Java and C (condensed)

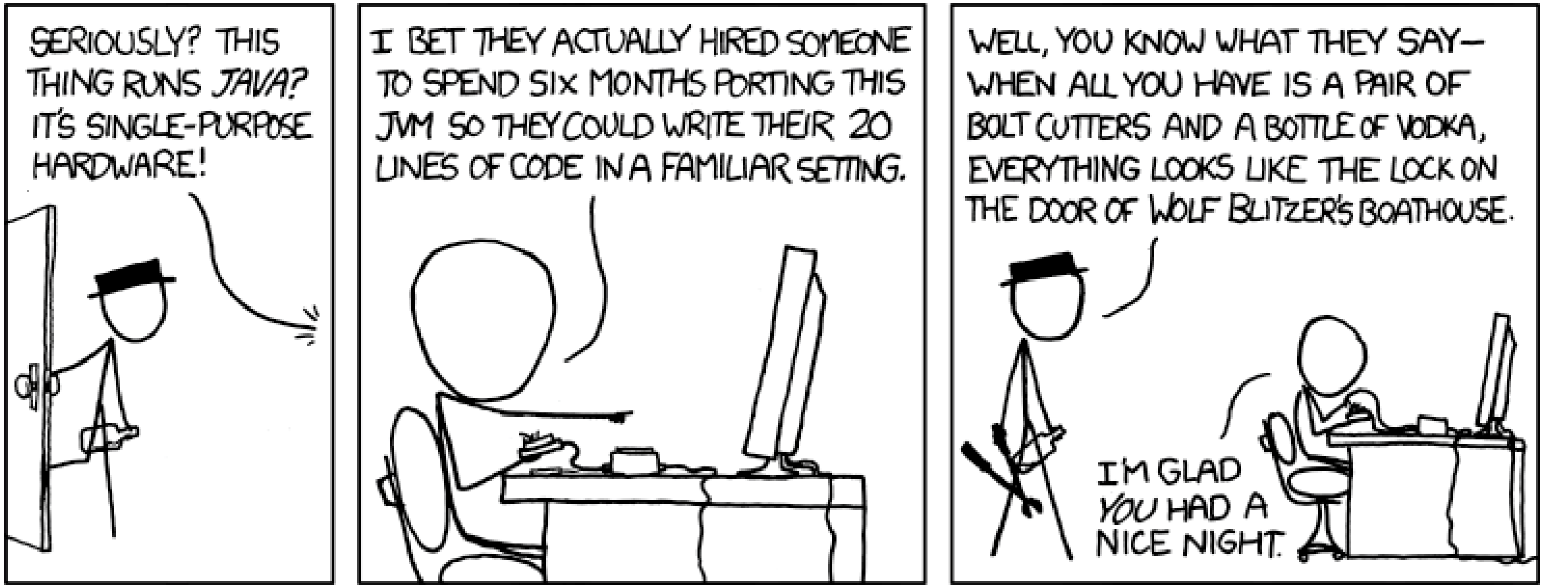
CSE 351 Autumn 2022

Instructor:

Justin Hsia

Teaching Assistants:

Angela Xu
Assaf Vayner
David Dai
James Froelich
Paul Stevans
Arjun Narendra
Carrie Hu
Dominick Ta
Jenny Peng
Renee Ruan
Armin Magness
Clare Edmonds
Effie Zheng
Kristina Lansang
Vincent Xiao



http://xkcd.com/801/

Relevant Course Information

- hw26 due Wednesday (12/7)
- Lab 5 due Friday (12/9)

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

- **Final Exam:** 12/12-14
  - Review Session: Friday 12/9 on Zoom, 2 hours TBD
  - Final review section on 12/8
  - Will be structured similarly to the Midterm

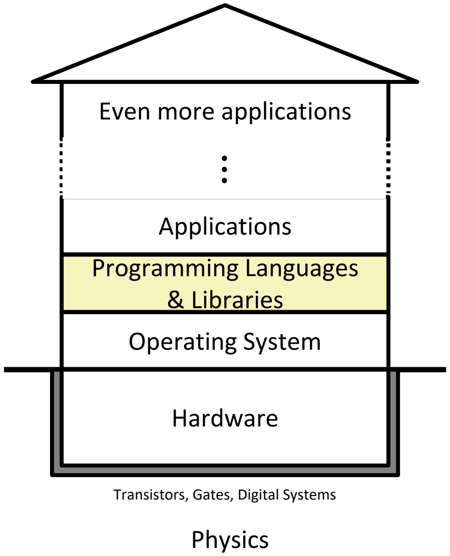
Java vs. C

- 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**
- Topic Group 2: **Programs**
  - x86-64 Assembly, **Procedures**, **Stacks**, **Executables**
- Topic Group 3: **Scale & Coherence**
  - Caches, Processes, Virtual Memory, Memory Allocation



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 how-one-could-implement-Java 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

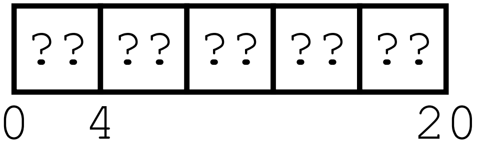
Data in Java

- 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
    - Example: `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**

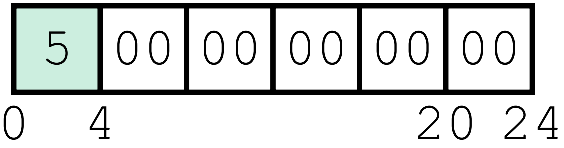
Data in Java: Arrays

- 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];



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

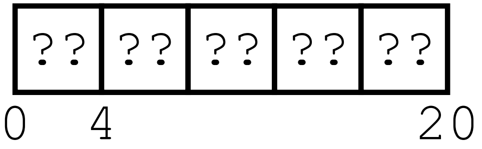


Data in Java: Arrays

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

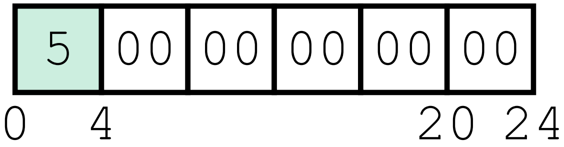
C:

int array[5];



Java:

