The Hardware/Software Interface

Java and C (condensed)

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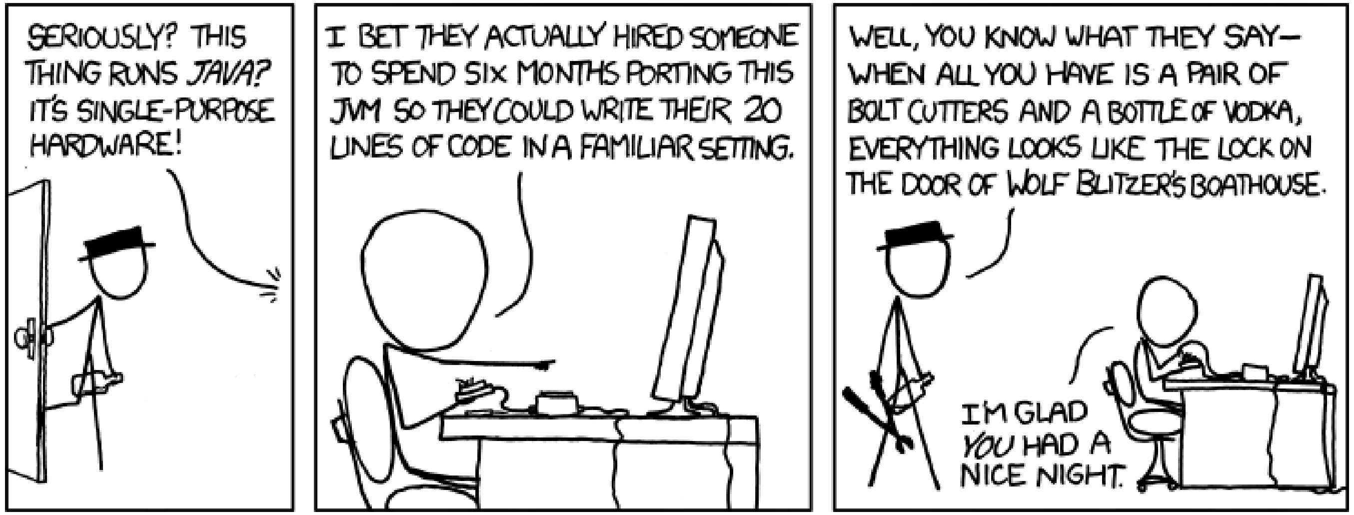


http://xkcd.com/801/

Relevant Course Information

- HW25 due tonight, HW26 due Wednesday (12/3)
- Lab 5 due Thursday (12/4)

- Course evaluations now open
  - See Ed Discussion post for links (separate for Lec and Sec)

- **Final Exam:** Wednesday, Dec. 10 from 12:30 – 2:20 pm in KNE 210/220
  - Ed post #547
  - Review Session: Friday 12/5 from 4:30 – 6:30 pm, in CSE2 G01 and on Zoom
  - *Cumulative*: Questions will be marked “M” (pre-midterm) or “F” (post-midterm)
  - TWO double-sided handwritten 8.5×11” cheat sheets + Final Reference Sheet

Lecture Outline (1/2)

- **Potential Java Data Implementation**
- The Java Virtual Machine (JVM)

Java vs. C

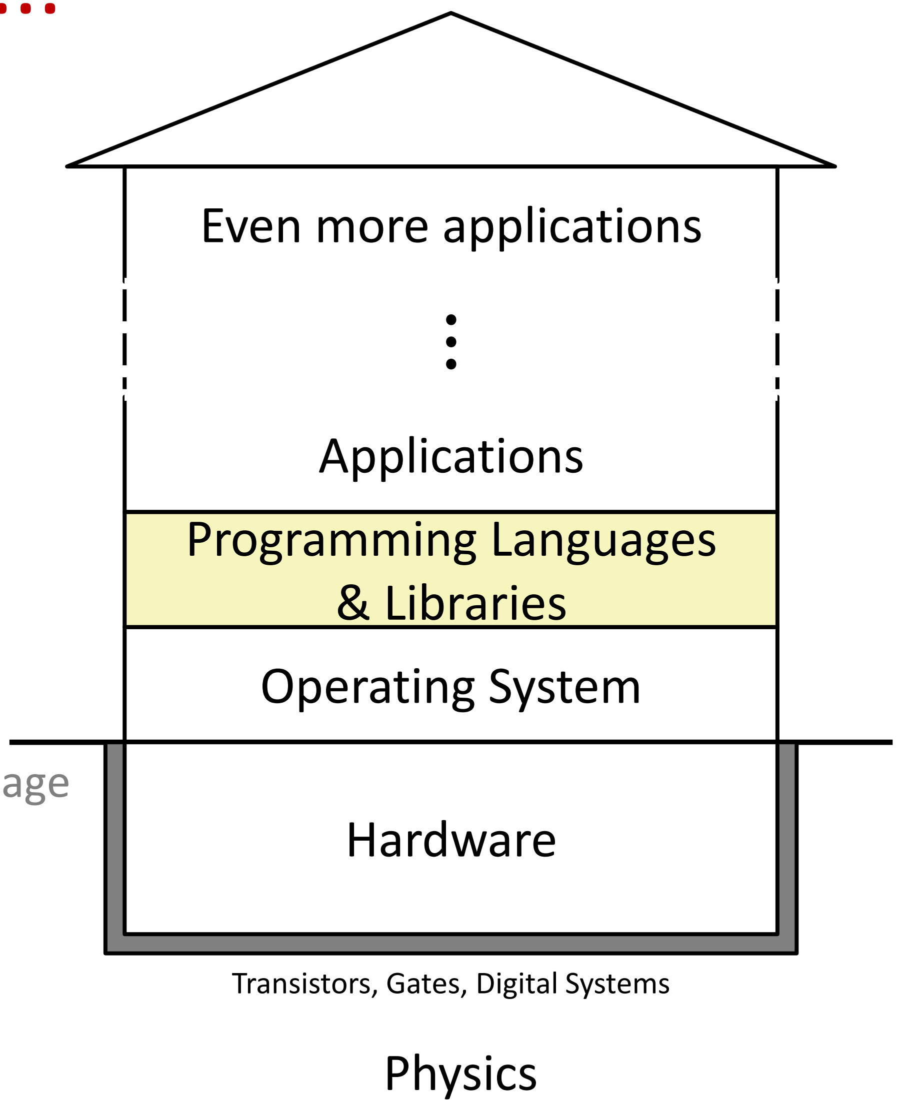
- Reconnecting to Java (hello, CSE123/143!)
  - But now you know a lot more about what really happens when we execute programs
- We’ve learned about the following items in C; now we’ll see what they look like for Java:
  - Representation of data
  - Pointers / references
  - Casting
  - Function / method calls including dynamic dispatch

The Hardware/Software Interface

Everything applies more generally than just C!!!

