CSE P 501 – Compilers

Code Shape II – Objects & Classes

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Agenda

- Object representation and layout
- Field access
- What is **`this`**?
- Object creation - **`new`**
- Method calls
  - Dynamic dispatch
  - Method tables
  - Super
- Runtime type information

(As before, more generality than we actually need for the project)

What does this program print?

```
class One {
  int tag;
  int it;
  void setTag()          { tag = 1; }
  int getTag()           { return tag; }
  void setIt(int it)     { this.it = it; }
  int getIt()            { return it; }
}

class Two extends One {
  int it;
  void setTag() {
    tag = 2;  it = 3;
  }
  int getThat()    { return it; }
  void resetIt()   { super.setIt(42); }
}
```

```
public static void main(String[] args) {
      Two two = new Two();
      One one = two;

      one.setTag();
      System.out.println(one.getTag());

      one.setIt(17);
      two.setTag();
      System.out.println(two.getIt());
      System.out.println(two.getThat());
      two.resetIt();
      System.out.println(two.getIt());
      System.out.println(two.getThat());

  }
```

Your Answer Here

Object Representation

- The naïve explanation is that an object contains:
  - Fields declared in its class and in all superclasses
    - Redeclaration of a field hides (shadows) superclass instance – but the superclass field is still there and is in scope for, and accessed by, code in superclass methods
  - All methods declared in its class and all superclasses
    - Redeclaration of a method overrides (replaces) – but overridden methods can still be accessed by super**.** , and all relevant methods are part of the object's "behavior"

- When a method is called, the appropriate method "inside" that particular object is called
  - Regardless of the static (compile-time) type of the variable that points to the object – i.e., if the variable has type Shape but the object it references has subclass type Circle, the Circle method gets called if it overrides one from type Shape
    - (But we really don't want to copy/duplicate all those methods in every object, do we?)

Actual representation

- Each object contains:
  - Storage for every field (instance variable)
    - Including all inherited fields (public or private or …)
  - A pointer to a runtime data structure for its class
    - Key component: method dispatch table (vtable, next slide)
- An object is basically a C struct
- Fields hidden (shadowed) by declarations in subclasses are *still* allocated in the object and are accessible from superclass method code (using offsets assigned as part of superclass object layout)
  - Subclass methods access new fields using offsets assigned when subclass fields appended to superclass struct layout

Method Dispatch Tables

- One of these per class, not per object
- Often called “vtable”, “vtbl”, or “vtab”
  - (virtual function table – term from C++; standard term in all languages with dynamic dispatch)
- One pointer for each method in the vtable – points to beginning of compiled method code

Method Tables and Inheritance

- A naïve, really simple implementation – dictionaries!
  - One method table for each class containing names of methods declared locally in that class (keys), with pointers to compiled code for each method (values)
  - Method table also contains a pointer to parent class method table
  - Method dispatch:
    - Look in table for object's class and use if method found
    - Look in parent class table if not local
    - Repeat
    - "Message not understood" if you can't find it after search
  - Actually used in typical implementations of some dynamic languages; almost required if changes are possible during execution (e.g. Ruby, SmallTalk, Python, JavaScipt etc.)

Better: *O*(1) Method Dispatch

- Idea: Method table for extended class has pointers to *all* inherited and local methods for that class
- First part of method table for extended class has pointers for the same methods in the same order as the parent class
  - BUT pointers actually refer to overriding methods if any
  - So, dispatch for a method can be done with an indirect jump using a fixed method offset known at compile time, regardless of whether it points to an overriding method
    - In C: `(*(object->vtbl[offset]))(parameters)`
- Pointers to additional methods declared (added) in subclass are included in the vtable after pointers to inherited or overridden superclass methods