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



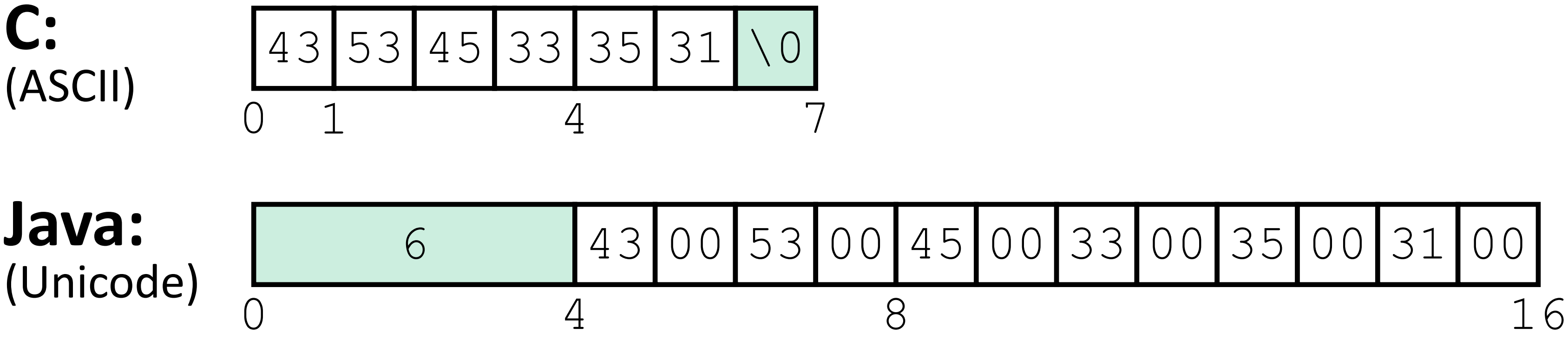
To speed up bounds-checking:

- 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
  - 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)

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



C:
(ASCII)

43	53	45	33	35	31	\0

Java:
(Unicode)

6	43	00	53	00	45	00	33	00	35	00	31	00

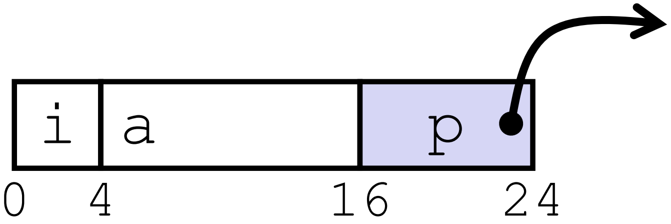
Data in Java: Objects

- 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;
};
```

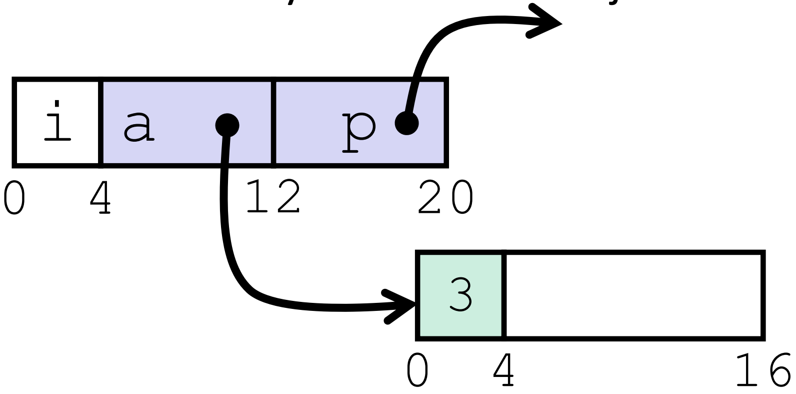
- `a[]` stored "inline" as part of struct



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:

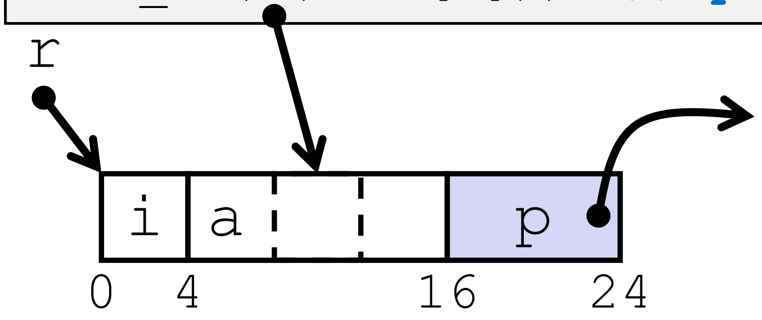
```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```

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

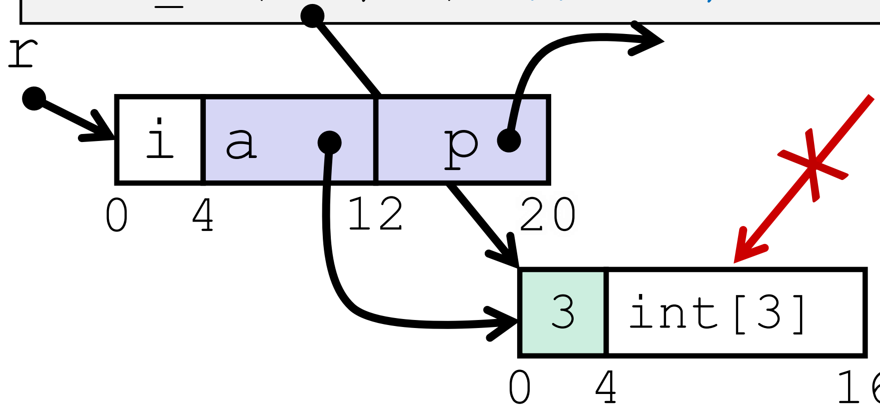
C:

```
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
```



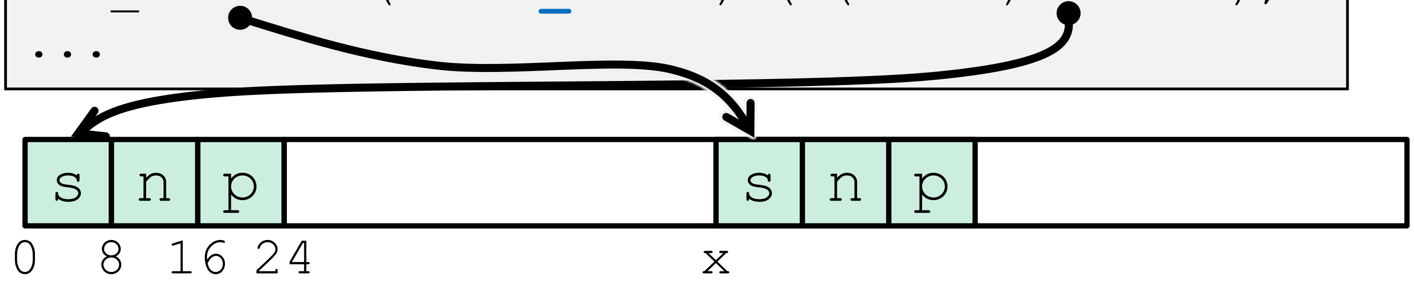
Casting in C (example from Lab 5)