- Topic Group 1: **Data**
  - **Memory**, **Data**, Integers, Floating Point, **Arrays**, ~~**Structs**~~ **Objects**
- Topic Group 2: **Programs**
  - x86-64 Assembly, **Procedures**, **Stacks**, **Executables**
- Topic Group 3: **Scale & Coherence**
  - Caches, Memory Allocation, Processes, Virtual Memory

These apply to execution regardless of source language



Lecture Meta-Point

- CSE351 has given you a "really different feeling" about what computers do and how programs execute
  - Java is not a different world – it's just a higher-level of abstraction
  - Connect these levels via how-one-could-implement-Java in 351 terms

- The Java language specification provides an ***abstraction***
  - Tells us how code should behave for different language constructs, but we can't easily tell how things are really represented
  - But it is important to understand an ***implementation*** of the lower levels – useful in thinking about your program
    - None of the data representations we are going to talk about are ***guaranteed*** by Java

Data in Java

- Integers, floats, doubles, pointers – same as C
  - *References* in Java are much more constrained than C *pointers* in that they can only point to [the starts of] objects
  - Java’s portability-guarantee fixes the sizes of all types
  - No unsigned types to avoid conversion pitfalls
    - Added some useful methods in Java 8 (also use bigger signed types)
- `null` is typically represented as `0` but “you can’t tell”

- Much more interesting:
  - **Arrays**
  - **Characters and strings**
  - **Objects**

Data in Java: Arrays (1/3)

- Every element initialized to `0` or `null`
- Length specified in immutable field at start of array (`int`: 4B)
  - `array.length` returns value of this field
- *Since it has this info, what can it do?*

C:

```
int array[5];
```

??	??	??	??	??

0 4 20

Java:

```
int[] array = new int[5];
```

5	00	00	00	00	00

0 4 20 24

Data in Java: Arrays (2/3)

- Every element initialized to `0` or `null`
- Length specified in immutable field at start of array (`int`: 4B)
  - `array.length` returns value of this field
- Every access triggers a bounds-check
  - Code is added to ensure the index is within bounds
  - Exception if out-of-bounds

C:

```
int array[5];
```

??	??	??	??	??

0 4 20

Java:

```
int[] array = new int[5];
```

5	00	00	00	00	00

0 4 20 24

Discussion questions:

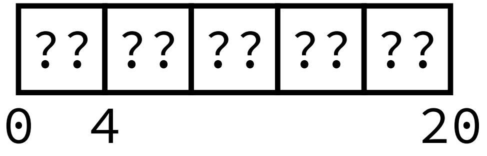
- What 351 concept does storing the array size here remind you of?
- What do you think the act of bounds-checking looks like at the assembly level?

Data in Java: Arrays (3/3)

- Every element initialized to `0` or `null`
- Length specified in immutable field at start of array (`int`: 4B)
  - `array.length` returns value of this field
- Every access triggers a <u>bounds-check</u>
  - Code is added to ensure the index is within bounds
  - Exception if out-of-bounds

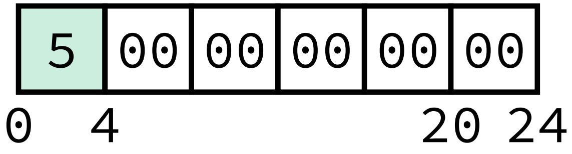
C:

```
int array[5];
```



Java:

```
int[] array = new int[5];
```



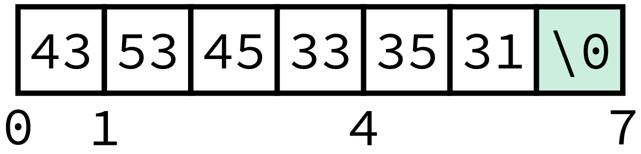
To speed up bounds-checking:
- Length field is likely in cache
- Compiler may store length field in register for loops
- Compiler may prove that some checks are redundant

Data in Java: Characters & Strings

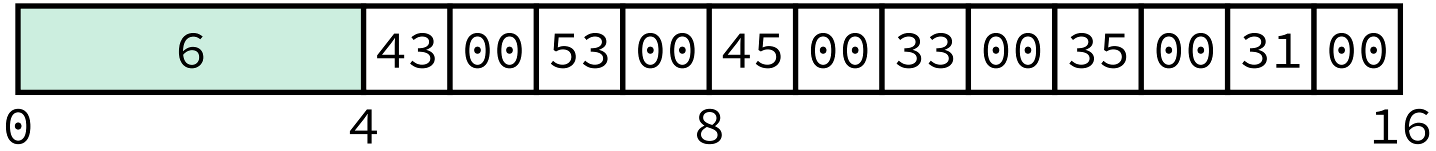
- Two-byte Unicode instead of ASCII
- `String` not bounded by a `'\0'` (null character)
  - Bounded by hidden length field at beginning of string
  - All `String` objects read-only (vs. `StringBuffer`)

- <u>Example</u>: the string `"CSE351"`

C:
(ASCII)



Java:
(Unicode)



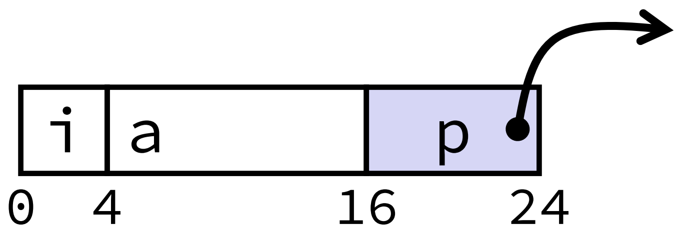
Data in Java: Objects

- Objects are always stored by reference, never stored "inline"
  - In Java, *all non-primitive variables are references to objects*
  - Access members using `r.a` notation (though just like `r->a` in C)

C:

```
struct rec {
  int i;
  int a[3];
  struct rec* p;
};
```

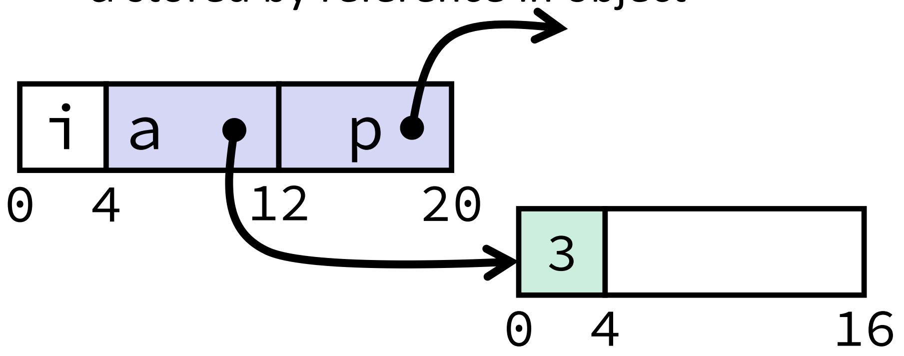
- `a[]` stored "inline" as part of struct



Java:

```
class Rec {
  int i;
  int[] a = new int[3];
  Rec p;
  ...
}
```

- a stored by reference in object



Struct vs. object discussion questions:

- What are the consequences for the memory layout?
- What are the consequences for the field access performance?

