

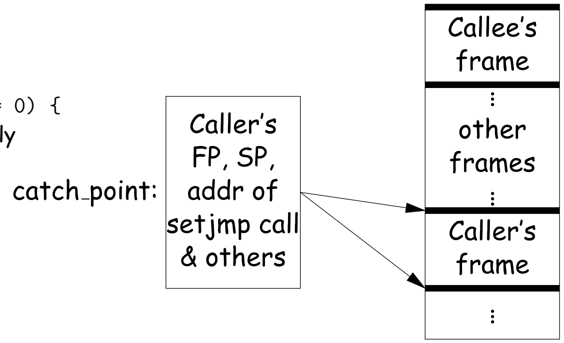
```
    call _f
    jmp  OK
    code to handle exception
OK:
    code for normal return
```

- To throw exception:
  - Put type of exception in some standard register or memory location.
  - Return to instruction *after* normal return.
- Awkward for the ia32 (above). Easier on machines that allow returning to a register+constant offset address [why?].
- Exception-handling code decides whether it can handle the exception, and does another exception return if not.
- Problem: Requires small distributed overhead for every function call.

## Approach III: Stack manipulation

- C does not have an exception mechanism built into its syntax, but uses library routines:

```
jmp_buf catch_point;

void Caller () {
   if (setjmp (catch_point) == 0) {
      normal case, which eventually
      gets down to Callee
   } else {
       handle exception
   }
}

void Callee () {
   ...
   // Throw exception:
   longjmp (catch_point, 42);
   ...
}
```






## Approach III: Discussion

- On exception, call to `setjmp` appears to return twice, with two different values.
- Does not require help from compiler,
- But implementation is architecture-specific.
- Overhead imposed on every `setjmp` call.
- If used to implement `try` and `catch`, therefore, would impose cost on every `try`.
- Subtle problems involving variables that are stored in registers:
  - The `jmp_buf` typically has to store such registers, but
  - That means the value of some local variables may revert unpredictably upon a `longjmp`.



## Approach IV: PC tables

- Sun's Java implementation uses a different approach.
- Compiler generates a table mapping instruction addresses (program counter (PC) values) to exception handlers for each function.
- If needed, compiler also leaves behind information necessary to return from a function ("unwind the stack") when exception thrown.
- To throw exception E:

```
while (current PC doesn't map to handler for E)
  unwind stack to last caller
```

- Under this approach, a **try-catch** incurs no cost unless there is an exception, but
- Throwing and handling the exception more expensive than other approaches, and
- Tables add space.



## New Topic: Dynamic Method Selection and OOP

- "Interesting" language feature introduced by Simula 67, Smalltalk, C++, Java: the *virtual function* (to use C++ terminology).
- Problem:
  - Arrange classes in a hierarchy of types.
  - Instance of subtype "is an" instance of its supertype(s).
  - In particular, inherits their methods, but can override them.
  - A *dynamic* effect: Cannot in general tell from program text what body of code executed by a given call.
- Implementation difficulty (as usual) depends on details of a language's semantics.
- Some things still static:
  - Names of functions, numbers of arguments are (usually) known
  - Compiler can handle overloading by inventing new names for functions. E.g., G++ encodes a function f(int x) in class Q as `_ZN1Q1fEi`, and f(int x, int y) as `_ZN1Q1fEii`.

# I. Fully Dynamic Approach

- Regular Python is completely dynamic:

```
class A:
   x = 2
   def f (self): return 42

a = A (); b = A ()
print a.x, a.f()   # Prints 2 42
a.x = lambda (self, z): self.w * z
a.f = 13; a.w = 5
print a.x(3), a.f, a.w  # Prints 15 13 5
print b.x(3), b.f, b.w  # Error (x not a function)
print A.x               # Prints 2
A.x = lambda (self): 19
A.f = 2
A.v = 1
c = A ()
print c.x (), c.f, c.v  # Prints 19, 2, 1
print b.x (), b.f, b.v  # Prints 19, 2, 1
```



# Characteristics of Dynamic Approach

- Each class instance is independent. Contents of class definition merely used until a new value is assigned to an attribute of the instance.
- New attributes can be added freely to instances or to class.
- In other variants of this approach, there are no classes at all, only instances, and we get new instances by cloning existing objects, and possibly then adding new attributes.