- 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 );
...
```

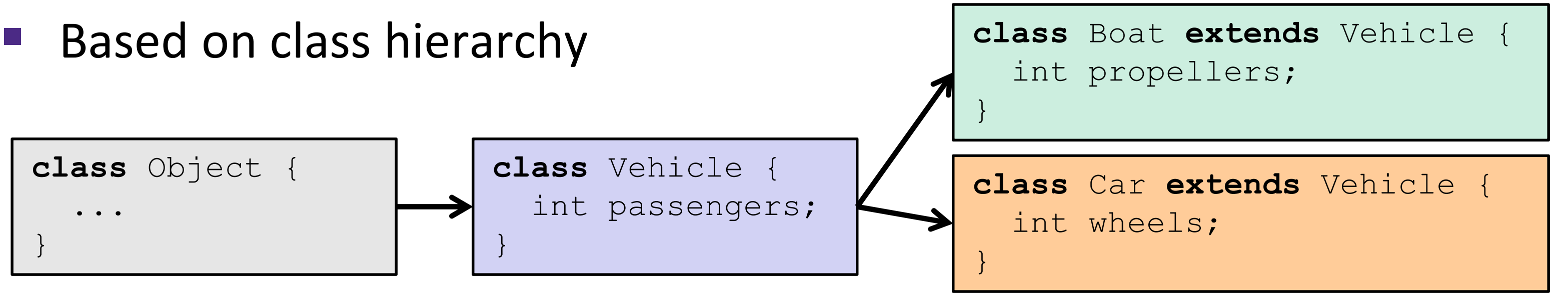
Cast b into `char*` to do unscaled addition

Cast back into `block_info*` to use as `block_info` struct



Type-safe casting in Java

- Can only cast compatible object references
  - Based on class hierarchy



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

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

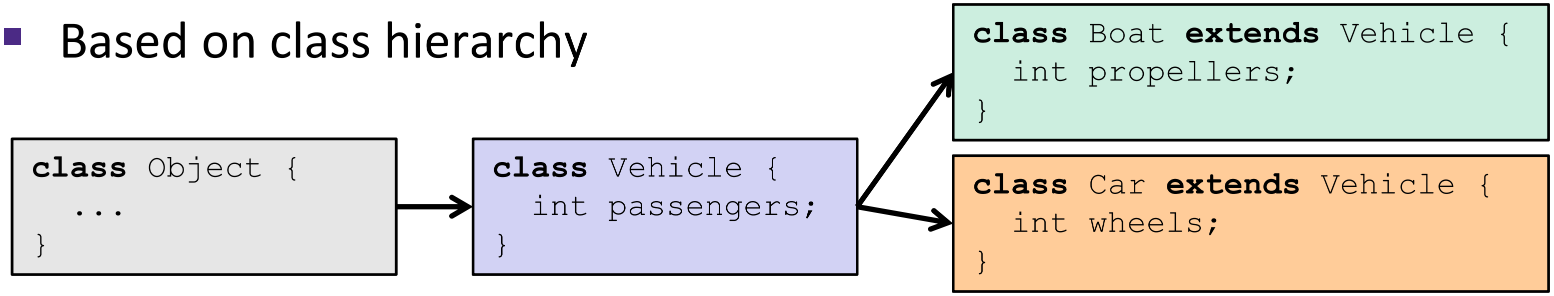
```
class Boat extends Vehicle {
  int propellers;
}
```

```
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 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();` ← ✓ 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)

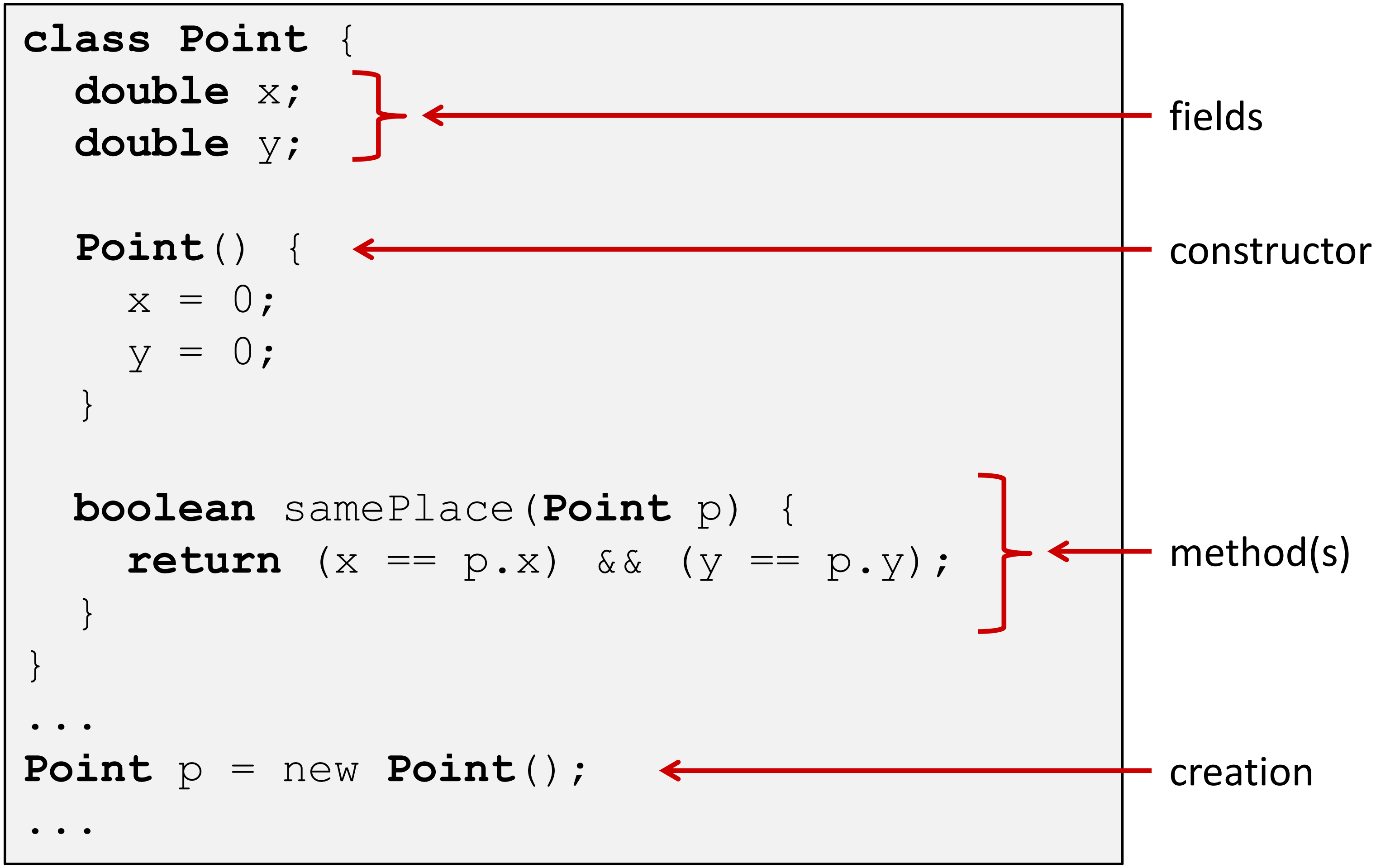
`Car c3 = new Vehicle();` ← ✗ Compiler error: Wrong direction – elements `Car` not in `Vehicle` (`wheels`)