Casting in C (example from Lab 5)

- Can cast any pointer into any other pointer
  - Changes dereference and arithmetic behavior

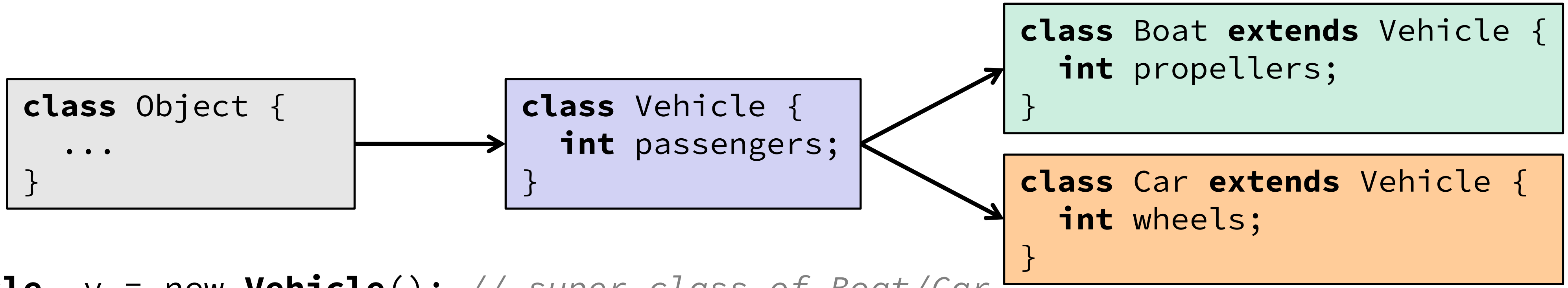
```
struct block_info {
  size_t size_and_tags;
  struct block_info* next;
  struct block_info* prev;
};
typedef struct block_info block_info;
...
int x;
block_info* b;
block_info* new_block;
...
new_block = (block_info*) ((char*)b + x);
...
```

Cast b into char* to do unscaled addition

Cast back into block_info* to use as block_info struct

Type-safe Casting in Java

- Can only cast compatible object references (class hierarchy)




```
Vehicle  v = new Vehicle(); // super class of Boat/Car
Boat    b1 = new Boat();    // |--> sibling
Car     c1 = new Car();     // |--> sibling

Vehicle v1 = new Car();
Vehicle v2 = v1;

Car     c2 = new Boat();
Car     c3 = new Vehicle();

Boat    b2 = (Boat) v;
Car     c4 = (Car) v2;
Car     c5 = (Car) b1;
```

Type-safe Casting in Java: Outcomes

- Can only cast compatible object references (class hierarchy)

```
class Object {
  ...
}
```

```
class Vehicle {
  int passengers;
}
```

```
class Boat extends Vehicle {
  int propellers;
}
```

```
class Car extends Vehicle {
  int wheels;
}
```

```
Vehicle  v = new Vehicle(); // super class of Boat/Car
Boat    b1 = new Boat();    // |--> sibling
Car     c1 = new Car();     // |--> sibling
```

```
Vehicle v1 = new Car();
Vehicle v2 = v1;
```
← ✓ Everything needed for `Vehicle` also in `Car`
← ✓ `v1` is declared as type `Vehicle`

```
Car     c2 = new Boat();
Car     c3 = new Vehicle();
```
← ✗ Compiler error: Incompatible type – fields in `Car` that are not in `Boat` (siblings)
← ✗ Compiler error: Wrong direction – fields `Car` not in `Vehicle` (`wheels`)

```
Boat    b2 = (Boat) v;
Car     c4 = (Car) v2;
Car     c5 = (Car) b1;
```
← ✗ Runtime error: `Vehicle` does not contain all fields in `Boat` (`propellers`)
← ✓ `v2` refers to a `Car` at *runtime*
← ✗ Compiler error: Unconvertable types – `b1` is declared as type `Boat`

Java Object Definitions

```
class Point {
  double x;
  double y;

  Point() {
    x = 0;
    y = 0;
  }

  boolean samePlace(Point p) {
    return (x == p.x) && (y == p.y);
  }
}
...
Point p = new Point();
...
```

fields

constructor

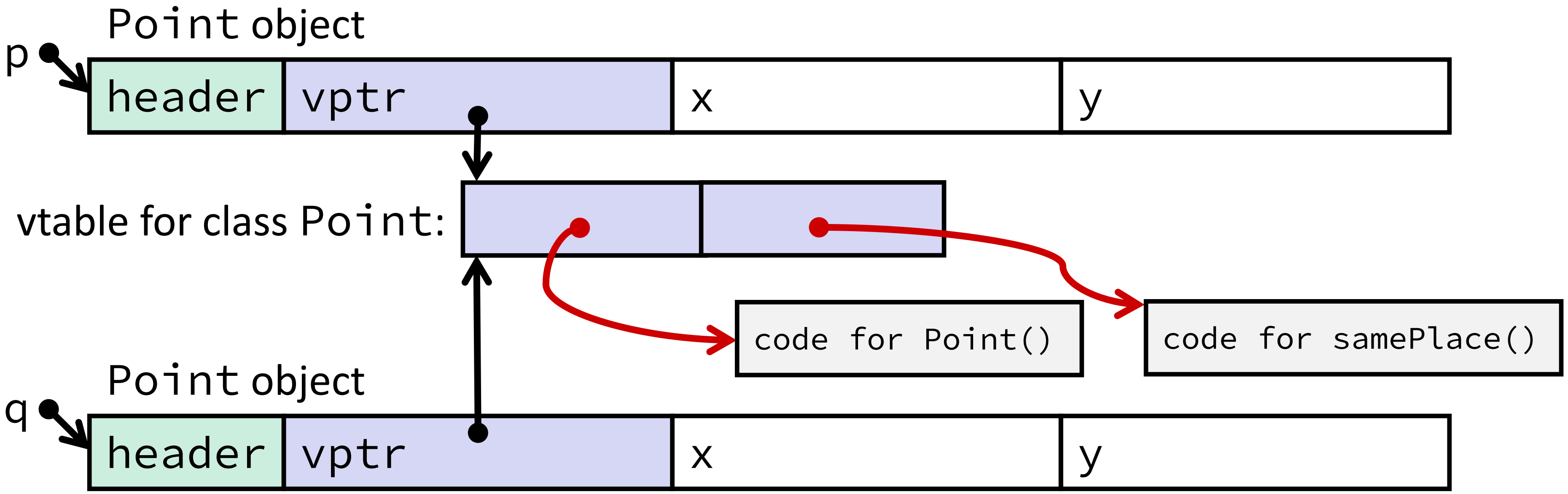
method(s)

creation

Discussion question:

- How might we represent Java objects in memory based on what we've learned in C?
  Hint: think about fields and methods separately.

