CS412/413

Introduction to Compilers
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Lecture 32: Implementing Objects
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Classes

- Components
  - fields/instance variables
    - values may differ from object to object
    - usually mutable
  - methods
    - values shared by all objects of a class
    - usually immutable
  - component visibility: public/private/protected

Inheritance

- Three traditional components of object-oriented languages
  - abstraction/encapsulation
  - subtyping/interface inheritance: interfaces inherit method signatures from supertypes
  - subclassing/implementation inheritance: a class inherits signatures and code from a superclass (possibly "abstract")

Code Generation for Objects

- Methods
  - Generating method code
  - Generating method calls (dispatching)
  - Constructors and destructors
- Fields
  - Memory layout
  - Generating code to access fields
  - Field alignment

Compiling Methods

- Methods look like functions, are type-checked like functions…what is different?
- Argument list: implicit receiver argument
- Calling sequence: use dispatch vector instead of jumping to absolute address

The Need for Dispatching

- Example:

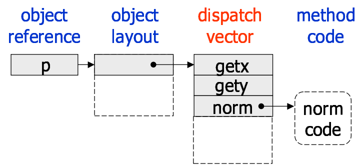
```
interface Point {
  int getx(); int gety(); float norm(); }
class ColoredPoint implements Point {…
  float norm() { return sqrt(x*x+y*y); }
class 3DPoint implements Point { …
  float norm() { return sqrt(x*x+y*y+z*z); }

Point p;
if (cond) p = new ColoredPoint();
else      p = new 3DPoint();
int n = p.norm();
```

- Compiler can't tell what code to run when method is called!

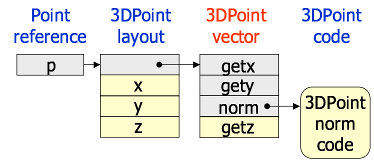
Dynamic Dispatch

- Solution: dispatch vector (dispatch table, selector table…)
  - Entries in the table are pointers to method code
  - Pointers are computed dynamically!
  - If T <: S, then vector for objects of type S is a prefix of vector for objects of type T



Why It Works

- If S <: T and f is a method of an object of type T, then
  - Objects of type S inherit f; f can be overridden by S
  - Pointer to f has same index in the DV for type T and S!
- Statically generate code to look up pointer to method f
- Pointer values determined dynamically



Dispatch Vector Lookup

- Every method has its own small integer index
- Index is used to look up method in dispatch vector

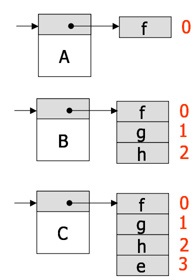
C <: B <: A

A f
B f,g,h
C f,g,h,e

```
interface A {
    void f();          0
}
class B implements A {
    void f() {…}  0
    void g() {…}  1
    void h() {…}  2
}
class C extends B {
    void e() {…}  3
}
```


Dispatch Vector Layouts

- Index of f is the same in any object of type T <: A
- Methods may have multiple implementations
  - For subclasses with unrelated types
  - If subclass overrides method
- To execute a method i:
  - Lookup entry i in vector
  - Execute code pointed to by entry value



Code Generation: Dispatch Vectors

- Allocate one dispatch vector per class
  - Objects of same class execute same method code
- Statically allocate dispatch vectors

```
.data
LenListDV    .long LenList$first
             .long LenList$rest
             .long LenList$length
```


Interfaces, Abstract Classes

- Classes define a type and some values (methods)
- Interfaces are pure object types : no implementation
  - no dispatch vector: only a DV layout
- Abstract classes are halfway:
  - define some methods
  - leave others unimplemented
  - no objects (instances) of abstract class
- DV needed only for concrete classes

Static Methods

- In Java, can declare methods static
  - they have no receiver object
- Called exactly like normal functions
  - don't need to enter into dispatch vector
  - don't need implicit extra argument for receiver
- Treated as methods as way of getting functions inside the class scope (access to module internals for semantic analysis)
- Not really methods

Method Arguments

- Methods have a special variable (Java, C++: this) called the receiver object
- Historically (Smalltalk): method calls thought of as messages sent to receivers
- Receiver object is (implicit) argument to method

```
class A {
  int f(int x, int y)
      { ... }
}
```

compile as

```
int f(A this, int x, int y)
    { ... }
```

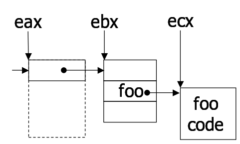

Code Generation: Method Calls

- Code for function calls: pre-call + post-call code
- Pre-function-call code:
  - Save registers
  - Push parameters
- Pre-method call:
  - Save registers
  - Push parameters
  - Push receiver object reference
  - Lookup method in dispatch vector

Example

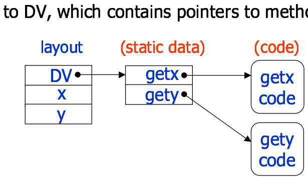
o.foo(2,3);

```
push $3
push $2
push %eax
mov (%eax), %ebx
mov 4(%ebx), ecx
call %ecx
add $12, %esp
```



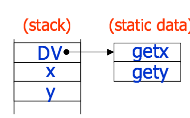
Object Layout

- Object consists of:
  - Methods
  - Fields
- Object layout consists of:
  - Pointer to DV, which contains pointers to methods
  - Fields

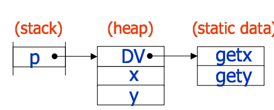


Allocation of Objects

- Objects can be stack- or heap-allocated
- Stack allocation:
  (C++) Point p;