`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: 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

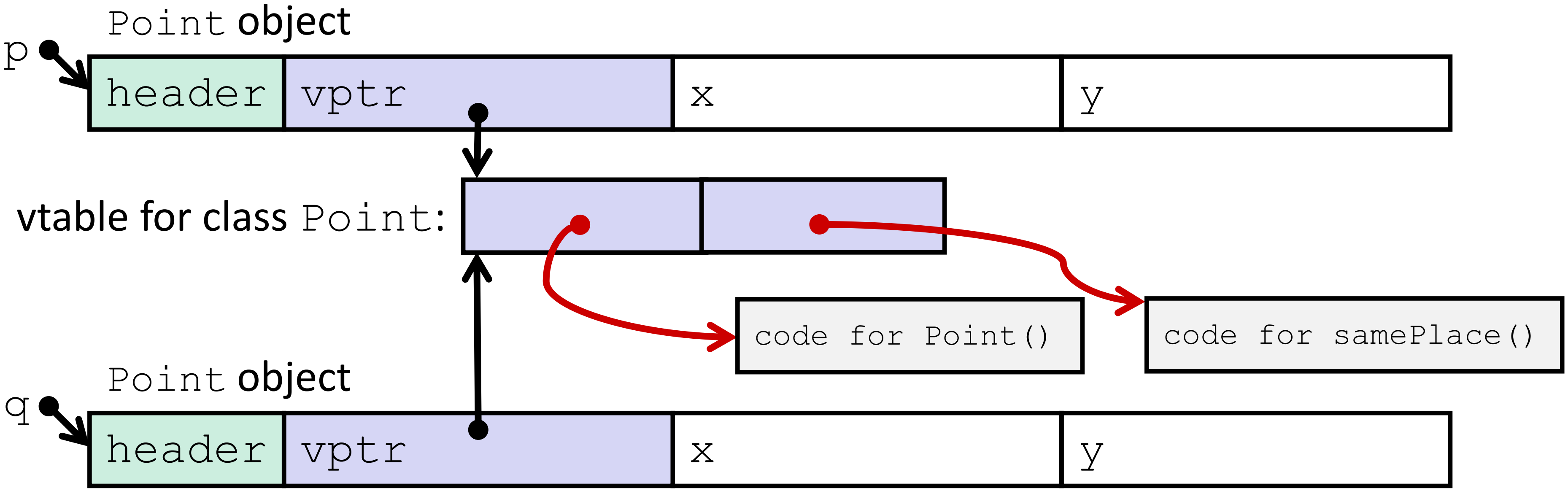
constructor

method(s)

creation

- How might we represent Java objects in memory based on what we've learned in C?

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

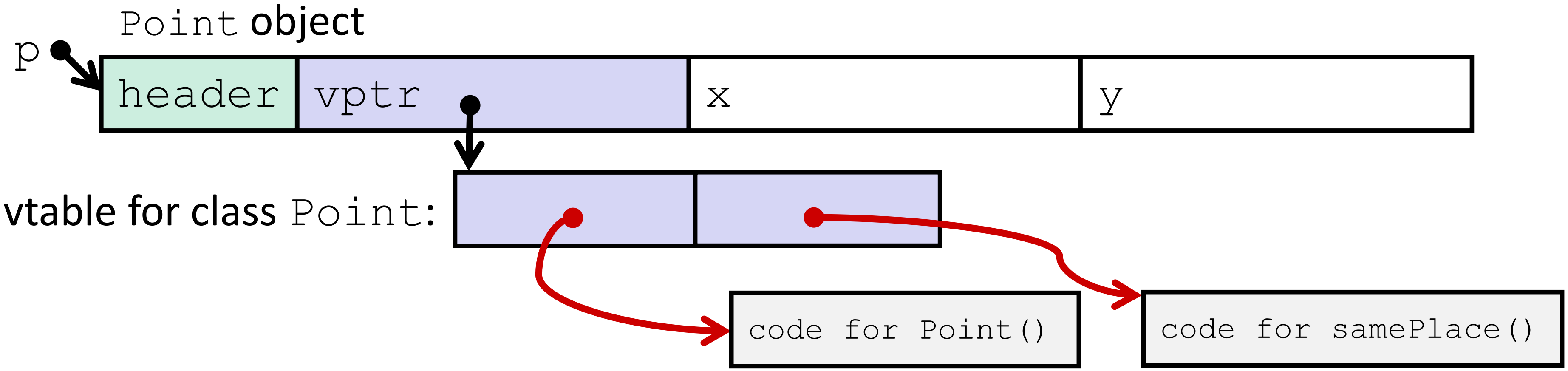
- **When we call `new`:** allocate space for object (data fields and references), initialize to zero/null, and run constructor method

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

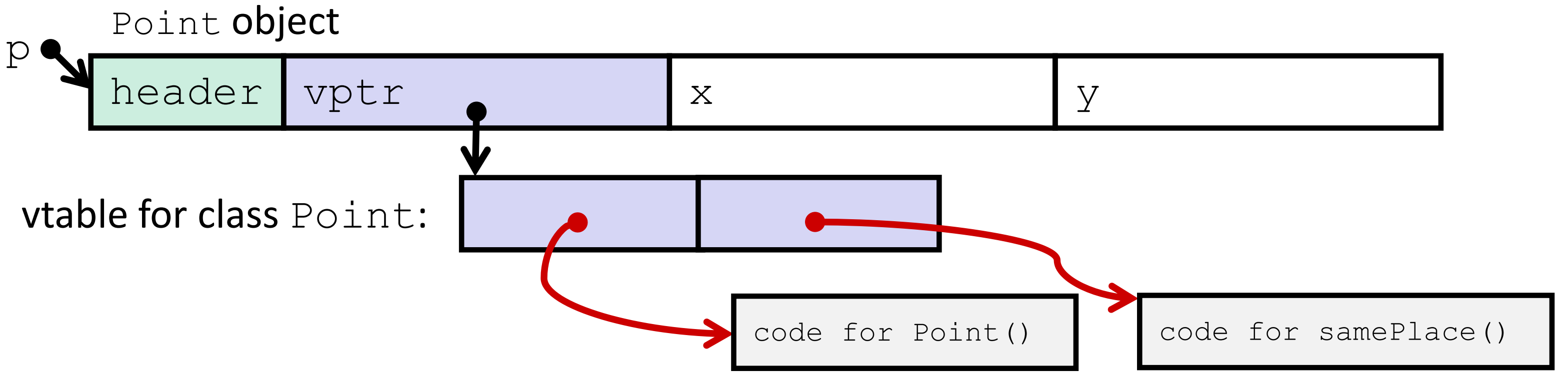
- Static methods are just like functions
- Instance methods:
  - Can refer to *this;*
  - Have an implicit first parameter for *this;* and
  - Can be overridden in subclasses
- The code to run when calling an instance method is chosen *at runtime* by lookup in the vtable