Java Objects and Method Dispatch



- *Object header* : GC info, hashing info, lock info, etc.
- *Virtual method table (vtable)*
  - Like a jump table for instance ("virtual") methods plus other class info
  - One table per class
  - Each object instance contains a *vtable pointer (vptr)*

Java Constructors

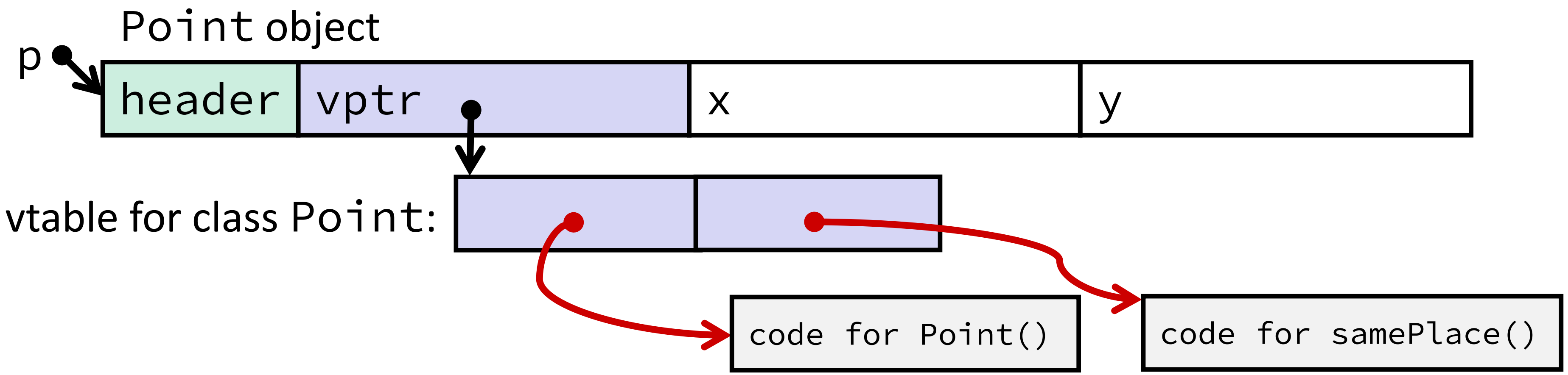
- **When we call new:** allocate space for object (data fields and references), initialize to zero/null, and run constructor method

Java:

```
Point p = new Point();
```

C pseudo-translation:

```
Point* p = calloc(1,sizeof(Point));
p->header = ...;
p->vptr = &Point_vtable;
p->vptr[0](p);
```



Java Methods

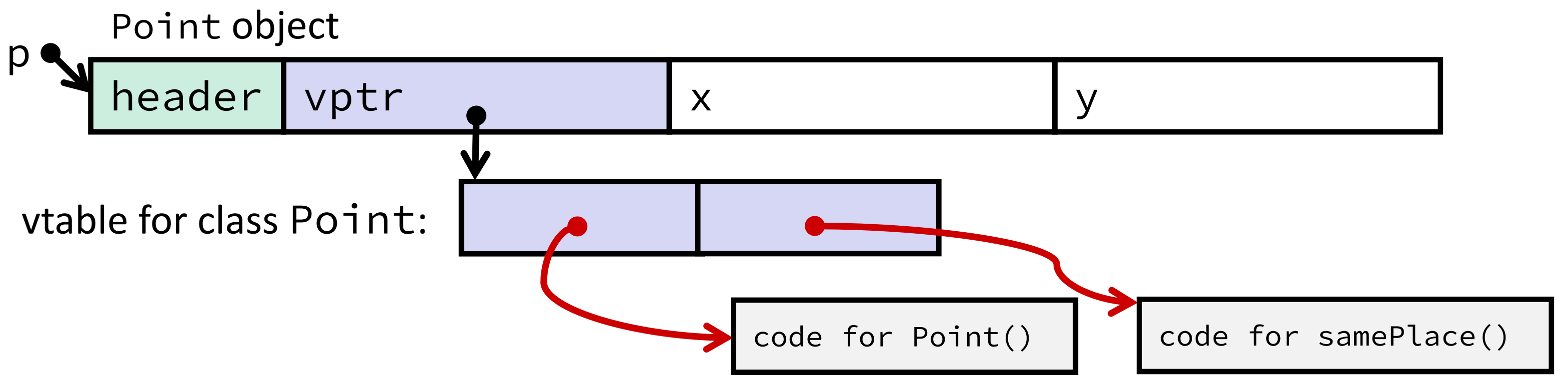
- Static methods are just like functions
- Instance methods:
  - Have an implicit first parameter for *this;* and
  - Can be overridden in subclasses
- The code to run when calling an instance method is chosen *at runtime* by lookup in the vtable

Java:

```
p.samePlace(q);
```

C pseudo-translation:

```
p->vptr[1](p, q);
```

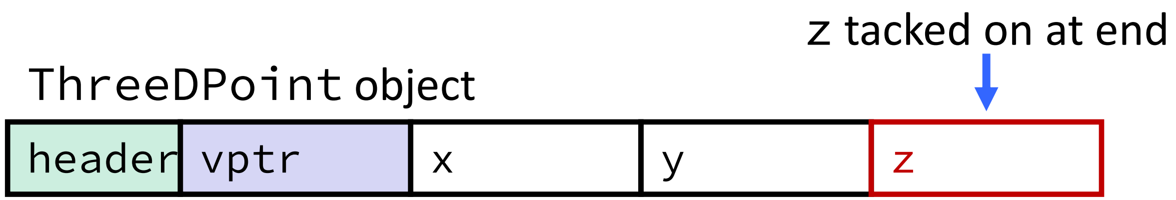


Subclassing (1/3)

```
class ThreeDPoint extends Point {
  double z;
  boolean samePlace(Point p2) {
    return false;
  }
  void sayHi() {
    System.out.println("hello");
  }
}
```

Subclassing (2/3)

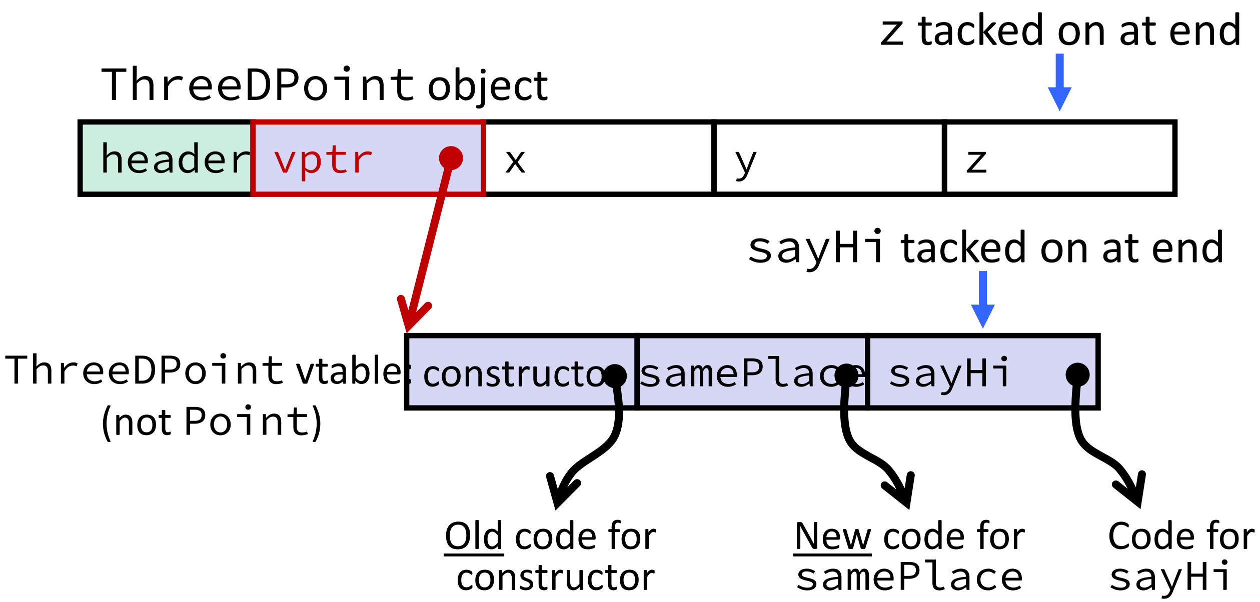
```
class ThreeDPoint extends Point {
  double z;
  boolean samePlace(Point p2) {
    return false;
  }
  void sayHi() {
    System.out.println("hello");
  }
}
```



