Java and C (condensed)
CSE 351 Autumn 2021

Guest   **Teaching Assistants:**

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http://xkcd.com/801/
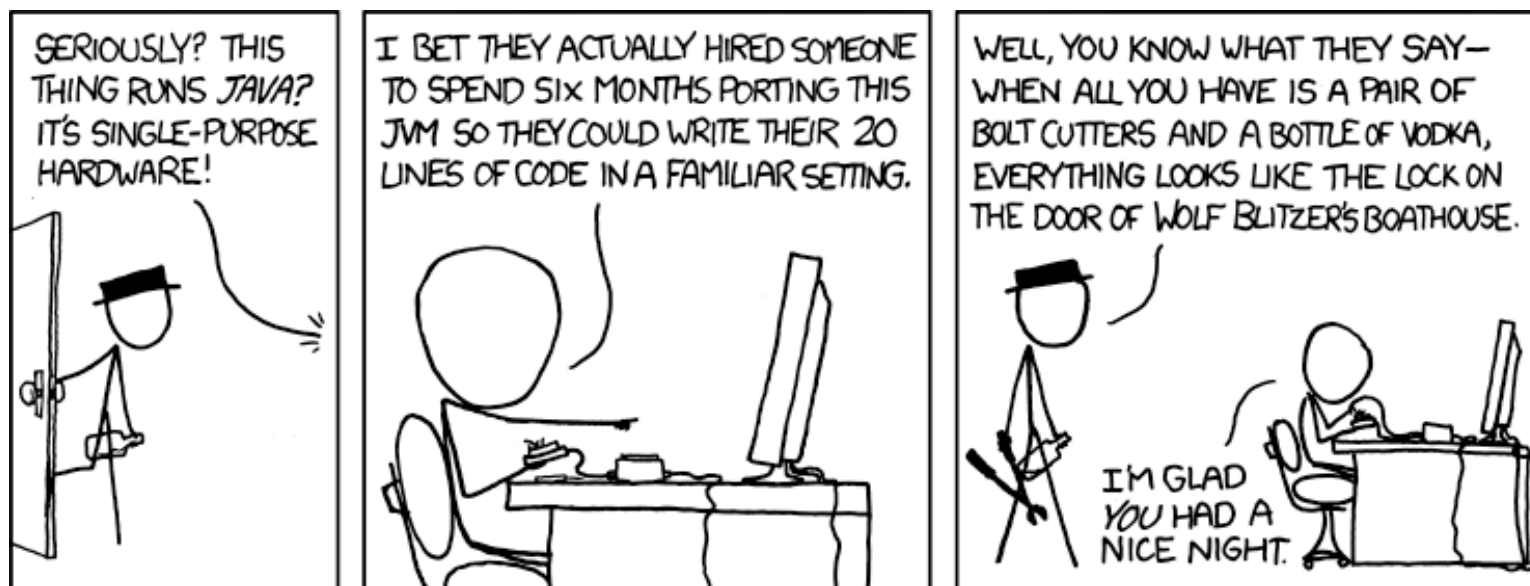
Relevant Course Information

❖ hw26 due Wednesday (12/8)

❖ Lab 5 due Friday (12/10)

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

❖ **Final Exam:** 12/13-15
  ▪ <u>Review Session</u>: Friday 12/10 at 4:30pm
  ▪ Final review section on 12/09
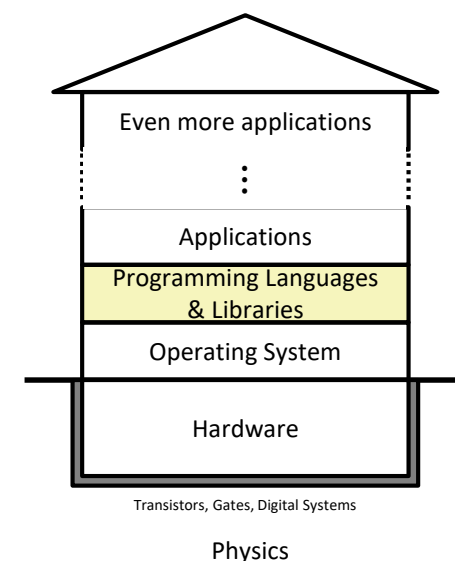 ▪ Will be structured similarly to the Midterm

Java vs. C

❖ Reconnecting to Java (hello, CSE143!)

■ 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

❖ Topic Group 1: **Data**
  - **Memory**, **Data**, Integers, Floating Point, **Arrays**, ~~Objects~~ Objects

❖ Topic Group 2: **Programs**
  - x86-64 Assembly, **Procedures**, **Stacks**, **Executables**

❖ Topic Group 3: **Scale & Coherence**
  - Caches, Processes, Virtual Memory, Memory Allocation

Even more applications
⋮
Applications
Programming Languages & Libraries
Operating System
Hardware
Transistors, Gates, Digital Systems
Physics

These apply to execution regardless of source language

Apply more generally than just C!!!

Worlds Colliding

❖ CSE351 has given you a "really different feeling" about what computers do and how programs execute

❖ We have occasionally contrasted to Java, but CSE143 may still feel like "a different world"
  - It's not – it's just a higher-level of abstraction
  - Connect these levels via <u>how-one-could-implement-Java</u> in 351 terms

Meta-point to this lecture

❖ None of the data representations we are going to talk about are *guaranteed* by Java

❖ In fact, the language simply provides an *abstraction* (Java language specification)

- 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
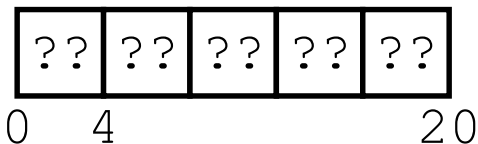
Data in Java

❖ Integers, floats, doubles, pointers – same as C

- ▪ "Pointers" are called "references" in Java, but are much more constrained than C's general pointers

- ▪ Java's portability-guarantee fixes the sizes of all types

  - • <u>Example</u>: `int` is 4 bytes in Java regardless of machine

- ▪ 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

❖ 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
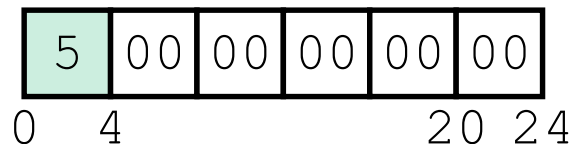❖ *Since it has this info, what can it do?*

C: **int** array[5];

??	??	??	??	??