Java:

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

C pseudo-translation:

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



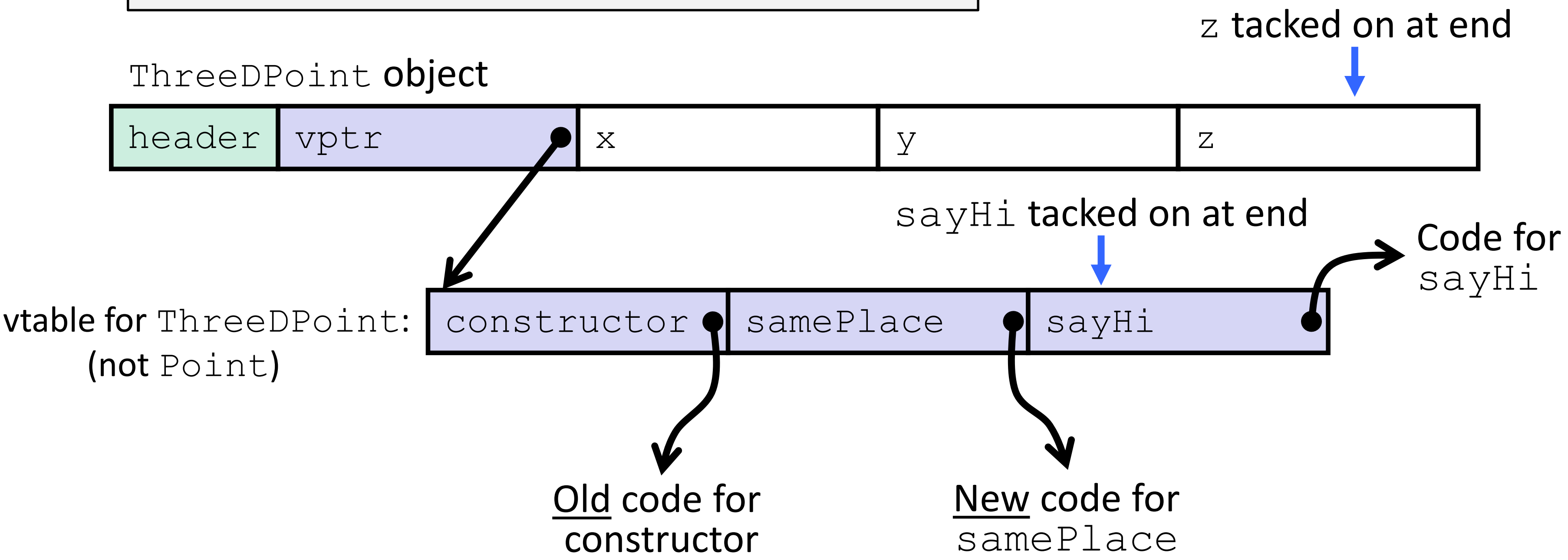
Subclassing

```
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

```
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

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

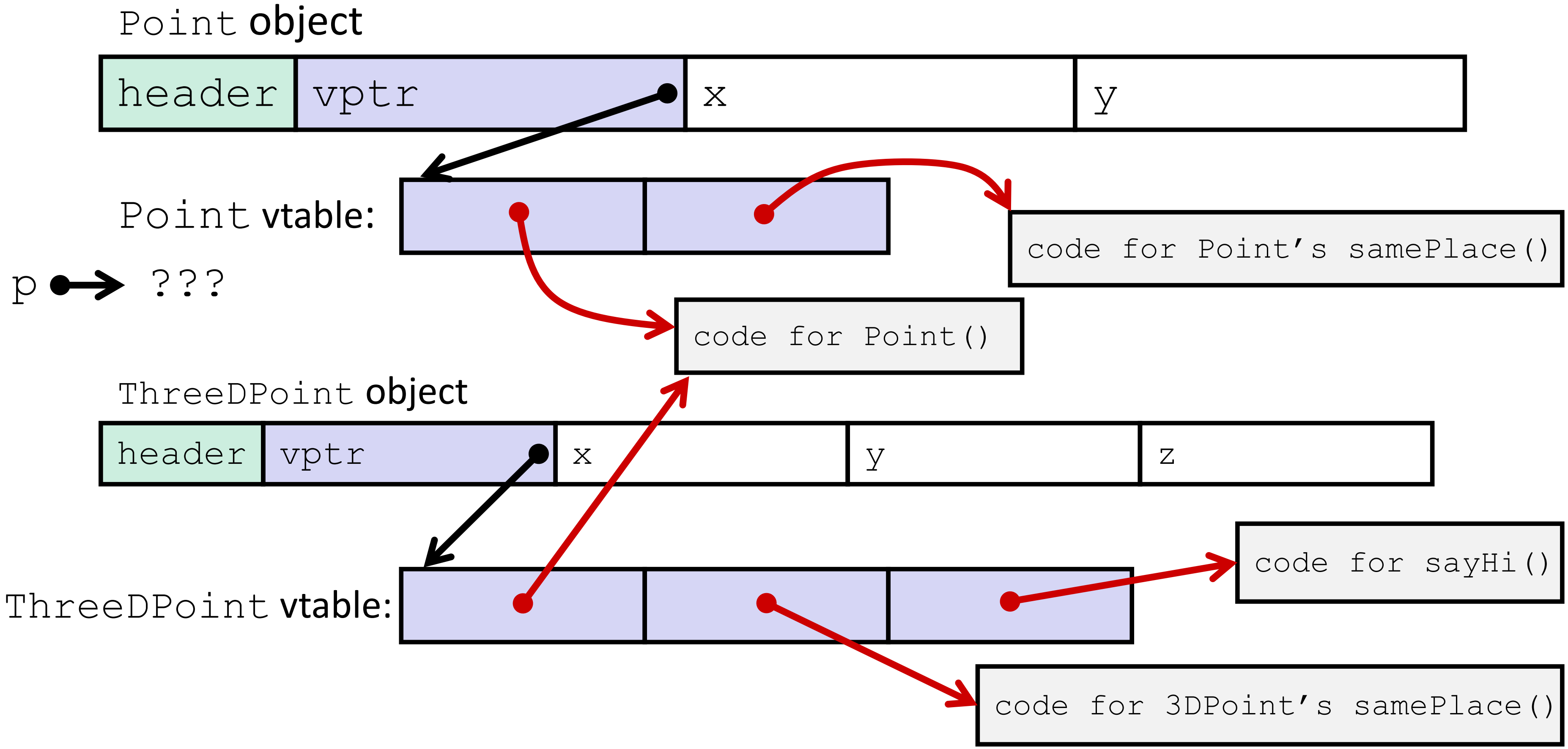
constructor	samePlace	sayHi

Code for `sayHi`

Old code for constructor

New code for `samePlace`

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 CSE143, it may have seemed "magic" that an *inherited* method could call an *overridden* method
  - You were tested on this endlessly