- New fields (z) added to end of fields of subclass (x, y)
  - Point fields remain in the same place, so Point code can run on ThreeDPoint objects without modification!

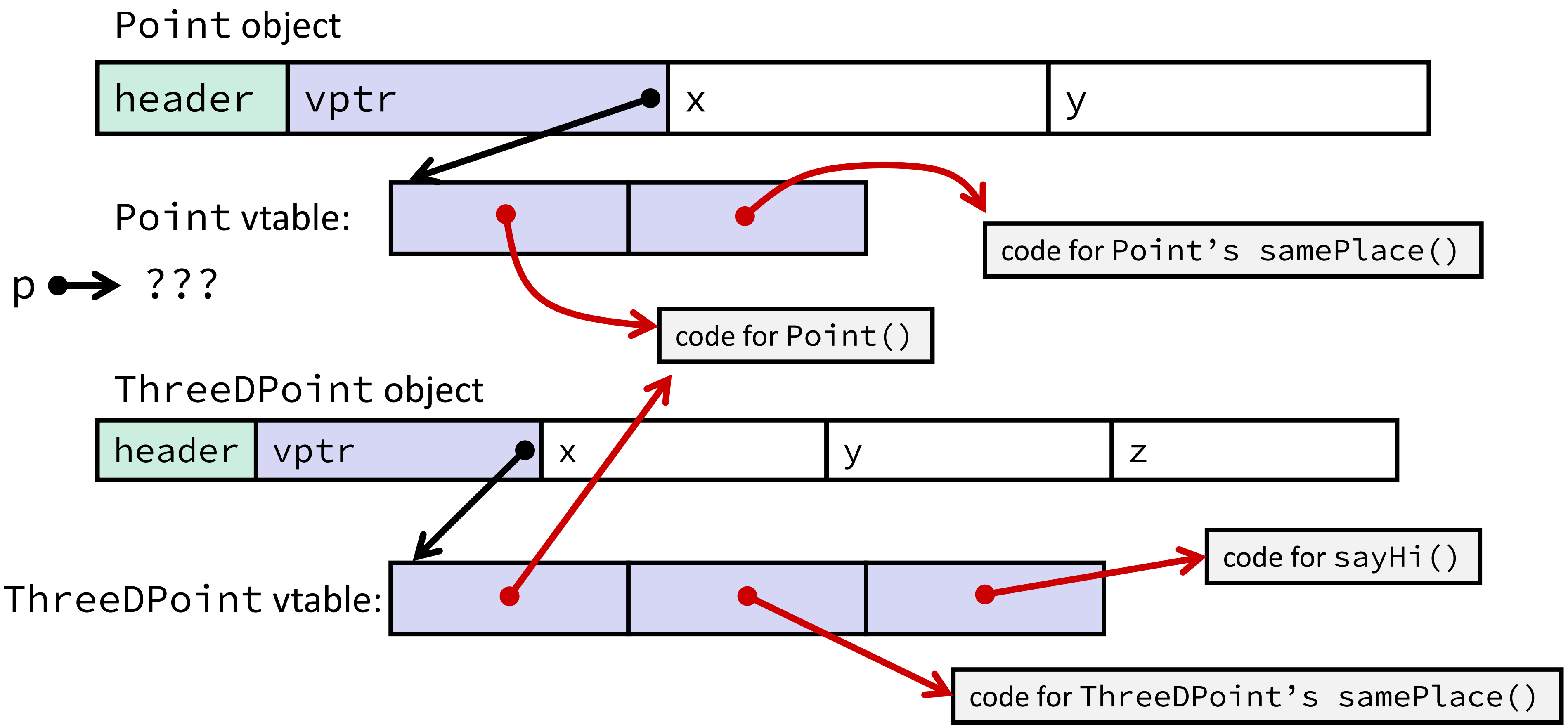
Subclassing (3/3)

```
class ThreeDPoint extends Point {
  double z;
  boolean samePlace(Point p2) {
    return false;
  }
  void sayHi() {
    System.out.println("hello");
  }
}
```



- Method modifications:
  - Add new pointer at end of vtable for new method "sayHi"
  - No constructor definition, so use default Point constructor
  - To override "samePlace", use same vtable position

Dynamic Dispatch



Java:

```
Point p = ???;
return p.samePlace(q);
```

C pseudo-translation:

```
// works regardless of what p is
return p->vptr[1](p, q);
```

Ta-da!