0   4   20

Java: int[] array = **new** int[5];

5	00	00	00	00	00

0   4   20 24

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Data in Java: Arrays

❖ 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>
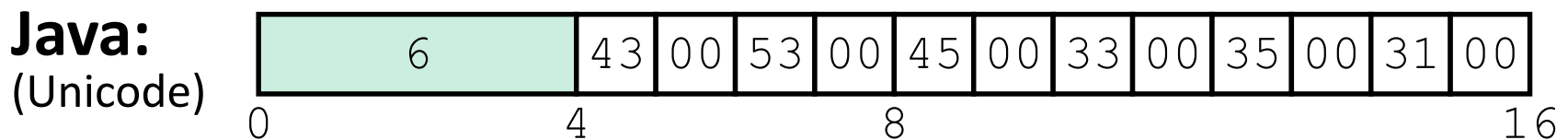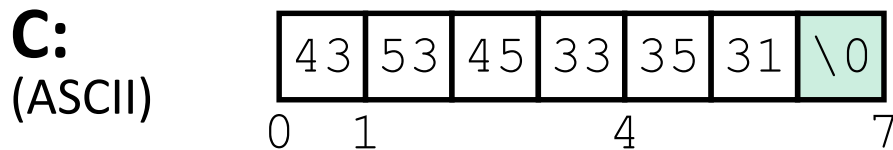 - Code is added to ensure the index is within bounds
  - Exception if out-of-bounds

C: **int** array[5];

??	??	??	??	??

0 4   20

Java: int[] array = **new** int[5];

5	00	00	00	00	00

0 4   20 24
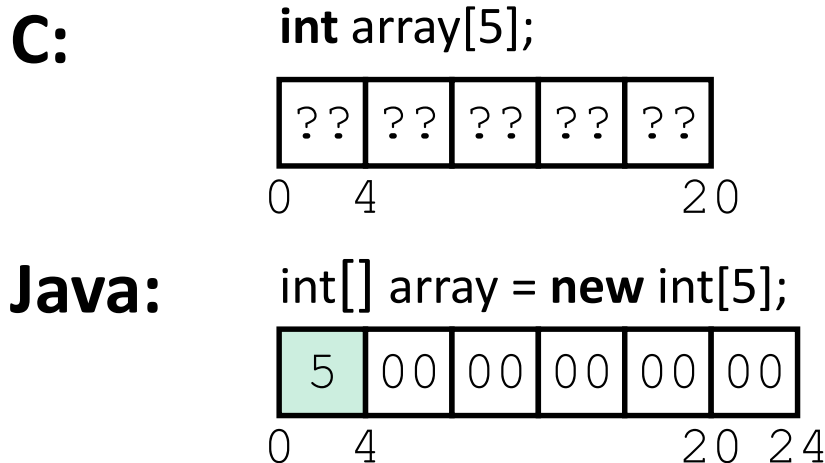
To speed up bounds-checking:
  - Length field is likely in cache
  - Compiler may store length field in register for loops
  - Compiler may prove that some checks are redundant

Data in Java: Characters & Strings

❖ Two-byte Unicode instead of ASCII

  ▪ Represents most of the world's alphabets

❖ String not bounded by a `'\0'` (null character)

  ▪ Bounded by hidden length field at beginning of string

❖ All String objects read-only (vs. StringBuffer)

Example: the string "CSE351"

C:
(ASCII)

43	53	45	33	35	31	\0
0	1			4		7

Java:
(Unicode)

6		43	00	53	00	45	00	33	00	35	00	31	00
0		4				8							16

Data in Java: Objects

❖ Data structures (objects) are always stored by reference, never stored "inline"

- Include complex data types (arrays, other objects, etc.) using references

C:

```
struct rec {
    int i;
    int a[3];
    struct rec *p;
};
```
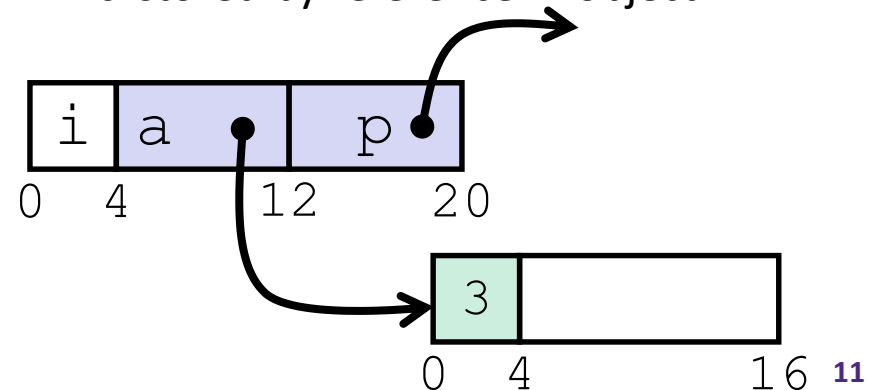
- `a[]` stored "inline" as part of struct
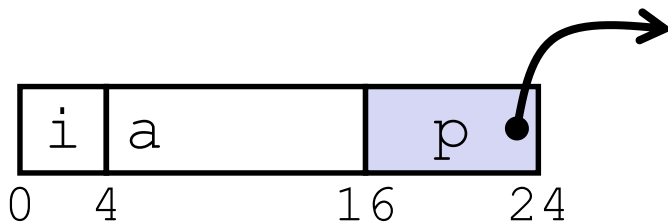
Java:

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

- `a` stored by reference in object

Pointer/reference fields and variables

- ❖ In C, we have "`->`" and "`.`" for field selection depending on whether we have a pointer to a struct or a struct
  - ▪ `(*r).a` is so common it becomes `r->a`
- ❖ In Java, *all non-primitive variables are references to objects*
  - ▪ We always use `r.a` notation
  - ▪ But really follow reference to `r` with offset to `a`, just like `r->a` in C
  - ▪ So no Java field needs more than 8 bytes

C:

```
struct rec *r = malloc(...);
struct rec r2;
r->i = val;
r->a[2] = val;
r->p = &r2;
```