Perverse Example Revisited

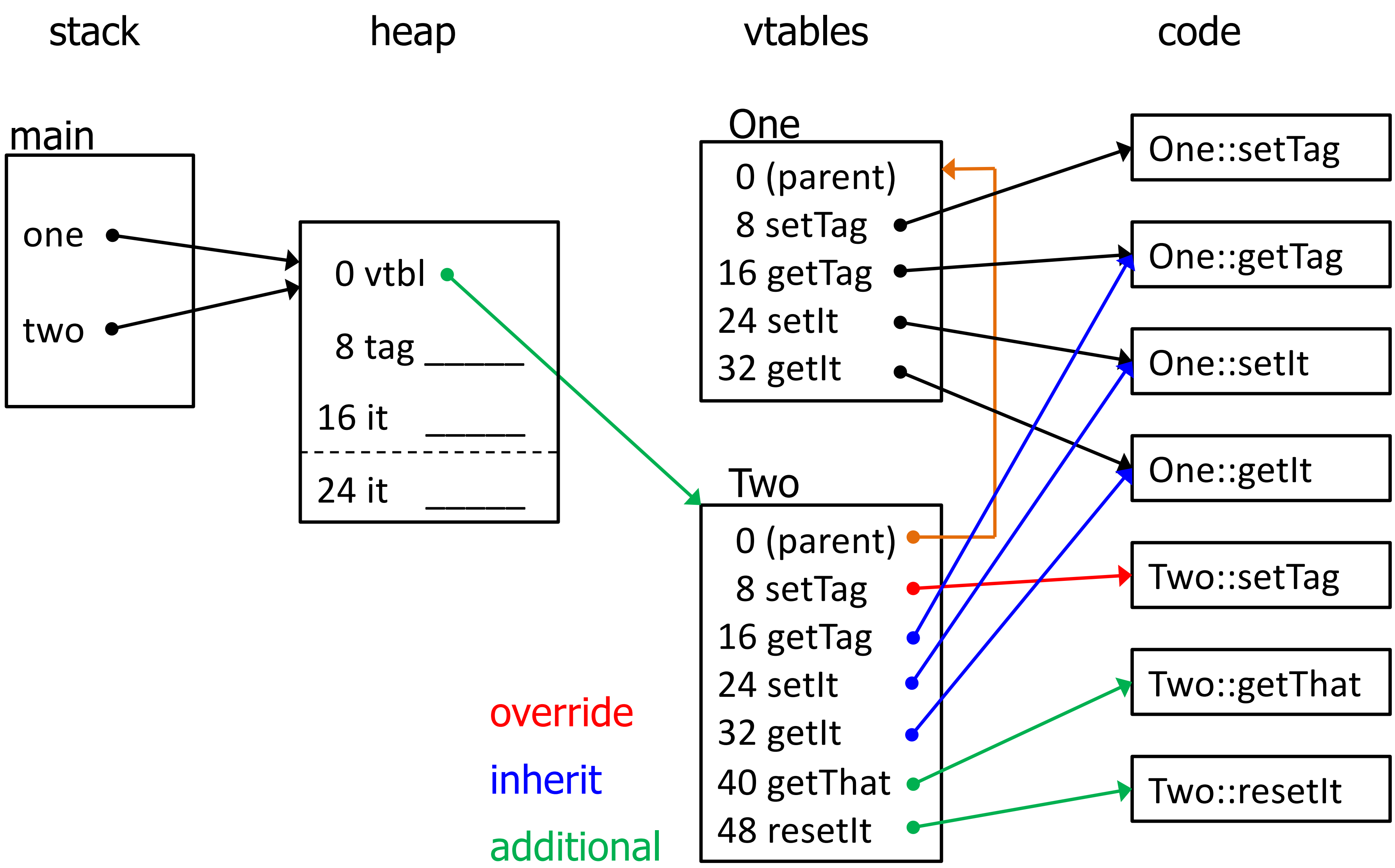
```
class One {
  int tag;
  int it;
  void setTag()    { tag = 1; }
  int getTag()     { return tag; }
  void setIt(int it) {this.it = it;}
  int getIt()      { return it; }
}
class Two extends One {
  int it;
  void setTag() {
    tag = 2;  it = 3;
  }
  int getThat()    { return it; }
  void resetIt()   { super.setIt(42); }
}
```

```
public static void main(String[] args) {
    Two two = new Two();
    One one = two;

    one.setTag();
    System.out.println(one.getTag());

    one.setIt(17);
    two.setTag();
    System.out.println(two.getIt());
    System.out.println(two.getThat());
    two.resetIt();
    System.out.println(two.getIt());
    System.out.println(two.getThat());

}
```