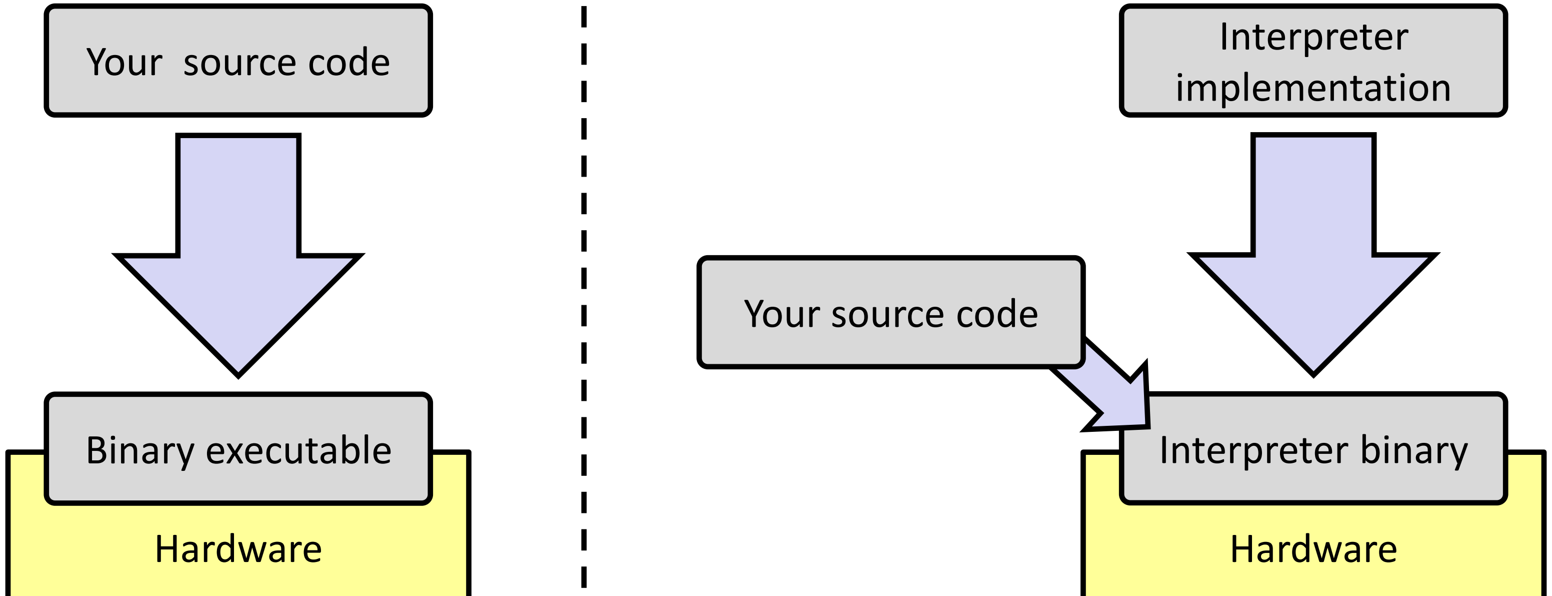
- In CSE123 or CSE143, it may have seemed "magic" that an *inherited* method could call an *overridden* method
  - You were tested on this endlessly
- The "trick" in the implementation is this part: **`p->vptr[i](p,q)`**
  - In the body of the pointed-to code, any calls to (other) methods of `this` will use `p->vptr`
  - Dispatch determined by p, not the class that defined a method

Lecture Outline (2/2)

- Potential Java Data Implementation
- **The Java Virtual Machine (JVM)**

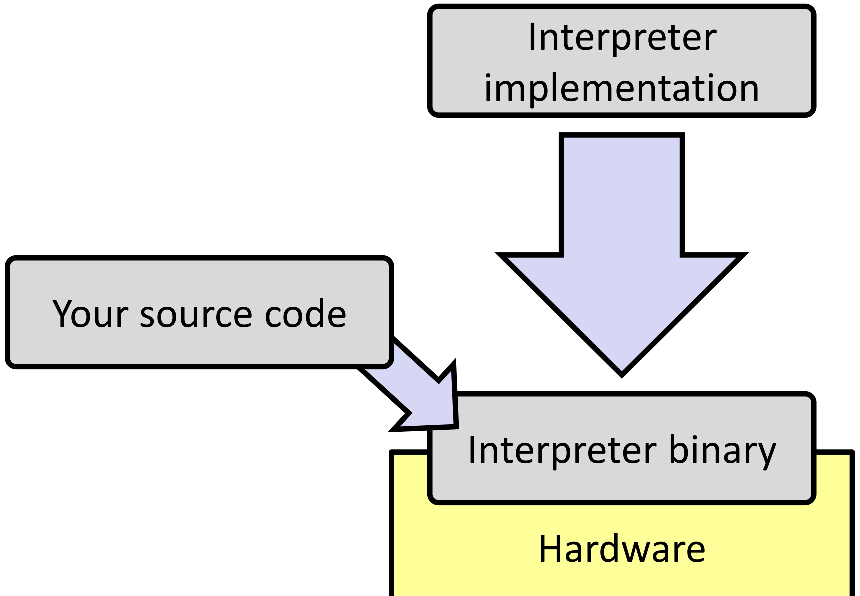
Implementing Programming Languages

- Many choices in programming model implementation
  - We've previously discussed compilation
  - One can also *interpret*
- Interpreters have a long history and are still in use
  - *e.g.*, Lisp, an early programming language, was interpreted
  - *e.g.*, Python, Javascript, Ruby, Matlab, PHP, Perl, …



Interpreters

- Execute (something close to) the *source code* directly, meaning there is less translation required
  - This makes it a simpler program than a compiler and often provides more transparent error messages
- Easier to run on different architectures – runs in a simulated environment that exists only inside the *interpreter* process
  - Just port the interpreter (program), and then interpreting the source code is the same
- Interpreted programs tend to be slower to execute and harder to optimize



Interpreters vs. Compilers

- Programs that are designed for use with particular language implementations
  - You can choose to execute code written in a particular language via either a compiler or an interpreter, if they exist
- "Compiled languages" vs. "interpreted languages" a misuse of terminology
  - But very common to hear this
  - And has *some* validation in the real world (*e.g.*, JavaScript vs. C)
- Some modern language implementations are a mix
  - *e.g.*, Java compiles to bytecode that is then interpreted
  - Doing just-in-time (JIT) compilation of parts to assembly for performance

Compiling and Running Java

1. Save your Java code in a `.java` file

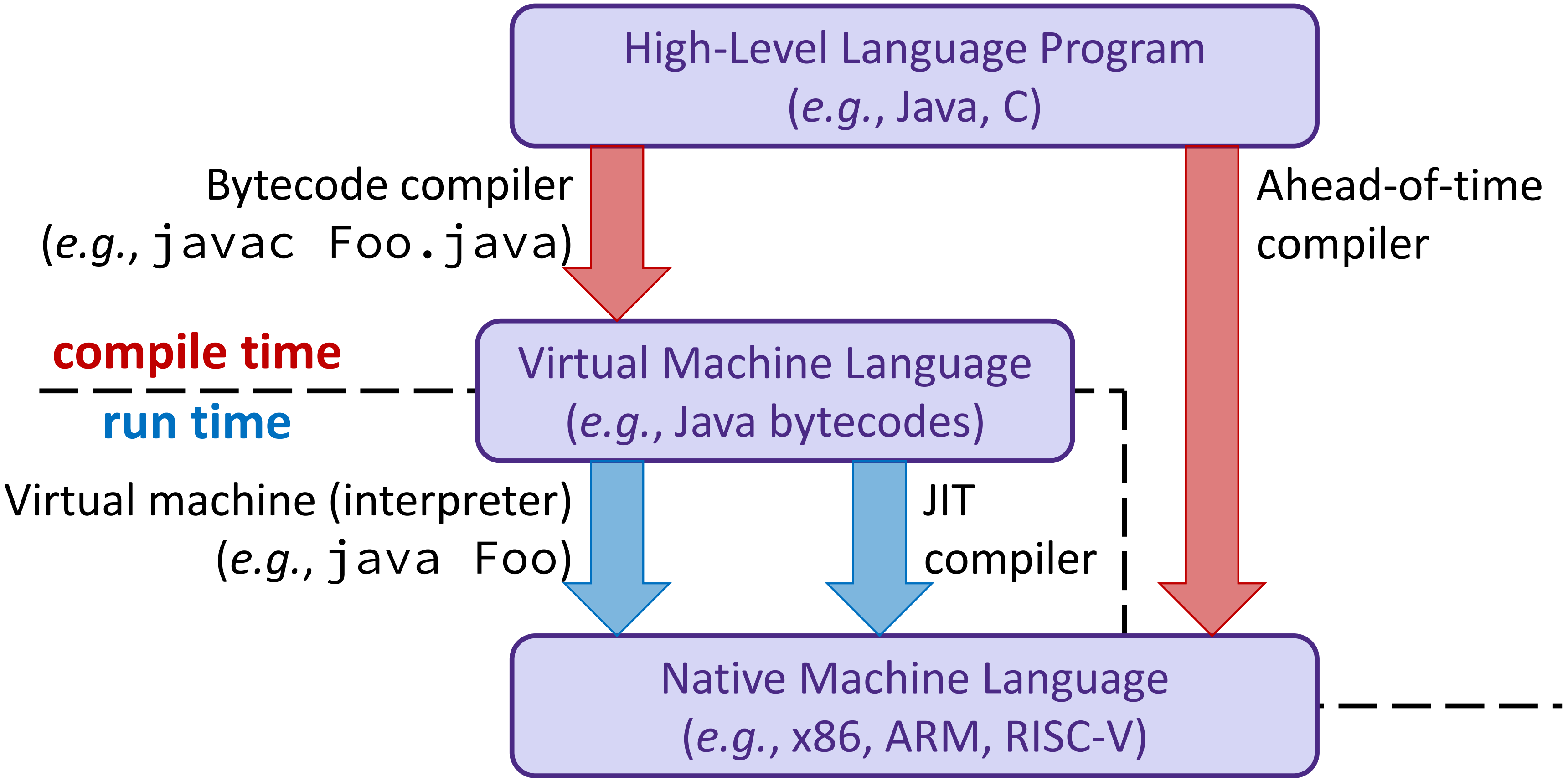
2. To run the Java compiler:
   - `javac Foo.java`
   - The Java compiler converts Java into *Java bytecodes*
     - Stored in a `.class` file