Java:

```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```
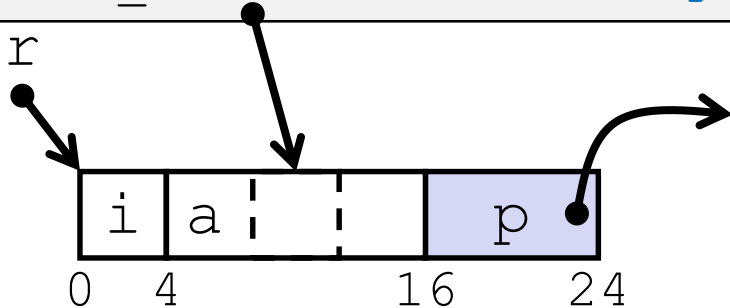
Pointers/References

❖ *Pointers* in C can point to any memory address

❖ *References* in Java can only point to [the starts of] objects

  ▪ Can only be dereferenced to access a field or element of that object
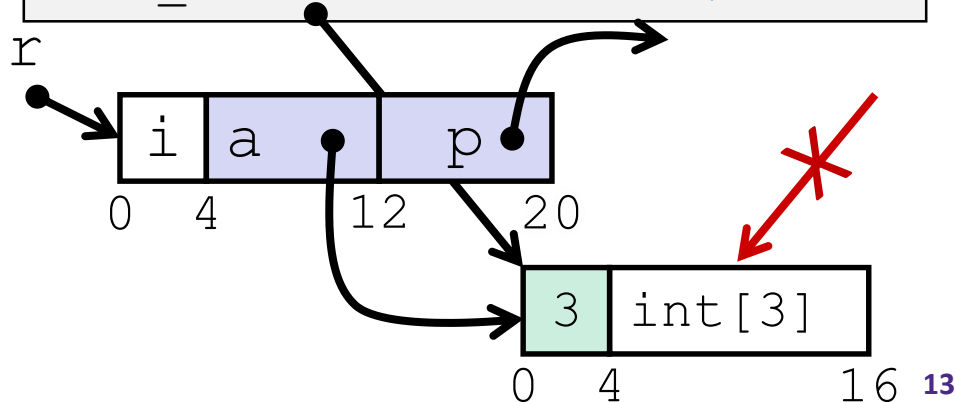
C:

```
struct rec {
   int i;
   int a[3];
   struct rec* p;
};
struct rec* r = malloc(…);
some_fn(&(r->a[1])); // ptr
```

Java:

```
class Rec {
   int i;
   int[] a = new int[3];
   Rec p;
}
Rec r = new Rec();
some_fn(r.a, 1); // ref, index
```

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 );
...
```
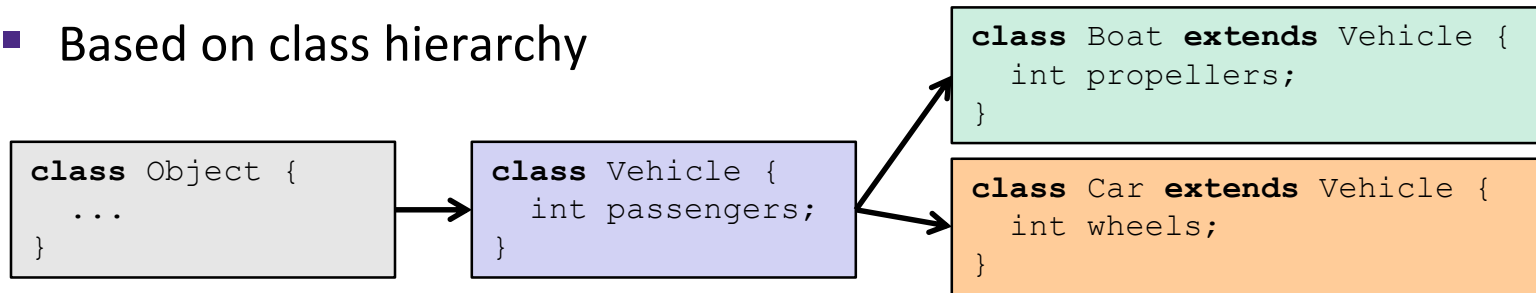
Cast b into char* to do unscaled addition

Cast back into block_info* to use as block_info struct
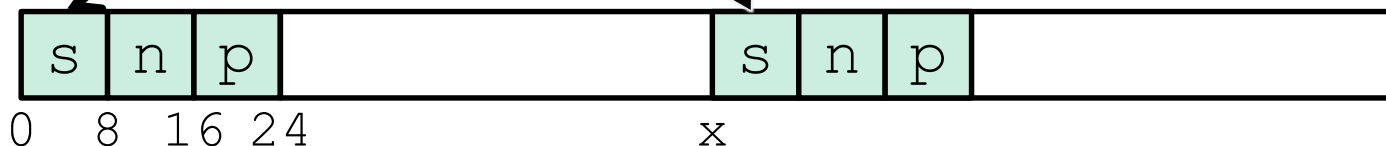
| s | n | p | | | s | n | p | | |

0 8 16 24   x

Type-safe casting in Java

❖ Can only cast compatible object references

  ▪ Based on 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 and 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;
```
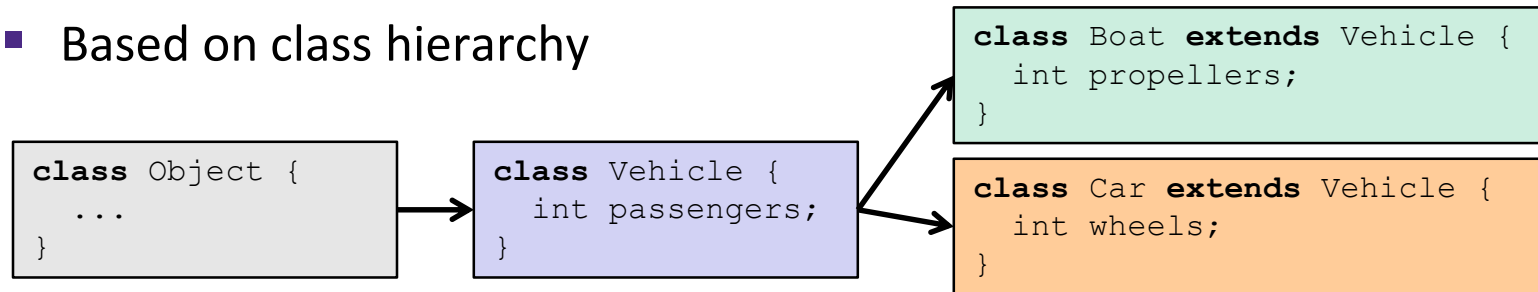
Type-safe casting in Java

❖ Can only cast compatible object references
  ■ Based on class hierarchy

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

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

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

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

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


Vehicle v1 = new Car();        ⟵  ✓ Everything needed for Vehicle also in Car
Vehicle v2 = v1;               ⟵  ✓ v1 is declared as type Vehicle
Car     c2 = new Boat();       ⟵  ✗ Compiler error: Incompatible type – elements in
                                       Car that are not in Boat (siblings)

Car     c3 = new Vehicle();    ⟵  ✗ Compiler error: Wrong direction – elements Car
                                       not in Vehicle (wheels)

Boat    b2 = (Boat) v;         ⟵  ✗ Runtime error: Vehicle does not contain all
                                       elements in Boat (propellers)

Car     c4 = (Car) v2;         ⟵  ✓ v2 refers to a Car at *runtime*
Car     c5 = (Car) b1;         ⟵  ✗ Compiler error: Unconvertible types – b1 is
                                       declared as type Boat
```