Implementation

stack	heap	vtables	code

Implementation



Method Dispatch Footnotes

- Don't need a pointer to parent class vtable to implement method calls, but often useful for other purposes
  - Casts and instanceof
- Multiple inheritance requires more complex mechanisms
  - Also true for multiple interfaces

Now What?

- Need to explore
  - – Object layout in memory
  - – Compiling field references
    - Implicit and explicit use of “this”
  - – Representation of vtables
  - – Object creation – new
  - – Code for dynamic dispatch
  - – Runtime type information – instanceof and casts

Object Layout

- Typically, allocate fields sequentially
- Follow processor/OS alignment conventions for structs/objects when appropriate/available
  - Include padding bytes for alignment as needed
- Use first word of object to hold pointer to method table (vtable)
- Objects are allocated on the heap (in Java)
  - Unlike C++ where objects can also be on stack
  - No bytes reserved for object data in generated code – use either heap or stack as appropriate

Object Field Access

- Source

  int n = obj.fld;

- x86-64
  - Assuming that obj is a local variable in the current method's stack frame

```
movq offset_obj(%rbp),%rax     # load obj ptr
movq offset_fld(%rax),%rax     # load fld
movq %rax,offset_n(%rbp)       # store n (assignment stmt)
```

  - Same idea used to reference fields of "this"
    - Use implicit "this" parameter passed to method instead of a local variable to get object address

Local Fields

- A method can refer to fields in the receiving object either explicitly as “this.f” or implicitly as “f”
  - Both compile to the same code – an implicit “this.” is assumed if not written explicitly
  - A pointer to the object (i.e., “this”) is an implicit, hidden parameter to all methods

Source Level View

What you write:

```
int getIt() {
  return it;
}
void setIt(int it) {
  this.it = it;
}
...
obj.setIt(42);
k = obj.getIt();
```

What compiler really does:

```
int getIt(Objtype this) {
  return this.it;
}
void setIt(ObjType this, int it) {
  this.it = it;
}
...
setIt(obj, 42);
k = getIt(obj);
```

x86-64 “this” Convention (C++)

- “this” is an implicit first parameter to every non-static method
- Address of object (“this”) placed in %rdi for every non-static method call
- Remaining parameters (if any) in %rsi, etc.

- We’ll use this convention in our project

MiniJava Method Tables (vtbls)

- Generate these as initialized data in the assembly language source program
  - One vtable for each class in the program
- Need to pick a naming convention for assembly language labels. This will work for us:
  - For methods, classname$methodname
    - Need something more sophisticated for overloading
  - For the vtables themselves, classname$$
- First method table entry points to superclass table (we might not use it in our project, but is helpful if you add instanceof or type cast checks, and can be useful for debugging to find parent vtbl)

Method Tables For Perverse Example (gcc/as syntax)

```
class One {
  void setTag()    { … }
  int getTag()     { … }
  void setIt(int it) {…}
  int getIt()      { … }
}

class Two extends One {
  void setTag() { … }        // override
  int getThat() { … }        // additional
  void resetIt() { … }
}
```

```
        .data
One$$:  .quad  0          # no superclass
        .quad  One$setTag
        .quad  One$getTag
        .quad  One$setIt
        .quad  One$getIt

Two$$:  .quad  One$$      # superclass
        .quad  Two$setTag
        .quad  One$getTag
        .quad  One$setIt
        .quad  One$getIt
        .quad  Two$getThat
        .quad  Two$resetIt
```

Method Table Layout

Key point: First entries in Two's method table are pointers to methods in *exactly the same order* as in One's method table

- Actual pointer(s) contain addresses of method(s) appropriate for objects of each class (inherited or overridden)