3. To execute the program stored in the bytecodes, these can be interpreted by the Java Virtual Machine (JVM)
   - Running the virtual machine: `java Foo`
   - Loads `Foo.class` and interprets the bytecodes

"The JVM"

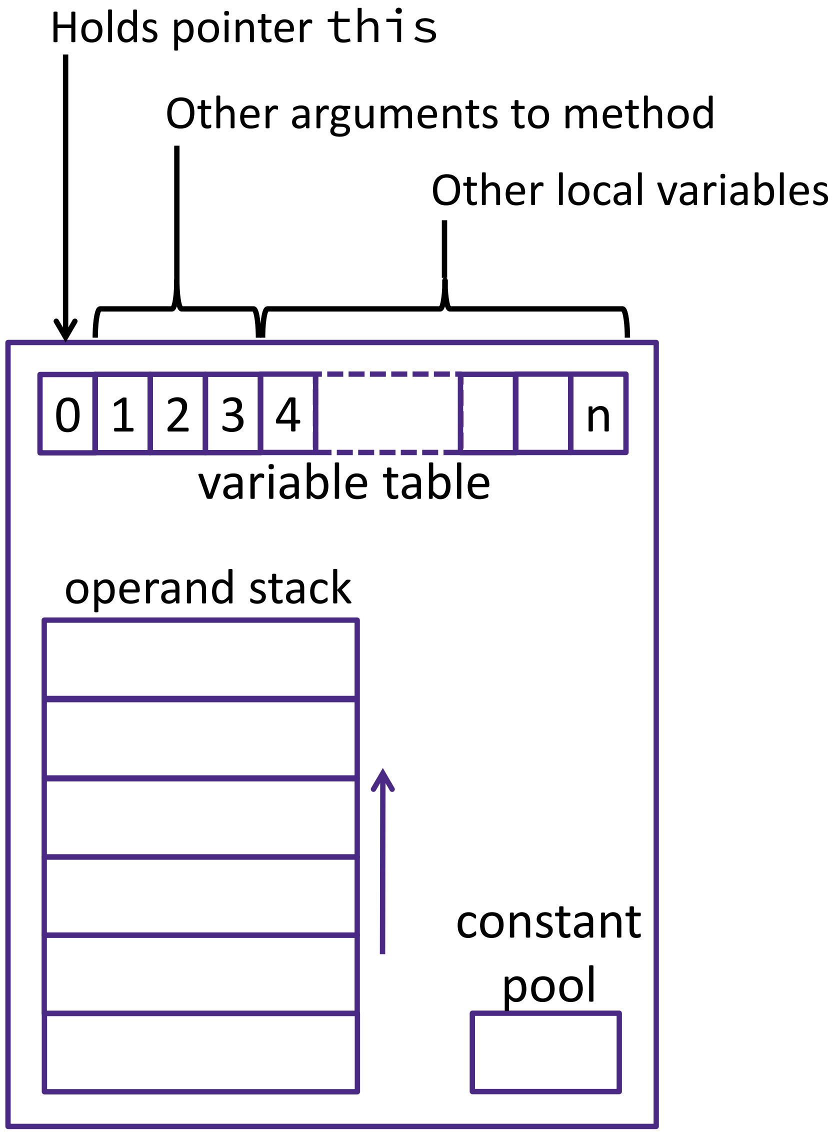
- Java programs are usually run by a Java *virtual machine* *(JVM)*
  - JVMs interpret an intermediate language called *Java bytecode*
  - Many JVMs compile bytecode to native machine code
    - **Just-in-time (JIT) compilation**
    - http://en.wikipedia.org/wiki/Just-in-time_compilation
  - Java is sometimes compiled ahead of time (AOT) like C