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Java Object Definitions

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

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

  boolean samePlace(Point p) {
    return (x == p.x) && (y == p.y);  ← method(s)
  }
}
...
Point p = new Point();               ← creation
...
```
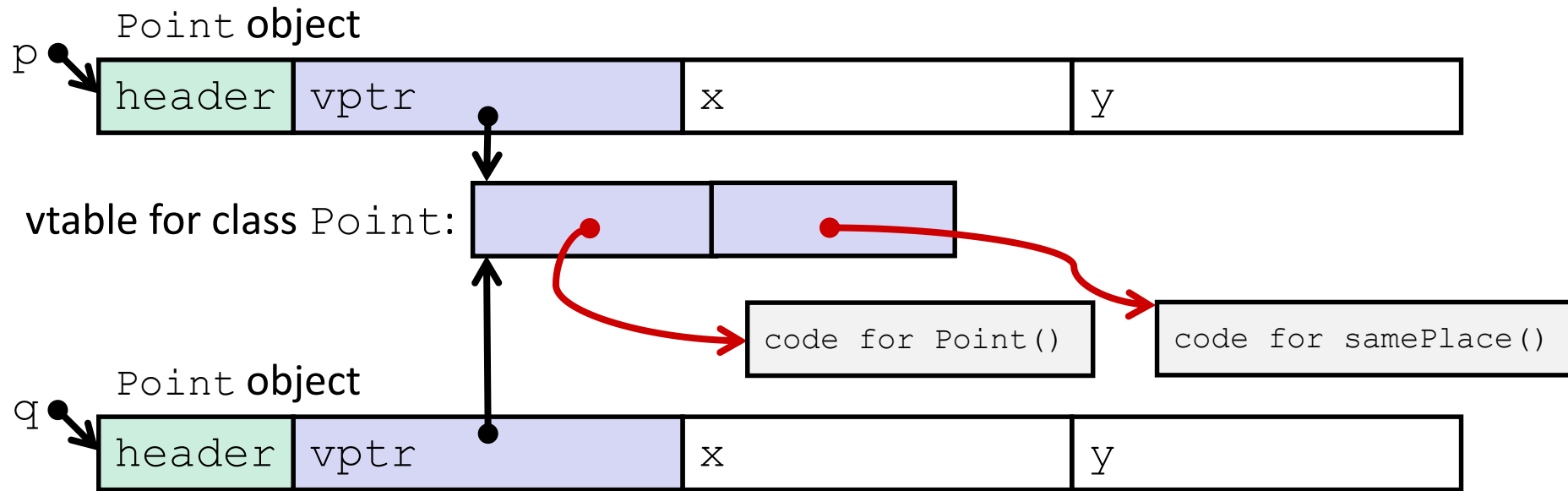
Java Objects and Method Dispatch

Point object

p

| header | vptr | x | y |

vtable for class Point:

| | |

code for Point()

code for samePlace()

Point object

q

| header | vptr | x | y |

❖ *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)*
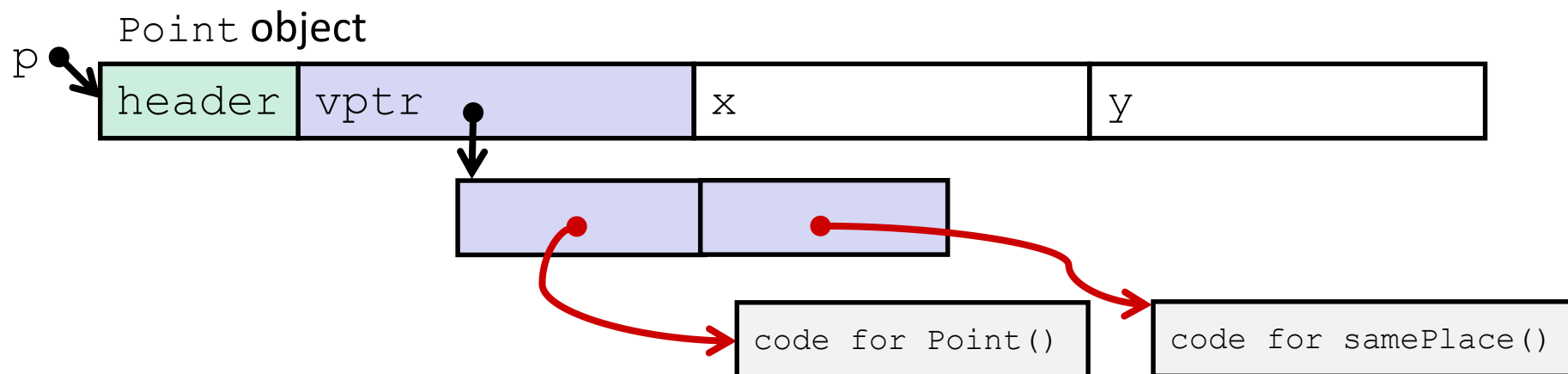
vtable for class `Point`:
Java Constructors

❖ **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);
```


`Point` **object**

header | vptr | x | y

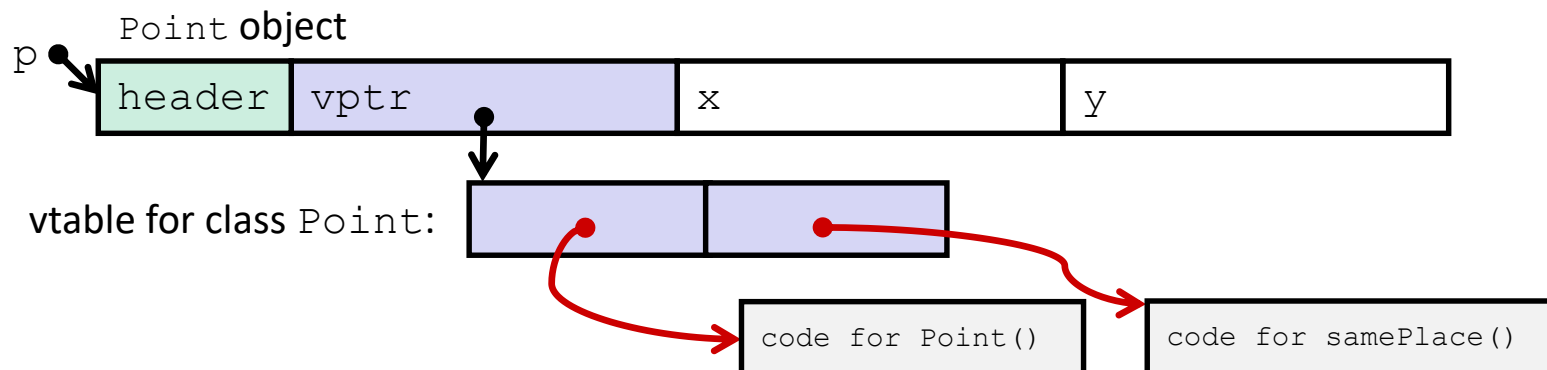code for Point() code for samePlace()