∴ Compiler knows correct offset for a particular method pointer *regardless of whether that method is overridden* and regardless of the actual type (dynamic) or subclass of the object referenced by the variable (the pointer)

Object Creation – new

Steps needed

- Call storage manager (malloc or equivalent) to get the raw bytes
- Initialize bytes to 0 (for Java, not in e.g., C++ *)
- Store pointer to method table (vtbl) in the first 8 bytes of the object
- Call a constructor with "this" pointer to the new object in %rdi and other parameters as needed
  - (Not in MiniJava since we don't have constructors)
- Result of new is a pointer to the new object

*Recent versions of C++ have new strange and wonderous rules about default initialization. Left as an exercise for aspiring programming language lawyers.

Object Creation

- Source

```
One one = new One(…);
```

- x86-64

```
movq    $nBytesNeeded,%rdi          # obj size + 8 (include space for vtbl ptr)
call    mallocEquiv                 # addr of allocated bytes returned in %rax
<zero out allocated object, or use calloc instead of malloc to get the bytes>
leaq    One$$(%rip),%rdx            # get method table address
movq    %rdx,0(%rax)                # store vtbl ptr at beginning of object
movq    %rax,%rdi                   # set up “this” for constructor
movq    %rax,offset_temp(%rbp)      # save “this” for later (or maybe pushq)
<load constructor arguments>        # arguments (if needed)
call    One$One                     # call ctor if we have one (no vtbl lookup)
movq    offset_temp(%rbp),%rax      # recover ptr to object
movq    %rax,offset_one(%rbp)       # store object reference in variable one
```

A weird addressing mode

- When we load the address of the vtable in the previous code we used

```
leaq        One$$(%rip),%rdx
```

- **WHAT????**
- "%rip can't be accessed directly in assembly code!!" (so says an earlier x86-64 slide)
- This is something called PC-relative addressing mode. The assembler should use it automatically when needed, but the linux assembler isn't always smart enough to figure that out. So we write it this way to be sure the assembler gets it right(!). Just do it this way in your generated code and it will work. We won't worry about it further.

Constructor

- Why don’t we need a vtable lookup to find the right constructor to call?

- Because at compile time we know the actual class (it says so right after “new”), so we can generate a call instruction to a known label
  - Same with super.method(…) or superclass constructor calls – at compile time we know all of the superclasses (need superclass details to compile subclass and construct method tables), so we know statically which class “super.method” belongs to

Method Calls

- Steps needed
  - Parameter passing: just like an ordinary C function, except load a pointer to the object in %rdi as the first ("this") argument
  - Get a pointer to the object's method table from the first 8 bytes of the object
  - Jump indirectly through the method table

Method Call

- Source

  obj.method(…);

- x86-64

```
<load arguments into registers as usual>  # as needed
movq   offset_obj(%rbp),%rdi     # first argument is obj ptr ("this")
movq   0(%rdi),%rax              # load vtable address into %rax
call   *offset_method(%rax)      # call function whose address is at
                                 #   the specified offset in the vtable†
```

†Can get same effect with:

```
addq offset_method,%rax
call *(%rax)
```

or with:

```
movq offset_method(%rax),%rax
call *%rax
```

Runtime Type Checking

- We can use the method table for the class as a "runtime representation" of the class
  - Each class has one vtable at a unique address
- The test for "o instanceof C" is:
  - Is o's method table pointer == **`&C$$`** ?
    - If so, result is "true"
  - Recursively, get pointer to superclass method table from the method table and check that
  - Stop when you reach Object (or a null pointer, depending on whether there is a ultimate superclass of everything)
    - If no match by the top of the chain, result is "false"
- Same test as part of check for legal downcast (e.g., how to check for ClassCastException in (type)obj cast)

Coming (& past) Attractions

- Other IRs besides ASTs
- Survey of code analysis and optimization, including dataflow, SSA
- Industrial-strength register allocation, instruction selection, and scheduling
- Other topics as time allows
  - GC? Dynamic languages? JVM? Other things?

- And simple code generation for the project
  - (later when we get closer to finishing semantics)