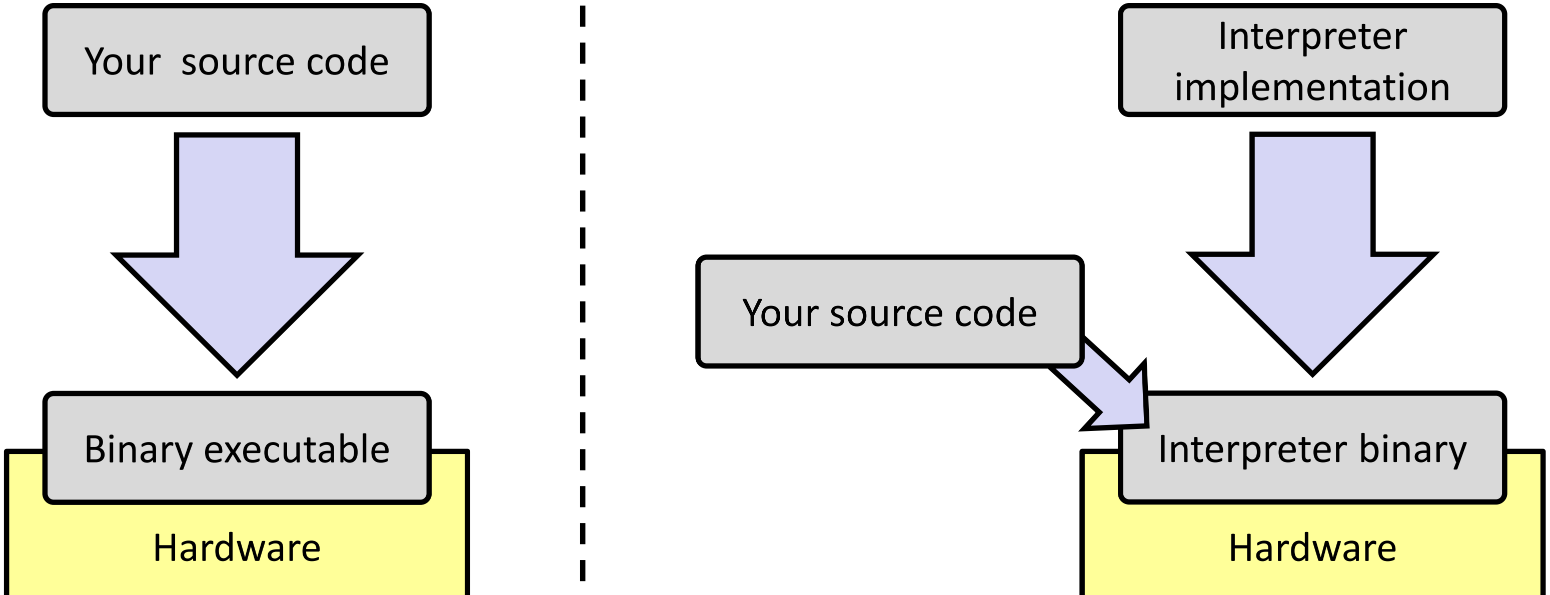
- The "trick" in the implementation is this part:

  `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

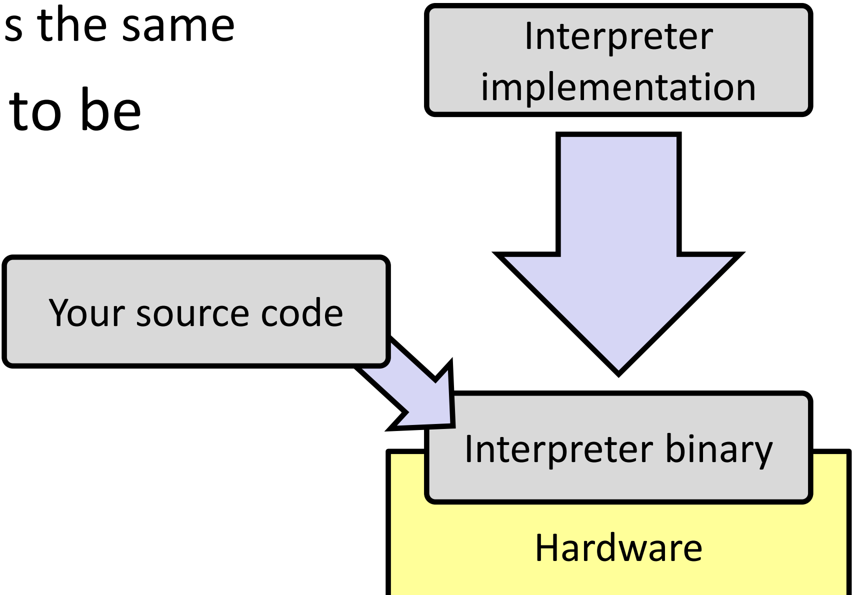
Implementing Programming Languages

- 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

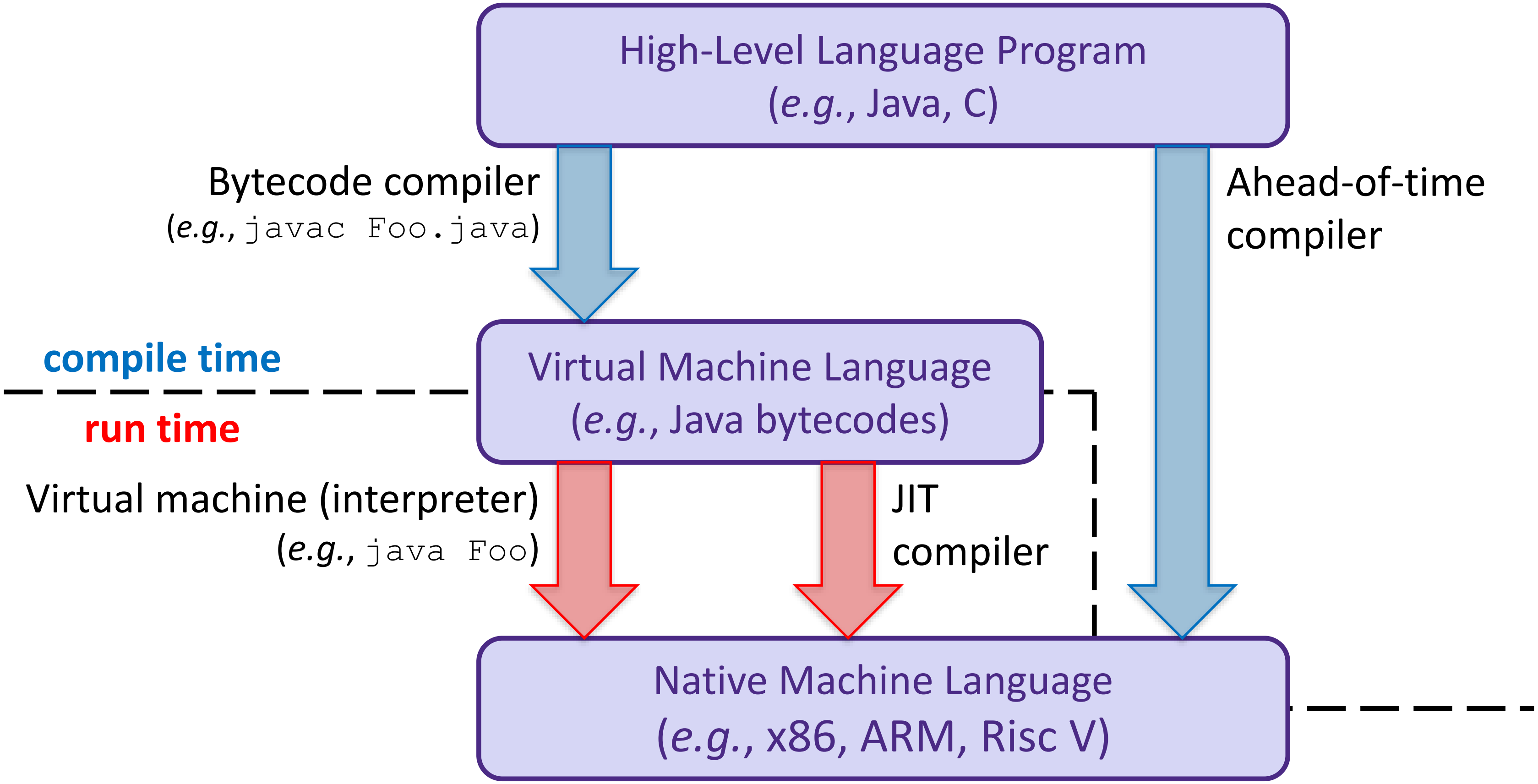
3. To execute the program stored in the bytecodes, these can be interpreted by the Java Virtual Machine (JVM)
   - Running the virtual machine: `java Foo`
   - Loads `Foo.class` and interprets the bytecodes

"The JVM"

Note: The JVM is different than the CSE VM running on VMWare. Yet *another* use of the word "virtual"!

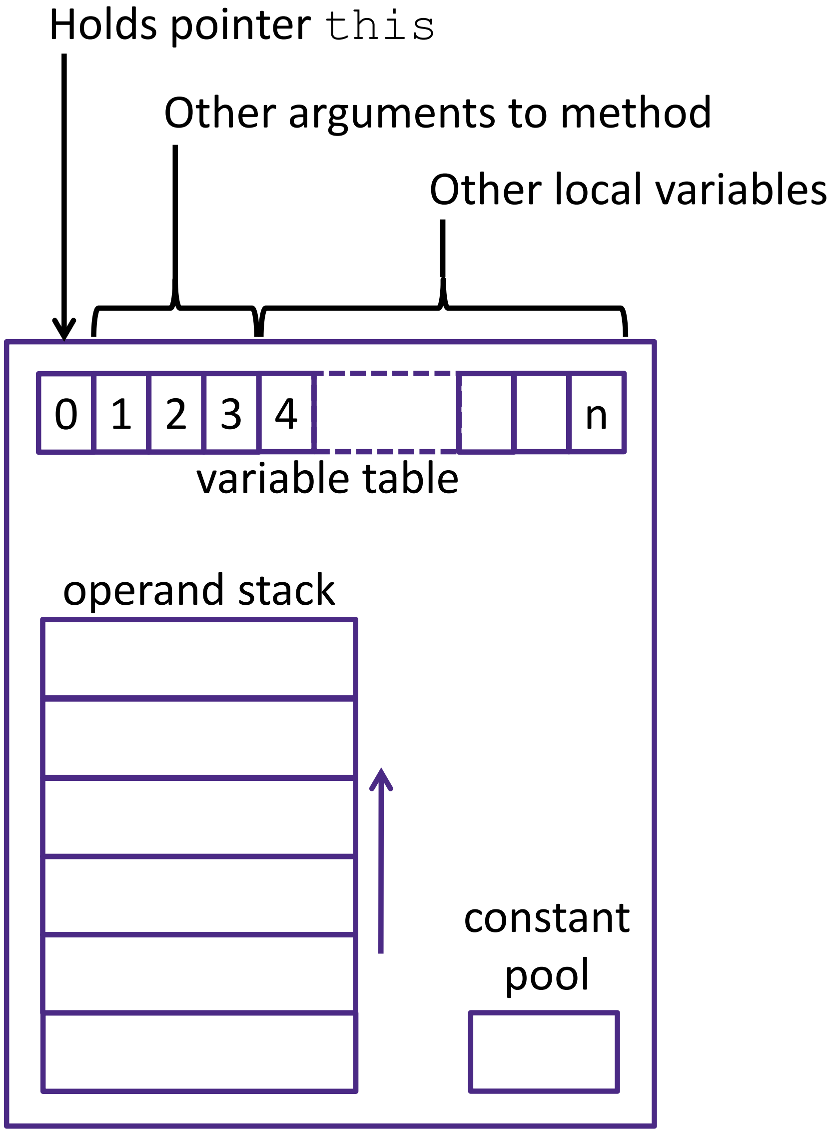
- Java programs are usually run by a Java *virtual machine* (JVM)
  - JVMs interpret an intermediate language called *Java bytecode*
  - Many JVMs compile bytecode to native machine code
    - **Just-in-time (JIT) compilation**
    - http://en.wikipedia.org/wiki/Just-in-time_compilation
  - Java is sometimes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