Java Methods

❖ <u>Static</u> methods are just like functions

❖ <u>Instance</u> methods:
  ▪ Can refer to *this;*
  ▪ 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);
```

`Point` **object**

p

| header | vptr | x | y |

vtable for class `Point`:

code for `Point()`

code for `samePlace()`

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Subclassing

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

❖ Where does "z" go? At end of fields of `Point`

- `Point` fields are always in the same place, so `Point` code can run on `ThreeDPoint` objects without modification

❖ Where does pointer to code for two new methods go?

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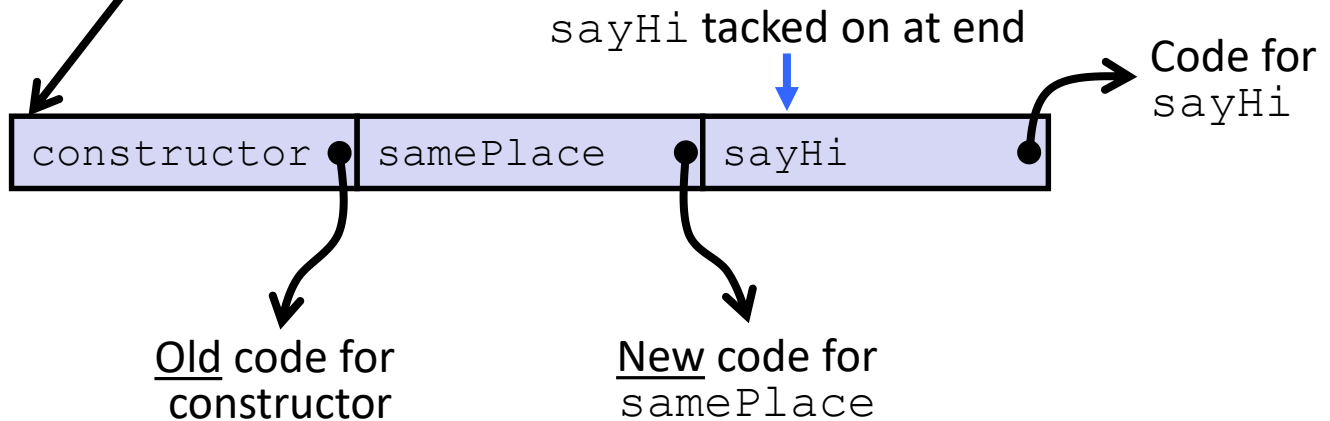
Subclassing

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

`z` tacked on at end

`ThreeDPoint` **object**

header	vptr	x	y	z

`sayHi` tacked on at end

Code for `sayHi`

vtable for `ThreeDPoint`:
(**not** `Point`)

constructor	samePlace	sayHi	

Old code for constructor

New code for samePlace

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Dynamic Dispatch

Point **object**

header	vptr	x	y

Point **vtable:**

p ➡ ???

code for Point's samePlace()

code for Point()

ThreeDPoint **object**

header	vptr	x	y	z

ThreeDPoint **vtable:**

code for sayHi()

code for 3DPoint's samePlace()
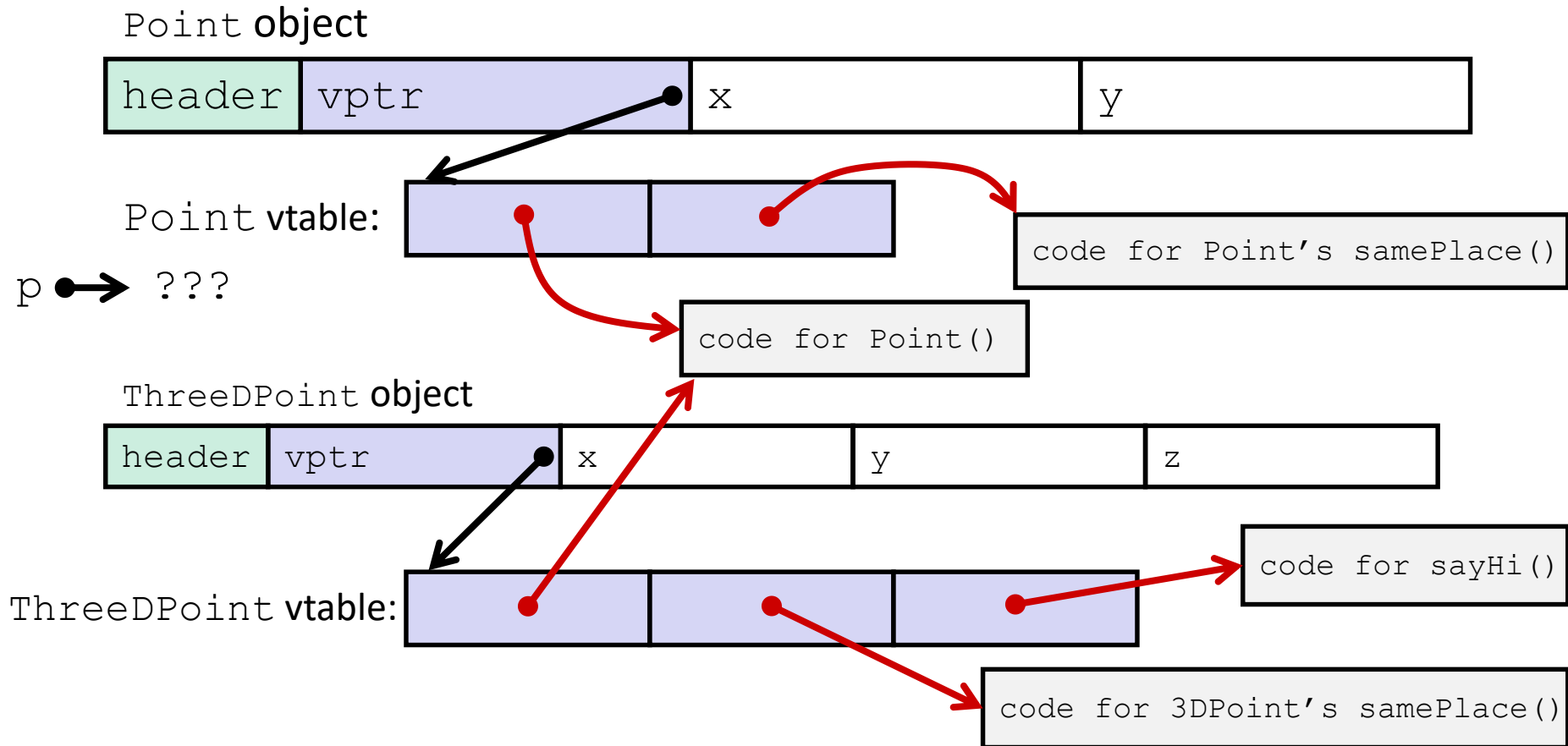
Java:

```
Point p = ???;
return p.samePlace(q);
```
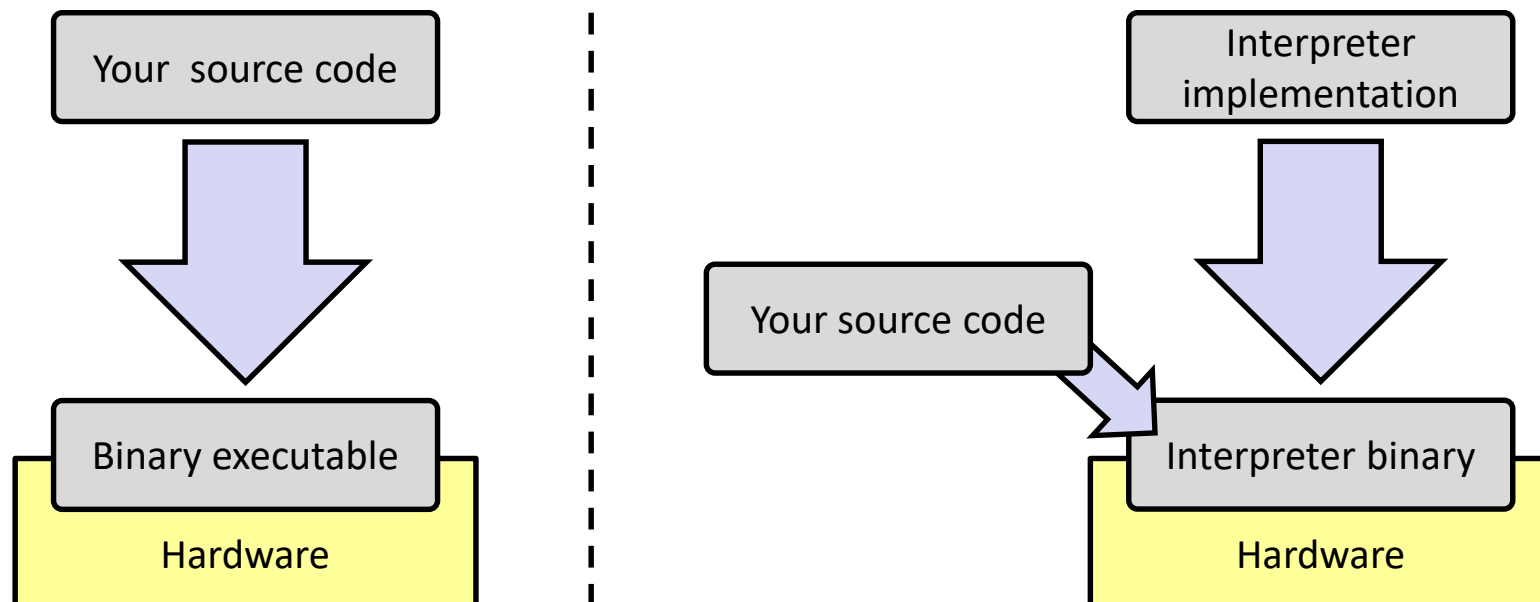
C pseudo-translation:

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

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Ta-da!

❖ In 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:

$$\texttt{p->vptr[i](p,q)}$$

- ■ 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

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, …

Your source code

Binary executable

Hardware

Interpreter implementation

Your source code

Interpreter binary

Hardware

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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

Interpreter implementation

Your source code

Interpreter binary

Hardware
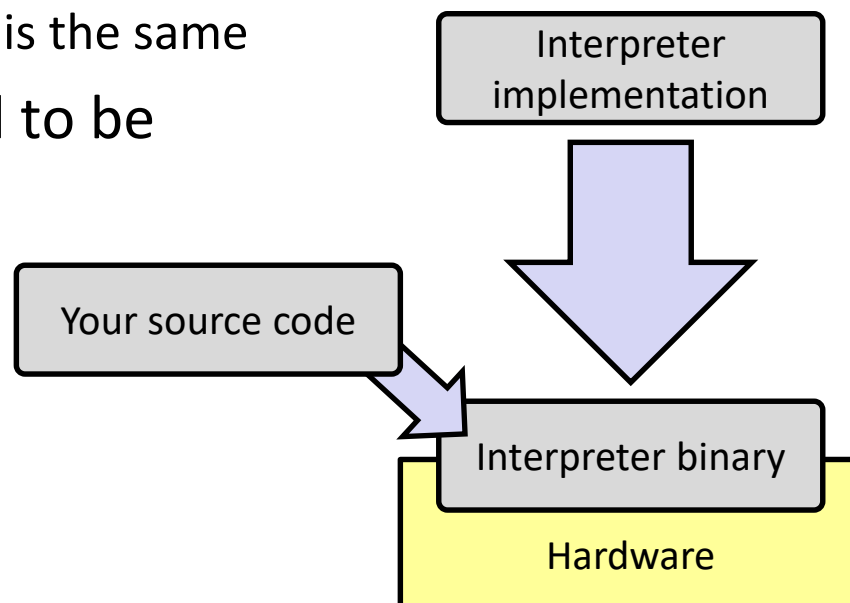
Interpreters vs. Compilers

❖ 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"