- Heap:
  (C++)
  Point *p = new Point;
  (Java)
  Point p = new Point();

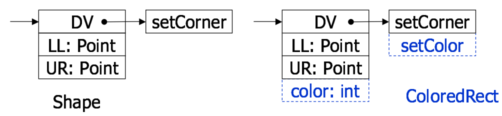


Inheritance and Object Layout

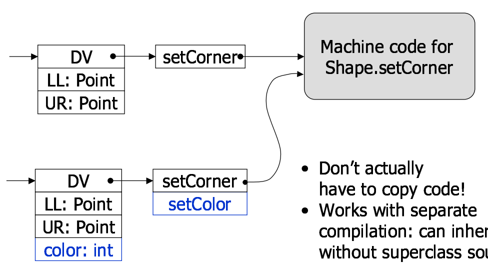
- Method code copied down from superclass if not overridden by subclass
- Fields also inherited (needed by inherited code in general)
- Inheritance: add fields, methods
  - Extend layout
  - Extend dispatch vector
  - A supertype object can be used whenever a subtype object can be used

Inheritance and Object Layout

```
class Shape {
  Point LL, UR;
  void setCorner(int which, Point p);
}
class ColoredRect extends Shape {
  int color;
  void setColor(int col);
}
```



Code Sharing



- Don't actually have to copy code!
- Works with separate compilation: can inherit without superclass source

Field Offsets

- Offsets of fields from beginning of object known statically, same for all subclasses
- Example:

```
class Shape {
  Point LL /* 4 */ , UR; /* 8 */
  void setCorner(int which, Point p);
}
class ColoredRect extends Shape {
  Color c; /* 12 */
  void setColor(Color c_);
}
```

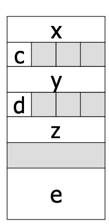
- Offsets known for stack and heap allocated objects

Field Alignment

- In many processors, a 32-bit load must be to an address divisible by 4, address of 64-bit load must be divisible by 8
- In rest (e.g. Pentium), loads are 10× faster if aligned -- avoids extra load

⇒ Fields should be aligned

```
struct {
    int x; char c; int y; char d;
    int z; double e;
}
```



Accessing Fields

- Access fields of current object
  - Access x equivalent to this.x
  - Current method has "this" as argument
- Access fields of other objects
  - Access of the form o.x
- In both cases:
  - Use pointer to object
  - Add offset to the field
- Access o.x depends on the kind of allocation of o
  - Stack allocation: stack access (%epb + stack offset)
  - Heap allocation: stack access + dereference

Code Generation: Allocation

- Heap allocation: o = new C()
  - Allocate heap space for object
  - Store pointer to dispatch vector

```
push $16   # 3 fields+DV
call _GC_malloc
mov $LenListDV, (%eax)
add $4, %esp
```

- Stack allocation:
  - Push object on stack
  - Pointer to DV on stack

```
sub $16, %esp   # 3 fields+DV
mov $LenListDV, -4(%ebp)
```


Constructors

- Java, C++: classes can declare object constructors that create new objects:
  new C(x, y, z)
- Other languages (Modula-3): objects constructed by "new C"; no initialization code

```
class LenList {
    int len;  Cell head, tail;
    LenList() { len = 0; }
}
```

- Need to know when objects are constructed
  - Heap: new statement
  - Stack: at the beginning of their scope (blocks for locals, procedures for arguments, program for globals)

Compiling Constructors

- Compiled similarly with methods:
  - pseudo-variable "this" passed to constructor
  - return value is "this"

l = new LenList();

```
push $16   # 3 fields+DV
call _GC_malloc
mov $LenListDV, (%eax)
add $4, %esp
push %eax
call LenList$constructor
add $4, %esp
```

LenList() { len = 0; }

```
LenList$constructor:
  push %ebp
  mov %esp,%ebp
  mov 8(%ebp), eax
  mov $0, 4(%eax)
  mov %ebp,%esp
  pop %ebp
  ret
```

Destructors

- In some languages (e.g. C++), objects can also declare code to execute when objects are destructed
- Heap: when invoking delete (explicit de-allocation)
- Stack: when scope of variables ends
  - End of blocks for local variables
  - End of program for global variables
  - End of procedure for function arguments

Analysis and Optimizations

- Dataflow analysis reasons about variables and values
- Records (objects) consist of a collection of variables (fields) – analysis must separately keep track of individual fields
- Difficult analysis for heap-allocated objects
  - Object lifetime outlives procedure lifetime
  - Need to perform inter-procedural analysis
- Constructors/destructors: must take into account their effects

Class Hierarchy Analysis

- Method calls = dynamic, via dispatch vectors
  - Overhead of going through DV
  - Prohibits function inlining
  - Makes other inter-procedural analyses less precise
- Static analysis of dynamic method calls
  - Determine possible methods invoked at each call site
  - Need to determine principal types of objects at each program point (Class Hierarchy Analysis)
  - If analysis determines object o is always of type T (not subtype), then it precisely knows the code for o.foo()
- Optimizations: transform dynamic method calls into static calls, inline method calls

Summary

- Method dispatch accomplished using dispatch vector, implicit method receiver argument
- No dispatch of static methods needed
- Inheritance causes extension of fields as well as methods; code can be shared
- Field alignment: declaration order matters!
- Each real class has a single dispatch vector in data segment: installed at object creation or constructor
- Analysis more difficult in the presence of objects
- Class hierarchy analysis = precisely determine object class