Virtual Machine Model

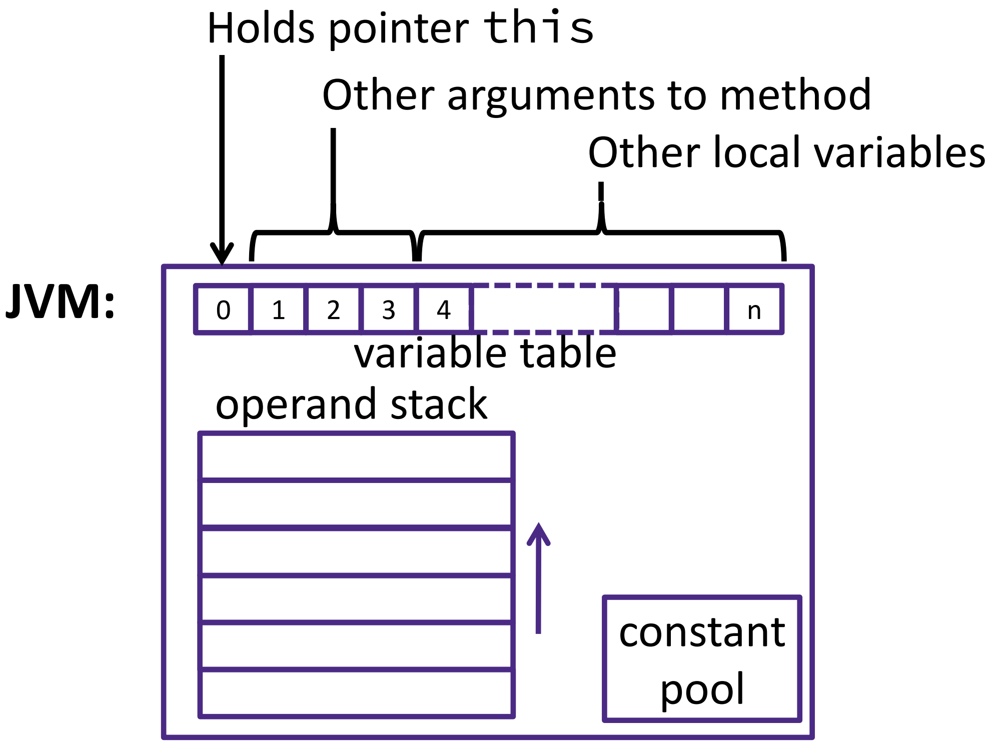


Java Bytecode

- Like assembly code for JVM, but works on *all* JVMs
  - Hardware-independent!
- Typed (unlike x86 assembly)
- Strong JVM protections



JVM Operand Stack



‘i’ = integer,
‘a’ = reference,
‘b’ for byte,
‘c’ for char,
‘d’ for double, ...

Bytecode:

```
iload 1    // push 1st argument from table onto stack
iload 2    // push 2nd argument from table onto stack
iadd       // pop top 2 elements from stack, add together, and
           // push result back onto stack
istore 3   // pop result and put it into third slot in table
```

No registers or stack locations!
All operations use operand stack

Compiled to (IA32) x86:

```
mov  8(%ebp),  %eax
mov  12(%ebp), %edx
add  %edx, %eax
mov  %eax, -8(%ebp)
```

Disassembled Java Bytecode

- Bytecode instruction listings
- Disassembled via:
  - `> javac Employee.java`
    `> javap -c Employee`

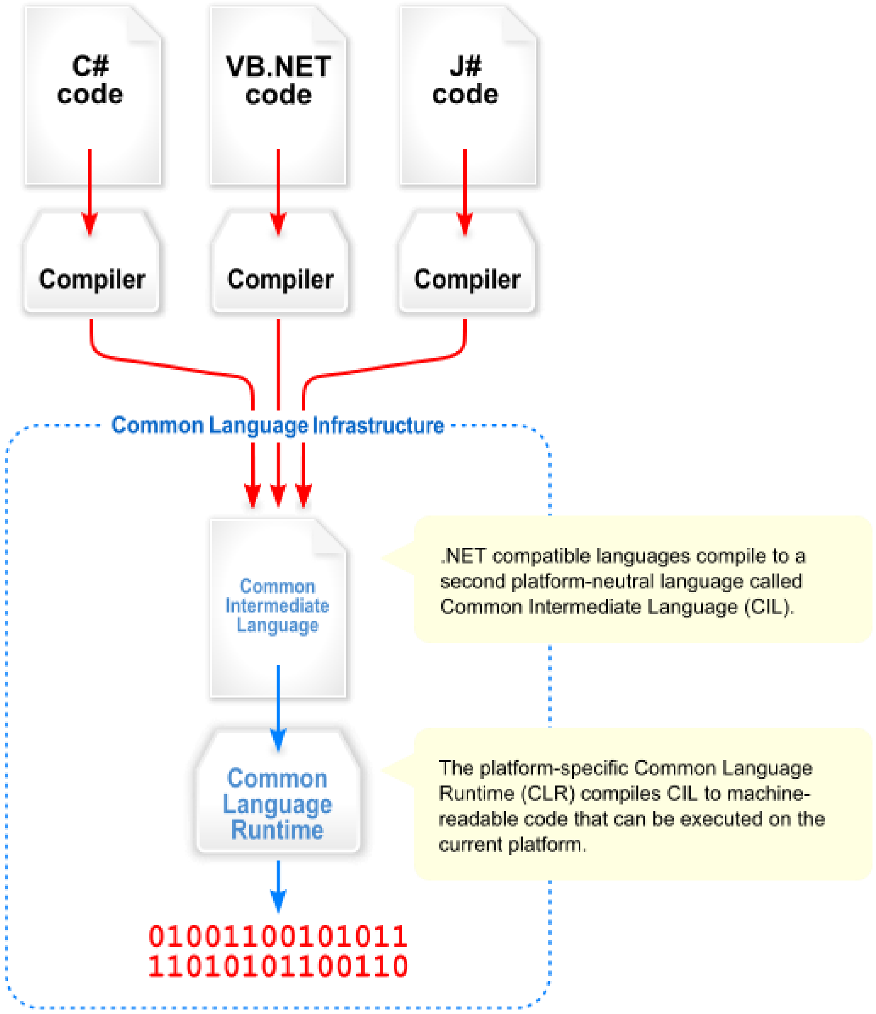
```
Compiled from Employee.java
class Employee extends java.lang.Object {
  public Employee(java.lang.String,int);
  public java.lang.String getEmployeeName();
  public int getEmployeeNumber();
}

Method Employee(java.lang.String,int)
0 aload_0
1 invokespecial #3 <Method java.lang.Object()>
4 aload_0
5 aload_1
6 putfield #5 <Field java.lang.String name>
9 aload_0
10 iload_2
11 putfield #4 <Field int idNumber>
14 aload_0
15 aload_1
16 iload_2
17 invokespecial #6 <Method void
                    storeData(java.lang.String, int)>
20 return

Method java.lang.String getEmployeeName()
0 aload_0
1 getfield #5 <Field java.lang.String name>
4 areturn

Method int getEmployeeNumber()
0 aload_0
1 getfield #4 <Field int idNumber>
4 ireturn

Method void storeData(java.lang.String, int)
…
```

Other languages for JVMs

- JVMs run on so many computers that compilers have been built to translate many other languages to Java bytecode:
  - **AspectJ**, an aspect-oriented extension of Java
  - **ColdFusion**, a scripting language compiled to Java
  - **Clojure**, a functional Lisp dialect
  - **Groovy**, a scripting language
  - **JavaFX** Script, a scripting language for web apps
  - **JRuby**, an implementation of Ruby
  - **Jython**, an implementation of Python
  - **Rhino**, an implementation of JavaScript
  - **Scala**, an object-oriented and functional programming language
  - And many others, even including C!
- Originally, JVMs were designed and built for Java (still the major use) but JVMs are also viewed as a safe, GC'ed platform

Microsoft's C# and .NET Framework

- C# has similar motivations as Java
  - Virtual machine is called the *Common Language Runtime*
  - *Common Intermediate Language* is the bytecode for C# and other languages in the .NET framework



We made it! ☺ 😎 😂

- Topic Group 1: **Data**
  - Memory, Data, Integers, Floating Point, Arrays, Structs
- Topic Group 2: **Programs**
  - x86-64 Assembly, Procedures, Stacks, Executables
- Topic Group 3: **Scale & Coherence**
  - Caches, Memory Allocation, Processes, Virtual Memory