Note: The JVM is different than the CSE VM running on VMWare. Yet *another* use of the word "virtual"!
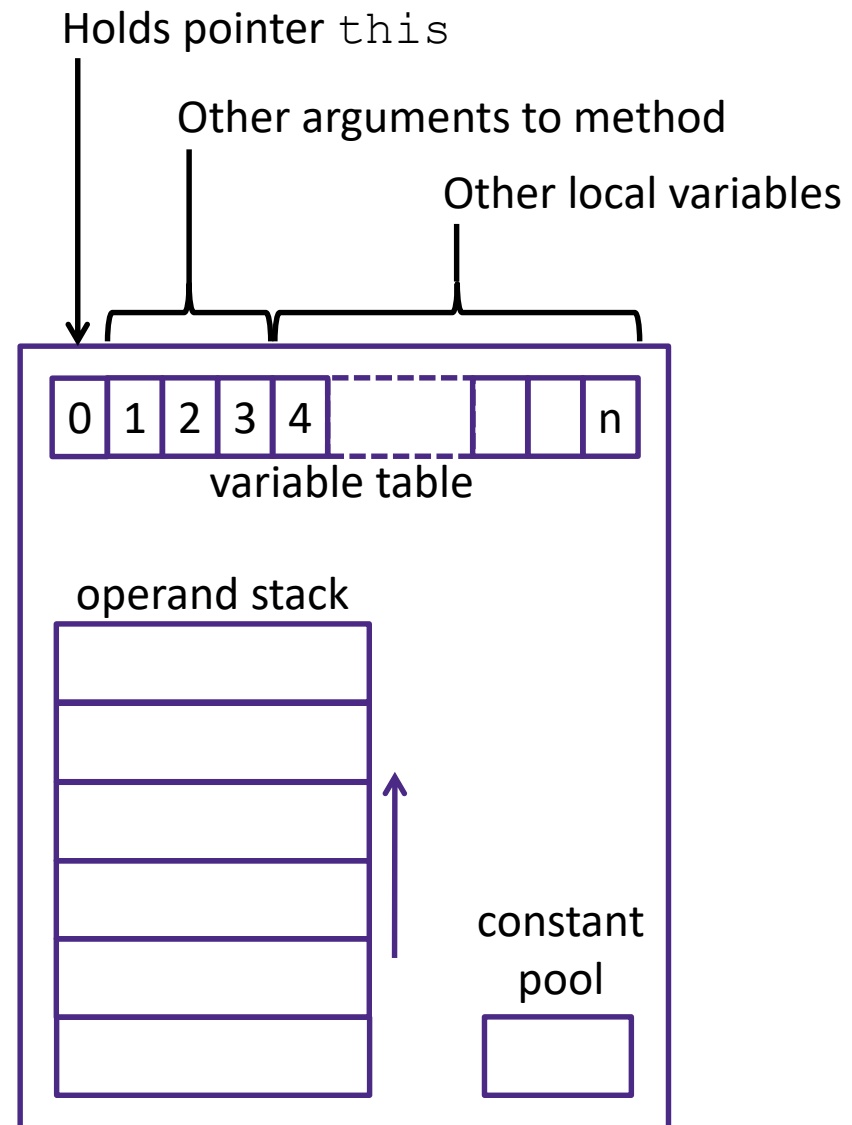
❖ Java programs are usually run by a
Java *virtual machine (JVM)*

- JVMs <u>interpret</u> 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
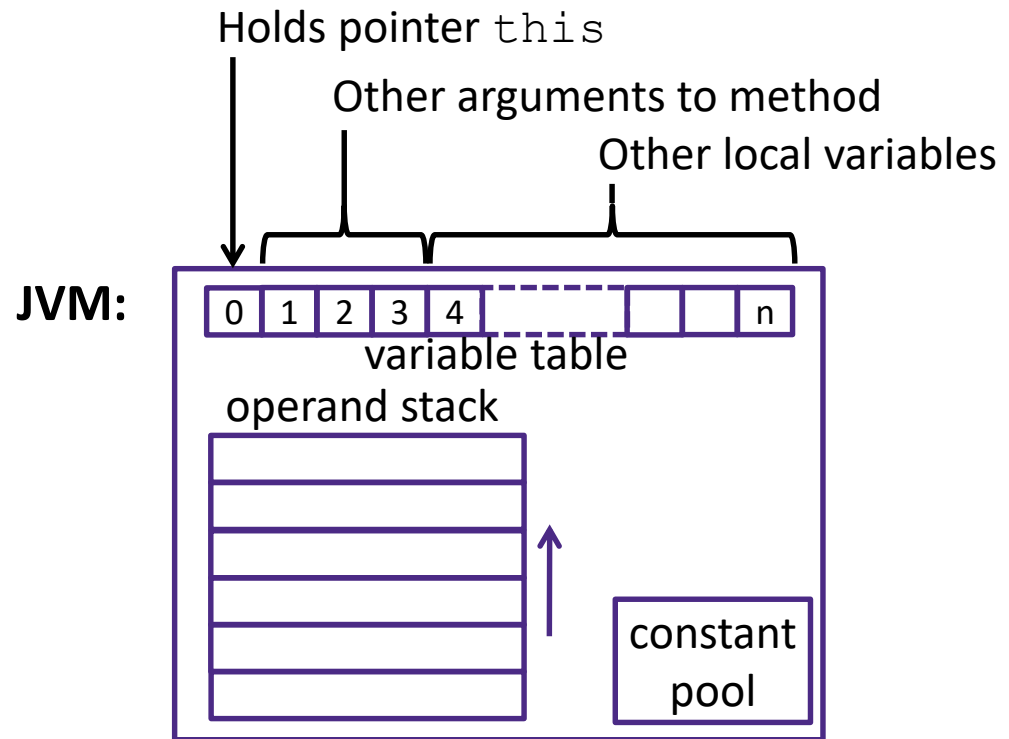
Virtual Machine Model
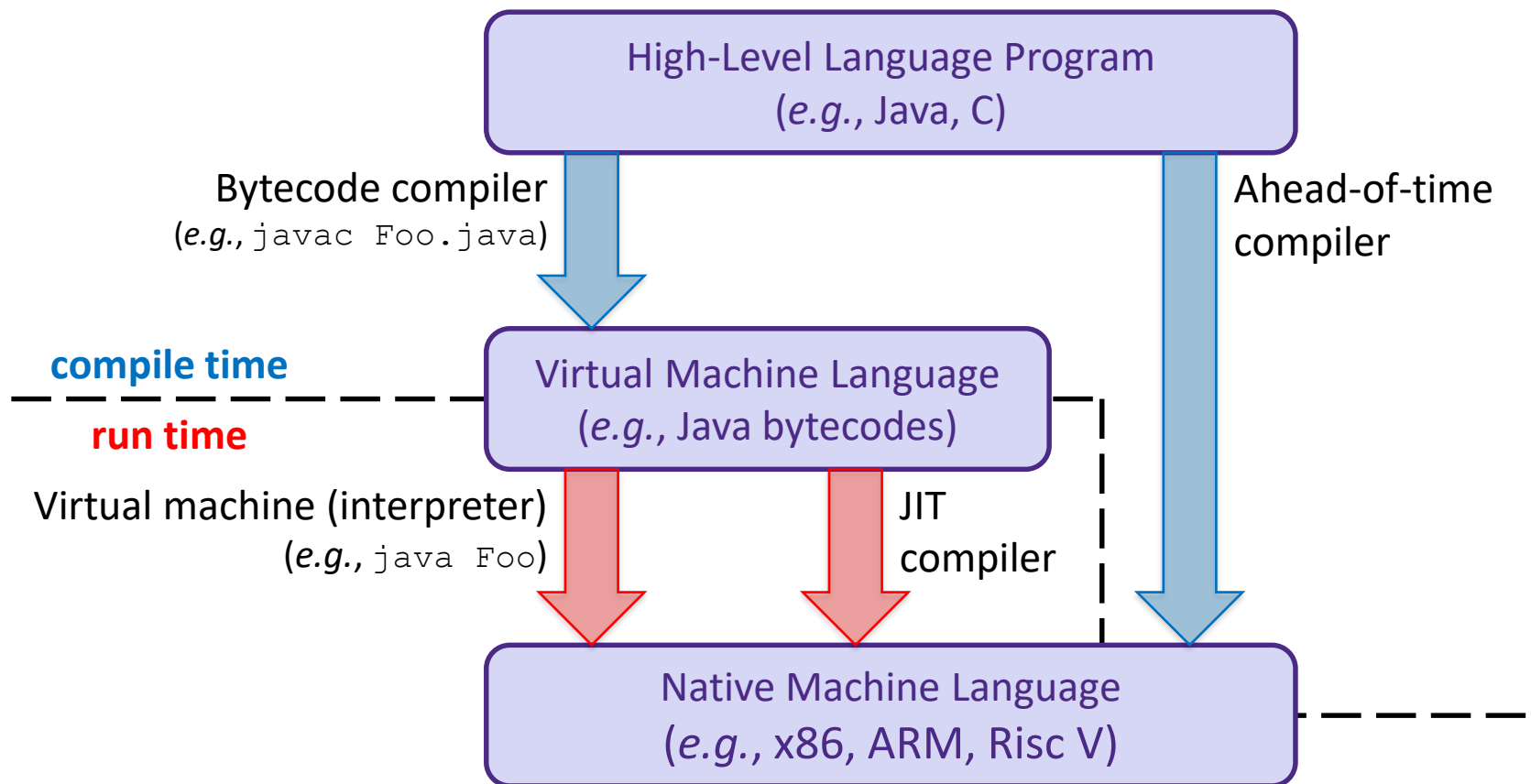
Java Bytecode

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

Holds pointer `this`

Other arguments to method

Other local variables

| 0 | 1 | 2 | 3 | 4 | | | | | n |

variable table

operand stack

constant pool

JVM Operand Stack

Holds pointer `this`

Other arguments to method

Other local variables

JVM:

| 0 | 1 | 2 | 3 | 4 | | | | n |

variable table

operand stack

constant pool

'`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)
```