# Implementing the Dynamic Approach

- Simple strategy: just put a dictionary in every instance, and in class.
- Create an instance by making fresh copy of class's dictionary.
- Check for value of attribute in object's dictionary, then in that of its class, superclass, etc.
- All checking at runtime.
- All objects (or pointers) carry around dynamic type.



# Pros and Cons of Dynamic Approach

- Extremely flexible
- Conceptually simple
- Implementation easy
- Space overhead: every instance has pointers to all methods
- Time overhead: lookup on each call
- No static checking

## II. Straight Single Inheritance, Dynamic Typing

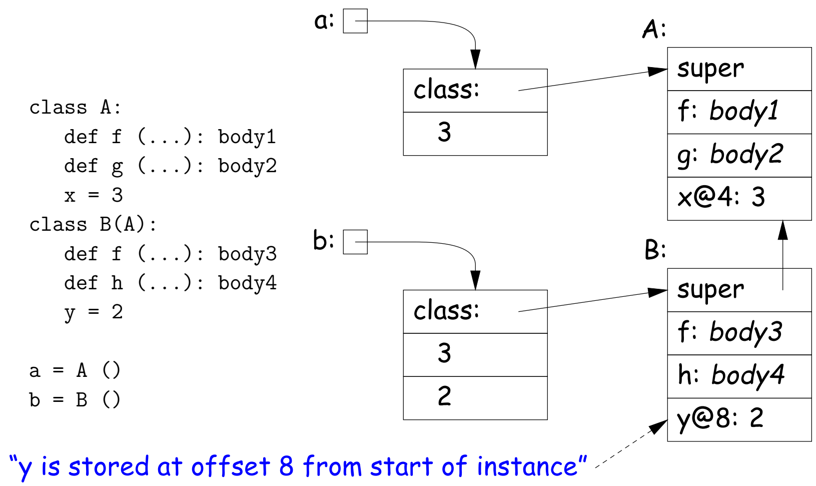
- Each class has fixed set of methods and instance variables
- Methods have fixed definition in each class.
- Classes can inherit from single superclass.
- Otherwise, types of parameters, variables, etc., still dynamic
- Basically technique in Smalltalk, Objective C.



## Implementing the Smalltalk-like Approach

- Instances need not carry around copies of function pointers.
- Instead, each *class* has a data structure mapping method names to functions, and instance-variable names to offsets from the start of the object.

```
class A:
   def f (...): body1
   def g (...): body2
   x = 3
class B(A):
   def f (...): body3
   def h (...): body4
   y = 2

a = A ()
b = B ()
```






## Pros and Cons of Smalltalk Approach

- Only need to store modifiable things—instance variables—in instances.
- Data structure can be a bit faster at accessing than fully dynamic method
- But still, not much static checking possible, and
- Some lookup of method names required.

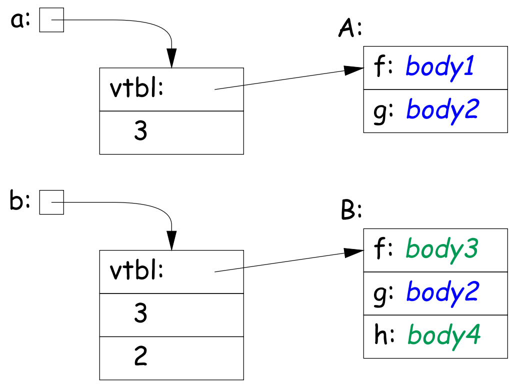


## Single Inheritance with Static Types

- Consider Java without interfaces. Type can inherit from at most one immediate superclass.
- For an access, x.w, insist that compiler knows a supertype of x's dynamic type that defines w.
- Insist that all possible overridings of a method have compatible parameter lists and return values.
- Use a technique similar to previous one, but put entries for all methods (whether or not overridden) in each class data structure.
- Such class data structures are called "virtual tables" or "vtables" in C++ parlance.