Virtual Machine Model

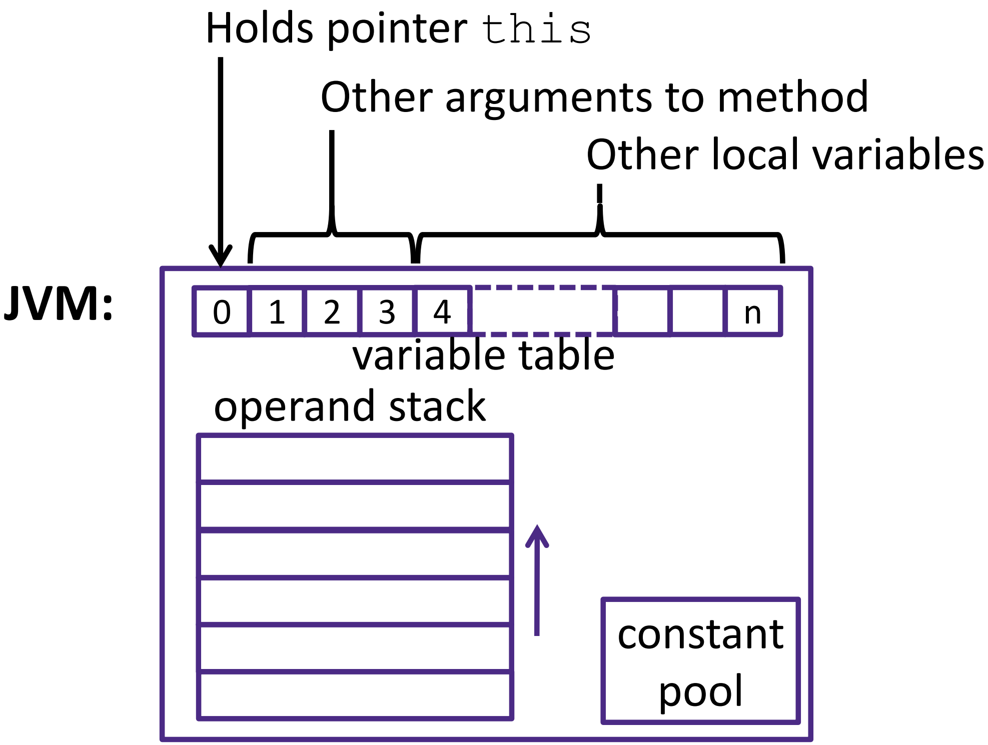


Java Bytecode

- 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

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

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

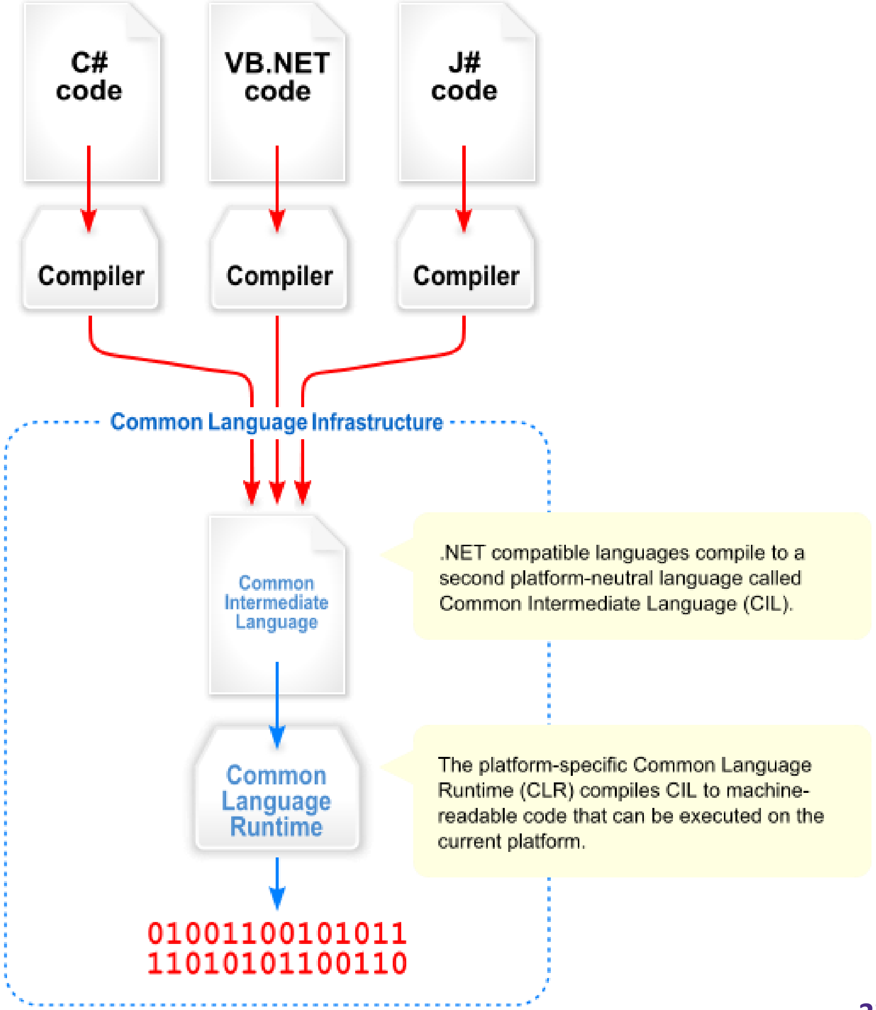
```
Compiled from Employee.java
class Employee extends java.lang.Object {
  public Employee(java.lang.String,int);
  public java.lang.String getEmployeeName();
  public int getEmployeeNumber();
}

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

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



.NET compatible languages compile to a second platform-neutral language called Common Intermediate Language (CIL).

The platform-specific Common Language Runtime (CLR) compiles CIL to machine-readable code that can be executed on the current platform.

We made it! 😊 😎 😂

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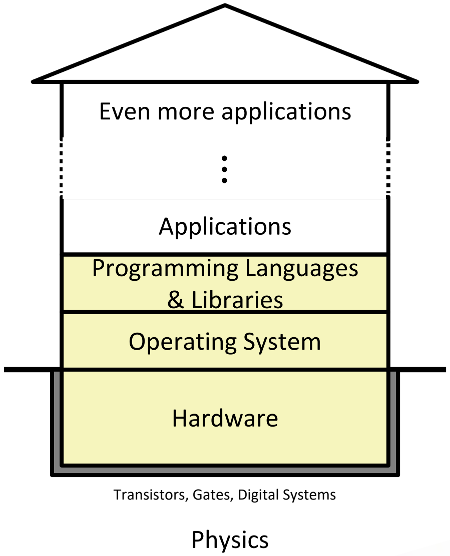
- Topic Group 3: **Scale & Coherence**
  - Caches, Processes, Virtual Memory, Memory Allocation



Even more applications

⋮

Applications

Programming Languages & Libraries

Operating System

Hardware

Transistors, Gates, Digital Systems

Physics