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Disassembled Java Bytecode

```
> javac Employee.java
> javap -c Employee
```

http://en.wikipedia.org/wiki/Java_bytecode_instruction_listings

```
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

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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
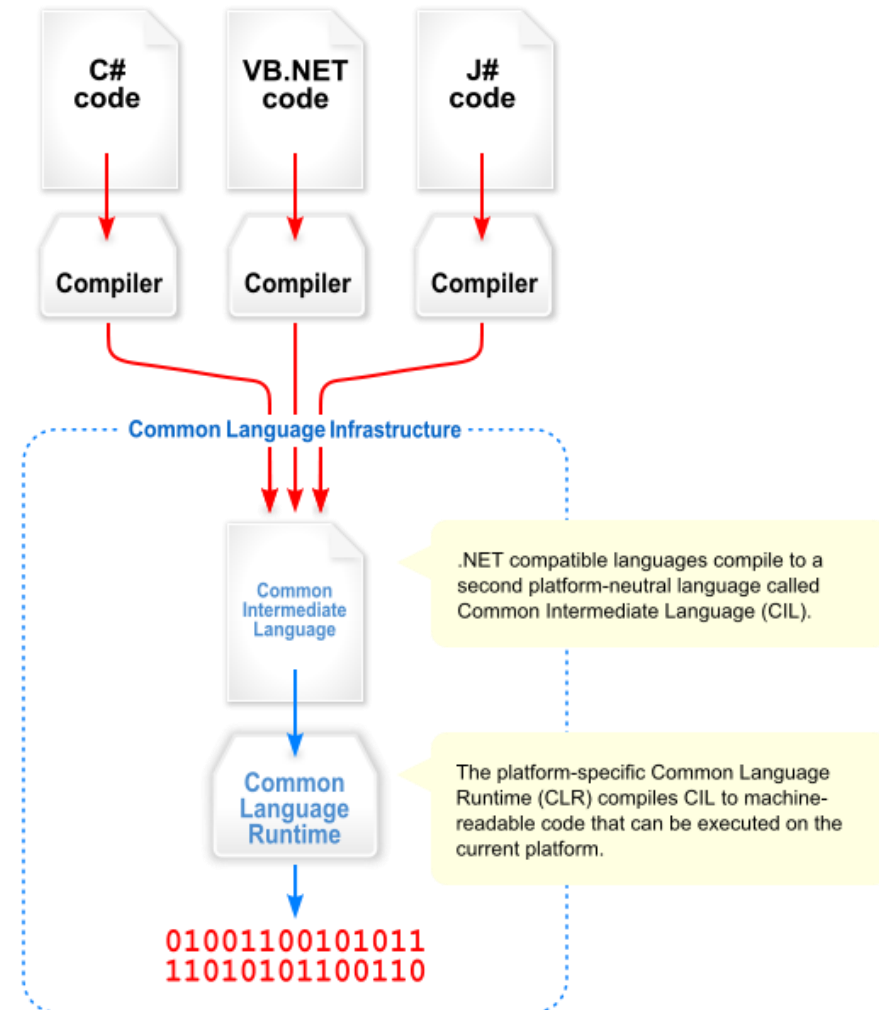
We made it! 😊 😎 😄

* ## 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, Processes, Virtual Memory, Memory Allocation

Even more applications

⋮

Applications

Programming Languages & Libraries

Operating System

Hardware

Transistors, Gates, Digital Systems

Physics

We'll explore the OUTSIDE of the House of Computing next lecture!

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