# Implementation of Simple Static Single Inheritance

```
class A {
  void f () { body1 }
  void g () { body2 }
  int x = 3
}
class B extends A {
  void f () { body3 }
  void h () { body4 }
  int y = 2
}
---------
a = new A ()
b = new B ()
```




- No need to store offsets of x and y; compiler knows where they are.
- Also, compiler knows where to find 'f', 'g', 'h' virtual tables.
- Important: offsets of variables in instances and of method pointers in virtual tables are *known constants*, the *same for all subtypes*.
- So compiler knows how to call methods of `b` even if static type is A!



# Interfaces

- Java allows *interface inheritance* of any number of interface types (introduces no new bodies).
- This complicates life: consider

```
class A {              class B {              interface C {
  int x;                 int y;                 f ();
  public f () { ... }    g () { ... }         }
}                        h () { ... }
                         public f () { ... }
                       }
    /*--------------------------------------------------*/
class A2 extends A          class B2 extends B
         implements C                implements C
{...}                       { ... }
    /*--------------------------------------------------*/
            void f (C y) { y.f () }   // How can this work?
```

- We can compile A and B without knowledge of C, A2, B2.
- How can we make the virtual table of A2 and B2 compatible with each other so that `f` is at same known offset regardless of whether dynamic type of C is A2 or B2? (Above isn't hardest example!)



# Interface Implementation I: Brute Force

- One approach is to have the system assign a different offset *globally* to each different function signature

  (Functions f(int x) and f() have different function signatures)
- So in previous example, the virtual tables can be:

```
A:                    B:                    C:
  0:  unused            0:  pntr to B.g       0: unused
  4:  unused            4:  pntr to B.h       4: unused
  8: pntr to A.f        8: pntr to B.f        8: unused

A2:                   B2:
  0:  unused            0:  pntr to B.g
  4:  unused            4:  pntr to B.h
  8: pntr to A.f        8: pntr to B.f
```

- No slowing of method calls.
- But, Total size of tables gets big (some optimization possible).
- And, must take into account all classes before laying out tables.

  Complicates dynamic linking.

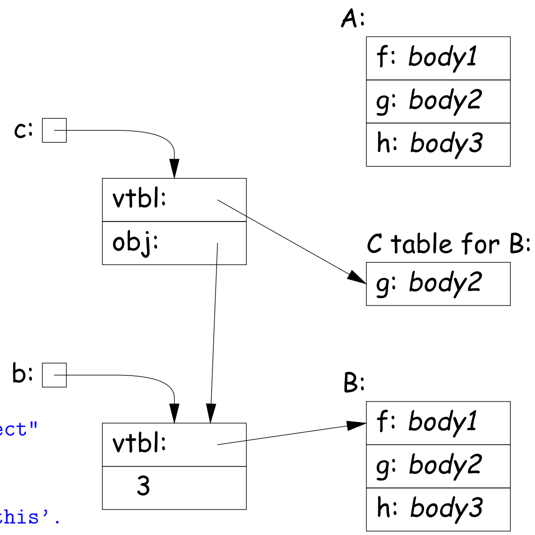


# Interface Implementation II: Make Interface Values Different

- Another approach is to represent values of static type C (an interface type) differently.
- Converting value x2 of type B2 to C then causes C to point to a two-word quantity:
  - Pointer to x2
  - Pointer to a cut-down virtual table containing just the f entry from B2 (at offset 0).
- Means that converting to interface requires work and allocates storage.

## Interface Implementation II, Illustrated

```
class A {
  void f () { body1 }
  void g () { body2 }
  void h () { body3 }
  int x = 3;
}

interface C { void g (); }

class B extends A
  implements C { }

B b = new B ();
C c = b;
  // Create "interface object"
c.g ();
  // Get g from c.vtbl, ...
  // ...and use c.obj as 'this'.
```






## Improving Interface Implementation II

- How can we avoid doing allocation to create value of interface type C?
- One method: extend the virtual table of all types to include an *interface vector*.
- Each entry in this vector identifies an interface the type implements, plus the table (e.g. "C table for B" in last slide).
- To implement '`C c = b`' from last slide, just copy pointer `b`, as for the usual cases when assigning to a variable whose type is a supertype of the value assigned.
- To implement '`c.g()`' from last slide, find the "C table" in the interface vector for object pointed to be `c` and fetch the entry for `g`. Just call as usual.
- Question for the reader: How best to design the interface vector?
  - Want fetching of `c.g` to be fast,
  - So best to avoid having to actually perform a search at execution time. How?



## Full Multiple Interitance

- Java allows multiple inheritance only via interfaces.
- Important point: *interfaces don't have instance variables*.
- Instance variables basically mess everything up for multiple inheritance, assuming we want to keep constant offsets to instance variables.

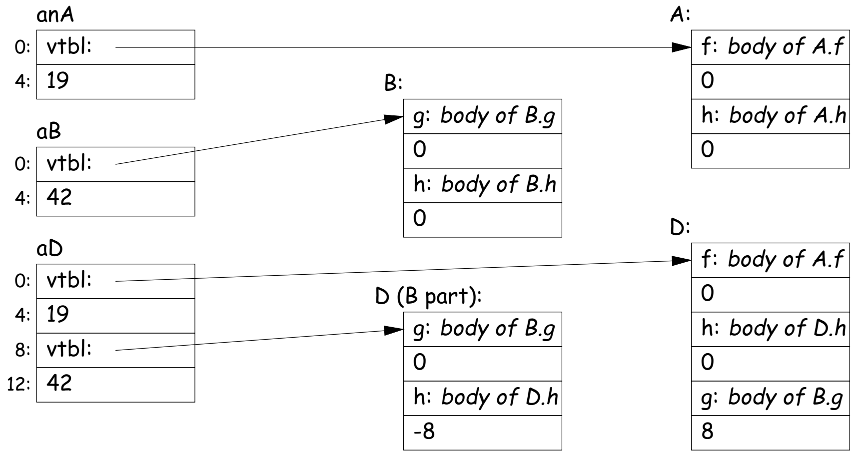
```
class A {
  int x = 19;
  void f () { ... x ... h() ... }
  void h () {... }
}

class B {
  int y = 42;
  void g () { ... y ... h() ... }
  void h () {... }
}

class D extends A, B {
   // Where do x and y go?
  void h () {... }
}
```

- If `aD` is a `D`, then aD.f expects that 'this' points to an A, aD.g expects that it points to a B, but aD.h expects it to point to a D.
- How can these all be true??



## Implementing Full Multiple Inheritance I

- Idea is to extend the contents of the virtual table with an offset for each method.
- Offset tells how to adjust the 'this' pointer before calling.
- For the classes from the last slide:



## Implementing Full Multiple Inheritance I (contd.)

- To call `aD.g`,
  - Fetch function address of `g` from `D` table.
  - Call it, but first add 8 to pointer value of `aD` so as to get a pointer to the "B part" of `aD`.
- When `aD.g` eventually calls `h` (actually `this.h`),
  - '`this`' refers to the "B part" of `aD`.
  - Its virtual table is "D (B part)" in the preceding slide.
  - Fetching `h` from that table gives us `D.h`, ...
  - ...which we call, after first adding the -8 offset from the table to "`this`."
  - Thus, we end up calling `D.h` with a "`this`" value that points to `aD`, as it expects.



## Implementing Full Multiple Inheritance II

- First implementation slows things down in all cases to accommodate unusual case.
- Would be better if only the methods inherited from B (for example) needed extra work.
- Alternative design: use stubs to adjust the 'this' pointer.
- Define B.$g_1$ to add 8 to the 'this' pointer and then call B.g; and D.$h_1$ to subtract 8 and then call D.h.: