Java & C (Whirlwind Tour)

CSE 351 Spring 2024

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Playlist: CSE 351 24Sp Lecture Tunes!

Announcements, Reminders

- Whirlwind week recap & effects
  - Midterm grades by tonight (forreal this time)
  - Possible changes still forthcoming!
- HW23 due tonight!
  - HW24/25 due Friday (24 May)
- Lab 5 due May 31st
  - No late days allowed; must submit by 11:59 PM on the 31st!
- Memorial Day holiday next Monday (27 May)
- Final Exam: June 3rd through June 5th, on Gradescope.
  - In-class review on May 31st

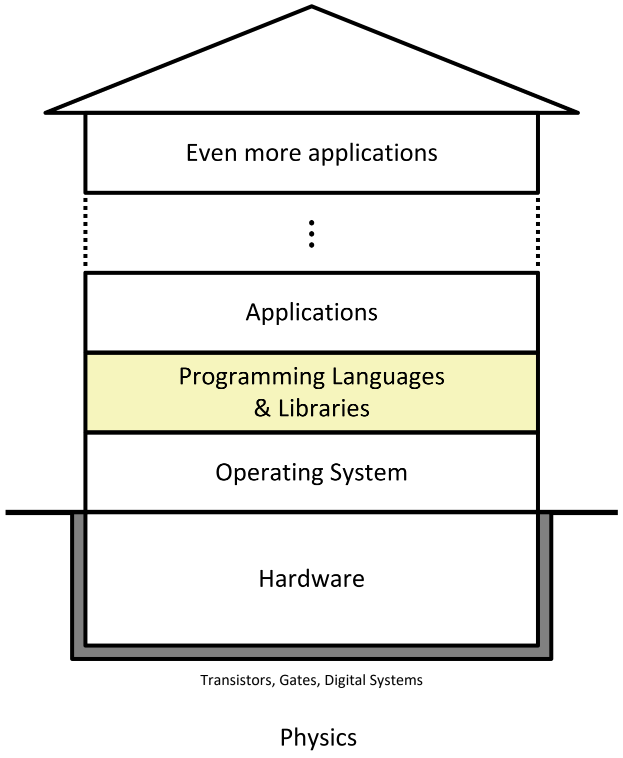
Java (1995) vs. C (1972)

- Reconnecting to Java (hello, CSE 12X & CSE14X!)
  - 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**, ~~Structs~~ 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



Worlds Colliding

- CSE351 has (hopefully) given you a "really different feeling" about what computers do and how programs execute

- We have occasionally contrasted to Java, but CSE 12X/CSE14X 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

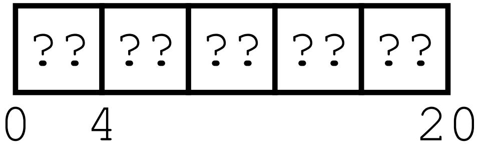
Data in Java

- 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! (Not true for C...)
  - 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**

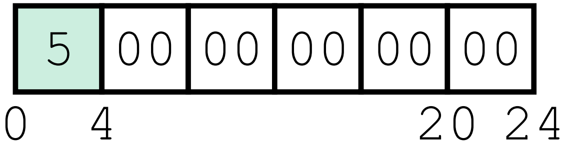
Data in Java: Arrays

- Every element initialized to `0` or `null`
- Arrays are objects; can apply methods to them
- Length specified in an 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];

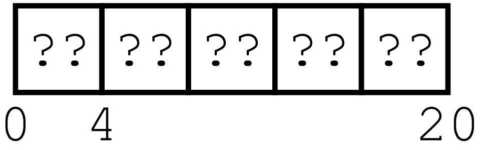


Data in Java: Arrays

- Every element initialized to `0` or `null`
- Arrays are objects; can apply methods to them
- 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 (no more buffer overflow!)
  - Exception if out-of-bounds

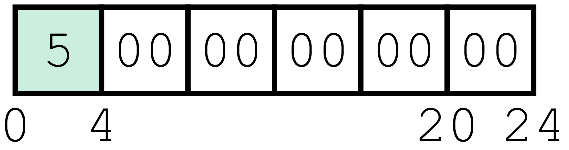
C:

int array[5];



Java:

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



To speed up bounds-checking:

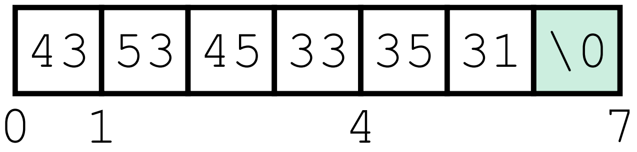
- Length field is likely in cache (spatial locality 🙏)
- Compiler may store length field in register for loops
- Compiler may prove that some checks are redundant

Data in Java: Characters & Strings

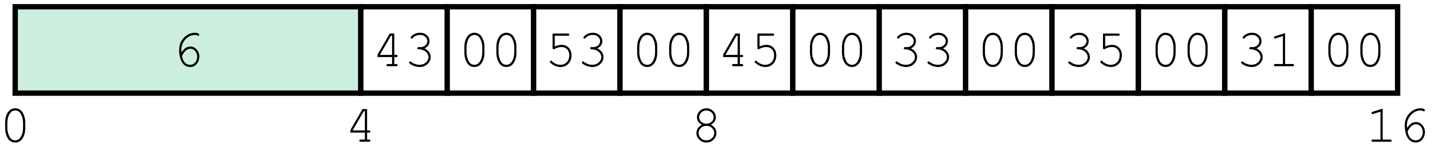
- Two-byte Unicode instead of ASCII
  - Represents most of the world's alphabets
- String not bounded by a `'\0'` (null character)
  - Bounded by hidden length field at beginning of string
- All String objects read-only (vs. `StringBuffer`)

Example: the string "CSE351"

C:
(ASCII)



Java:
(Unicode)



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;
};
```

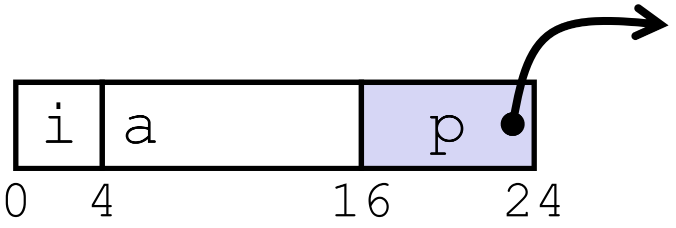
- `a[]` stored "inline" as part of struct

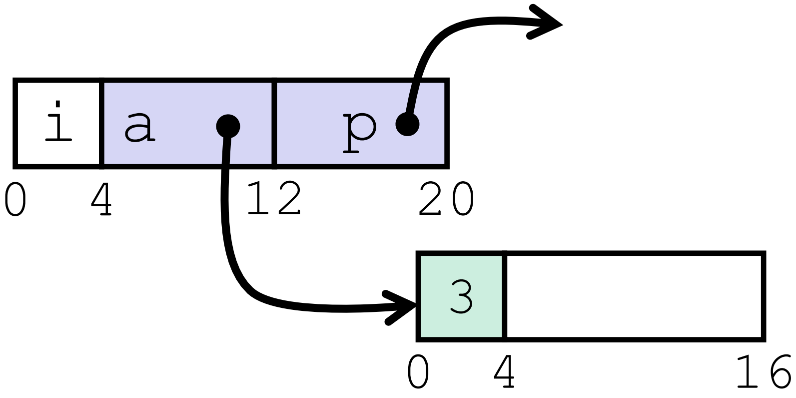
Java:

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

- `a` stored by reference in object

In Memory:





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:

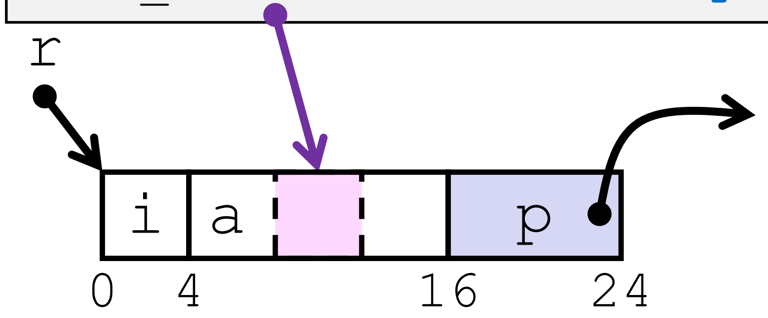
```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```

Pointers/References

- **Pointers** in C can point to <u>any</u> memory address
- **References** in Java can only point to [the <u>starts</u> of] objects
  - Can only be dereferenced to access a field or element of that object

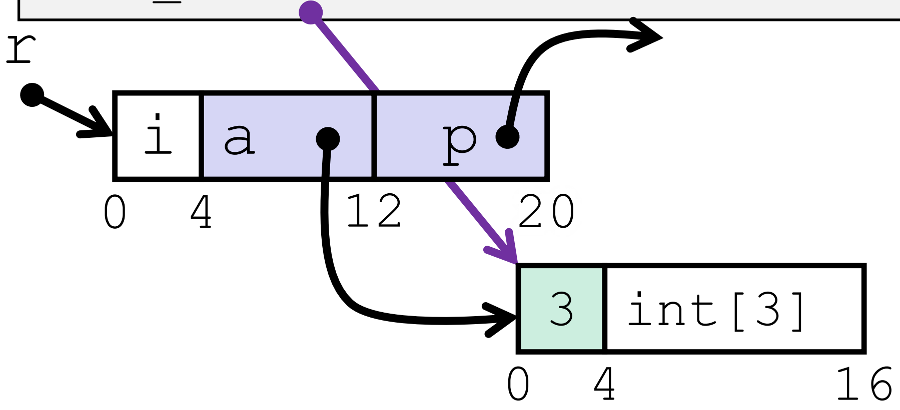
C:

```
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
```



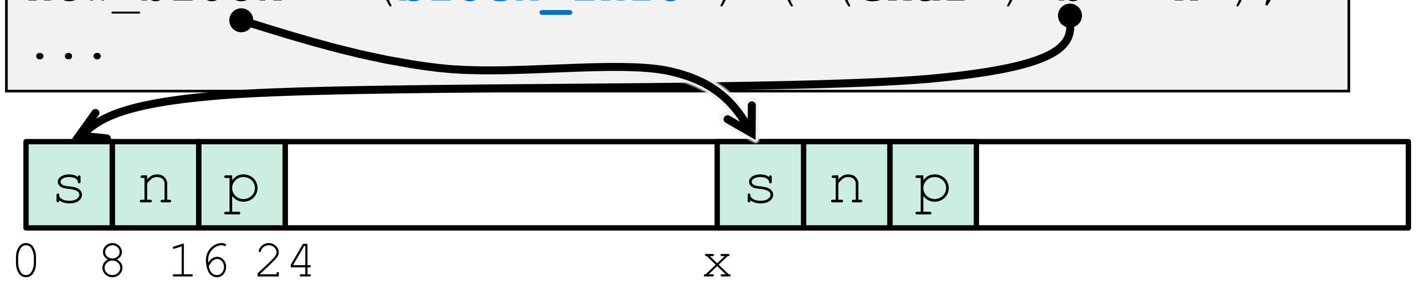
Casting in C (example from Lab 5)

- 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 );
...
```

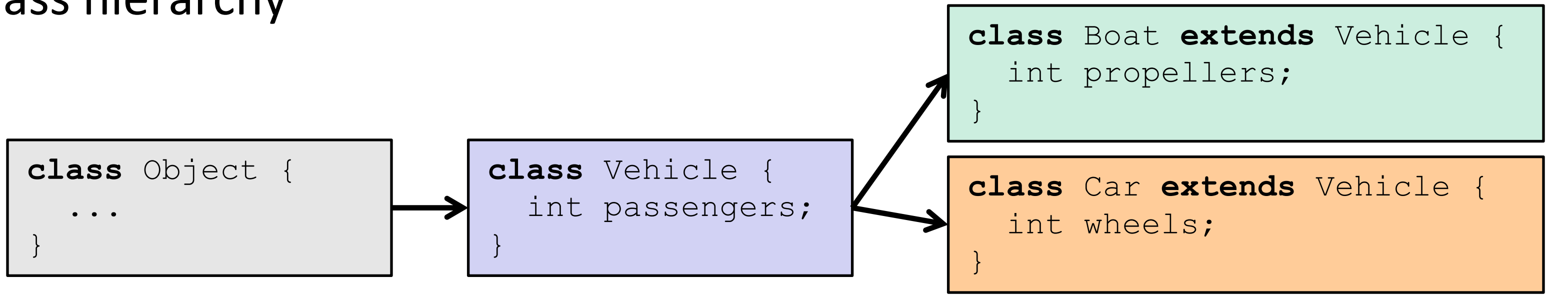
Cast b into char* to do unscaled addition

Cast back into block_info* to use as block_info struct



Type-safe casting in Java

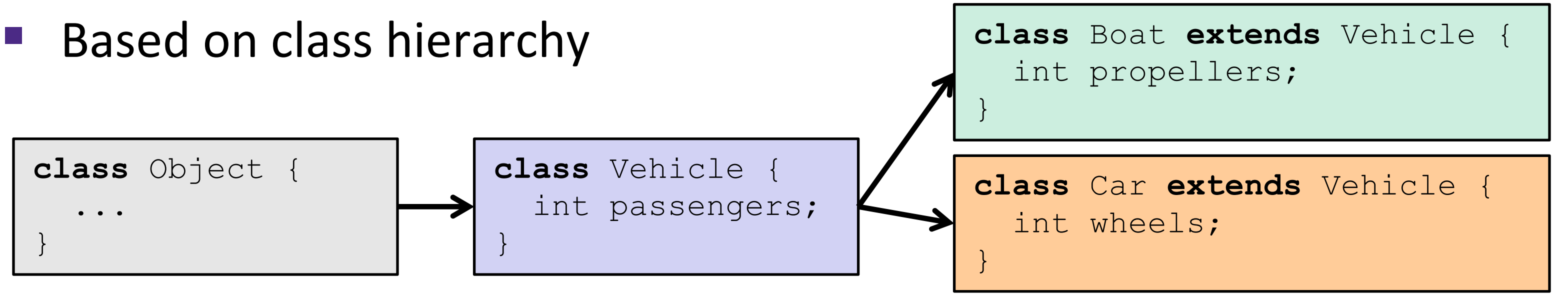
- Can only cast compatible object references; makes casting safe but constrained
  - Based on class hierarchy




```
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




```
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();
```

- `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`)

Casting:

```
Boat    b2 = (Boat) v;

Car     c4 = (Car) v2;
Car     c5 = (Car) b1;
```

- `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 (double x; double y;)

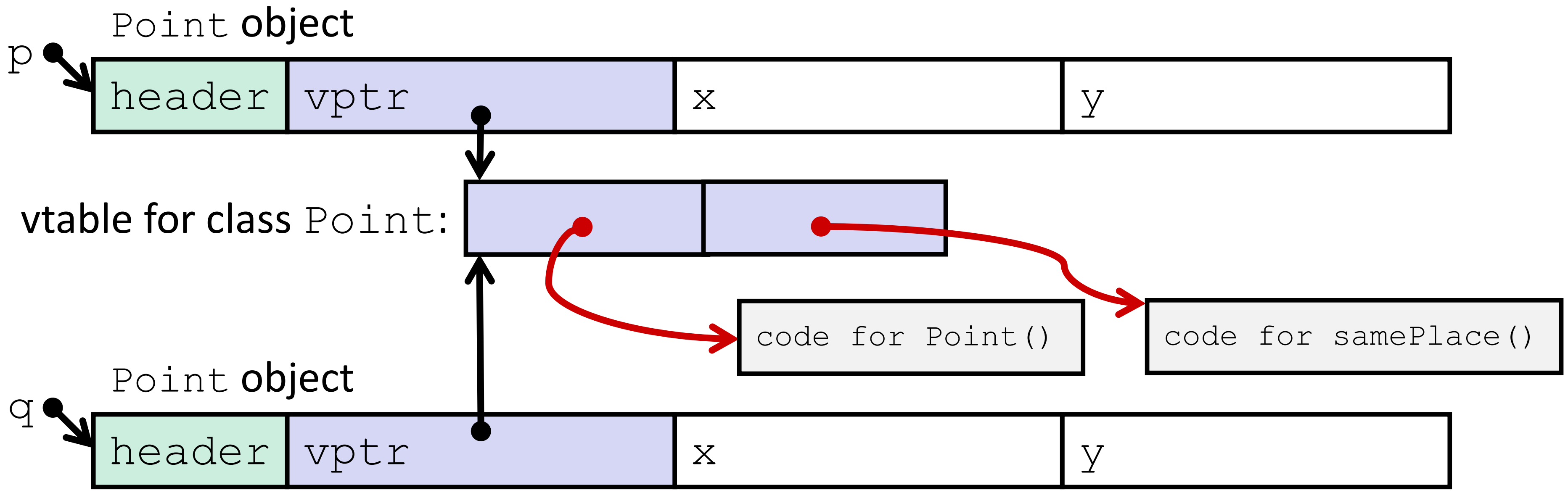
constructor (Point() { ... })

method(s) (boolean samePlace(Point p) { ... })

creation (Point p = new Point();)

- 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
  - Only one table per class
  - Each object instance contains a *vtable pointer (vptr)*

Java Constructors

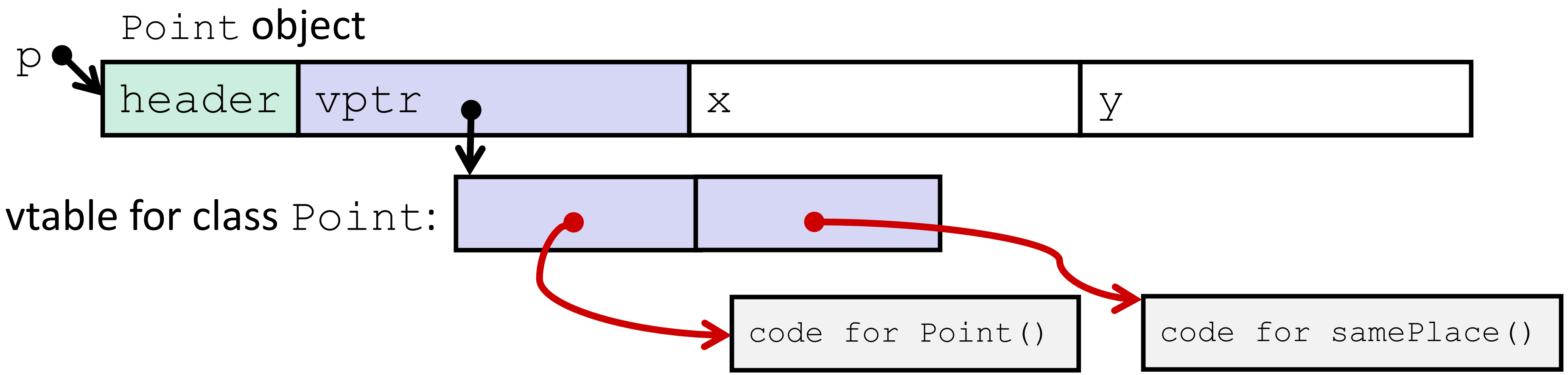
- **When we call `new`:** allocate space for object (data fields and references), initialize to zero/null, and run constructor method

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

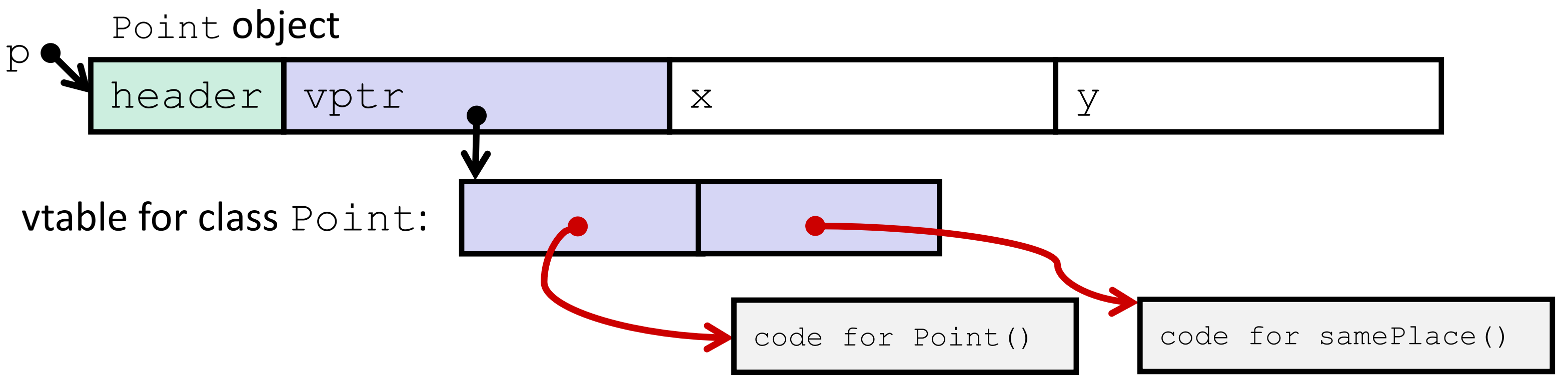
- Static methods are just like functions
- Instance methods:
  - Can refer to *this;*
  - Have an implicit first parameter for *this;* and
  - Can be overridden in subclasses
- The code to run when calling an instance method is chosen *at runtime* by lookup in the vtable

Java:

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

C pseudo-translation:

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



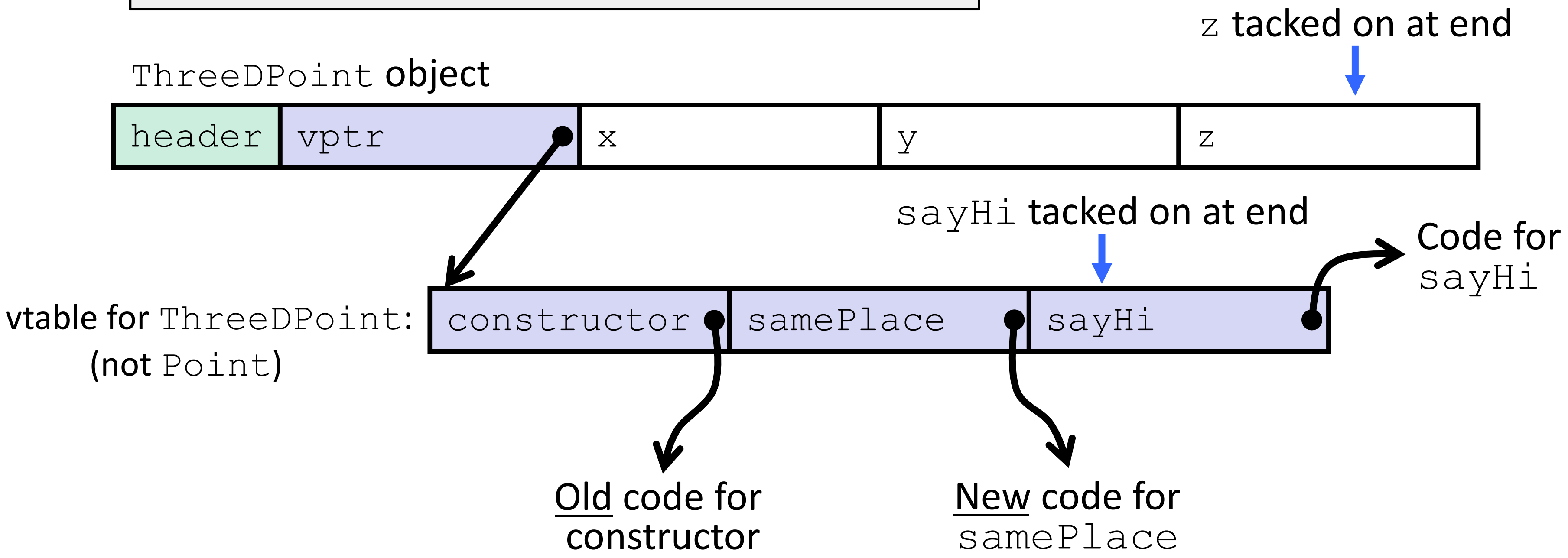
Subclassing

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

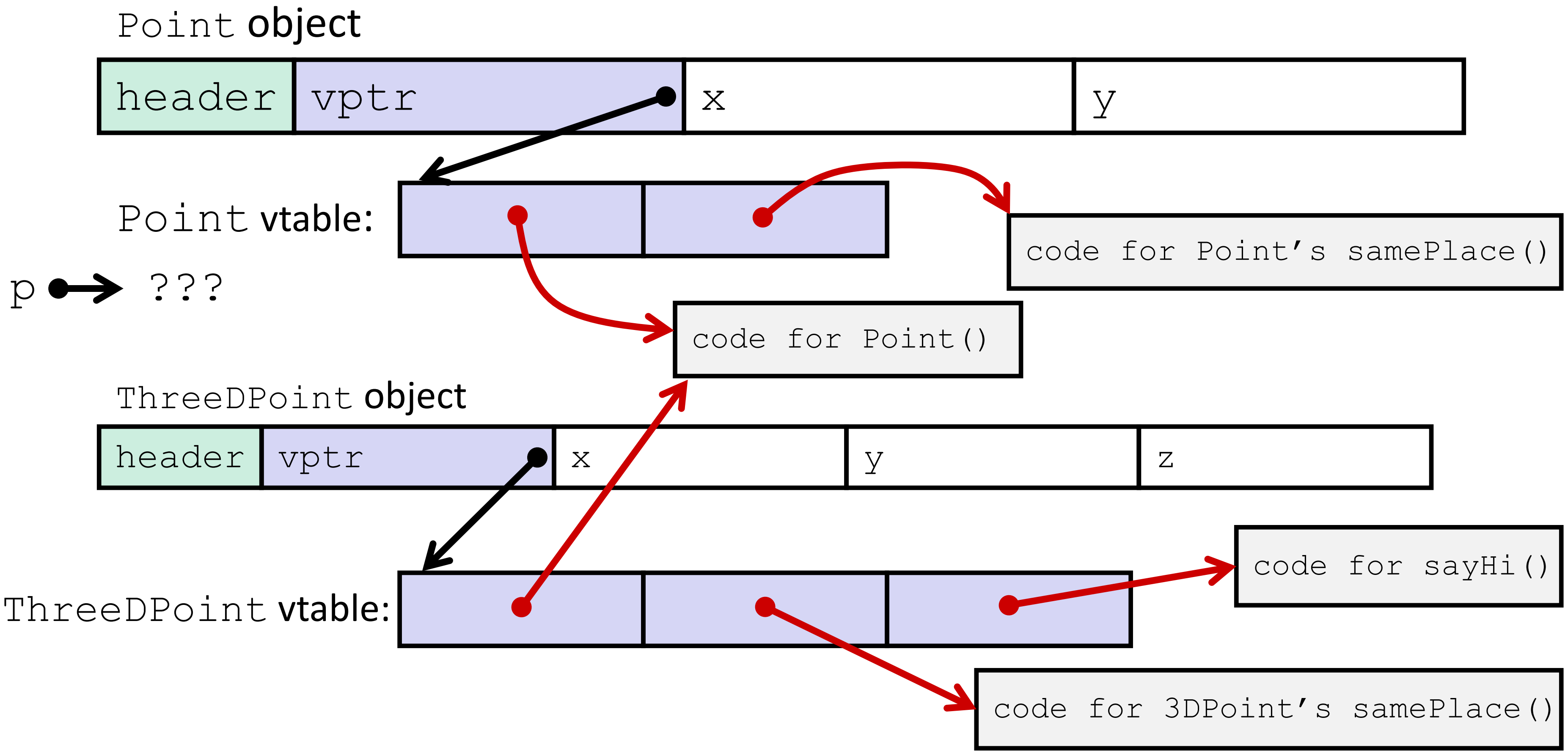
- Where does "`z`" go? At end of fields of `Point`
  - `Point` fields are always in the same place, so `Point` code can run on `ThreeDPoint` objects without modification
- Where does pointer to code for two new methods go?
  - No constructor, so use default `Point` constructor
  - To override "`samePlace`", 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");
    }
}
```



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 CSE12X/14X, it may have seemed "magic" that an inherited method could call an overridden method

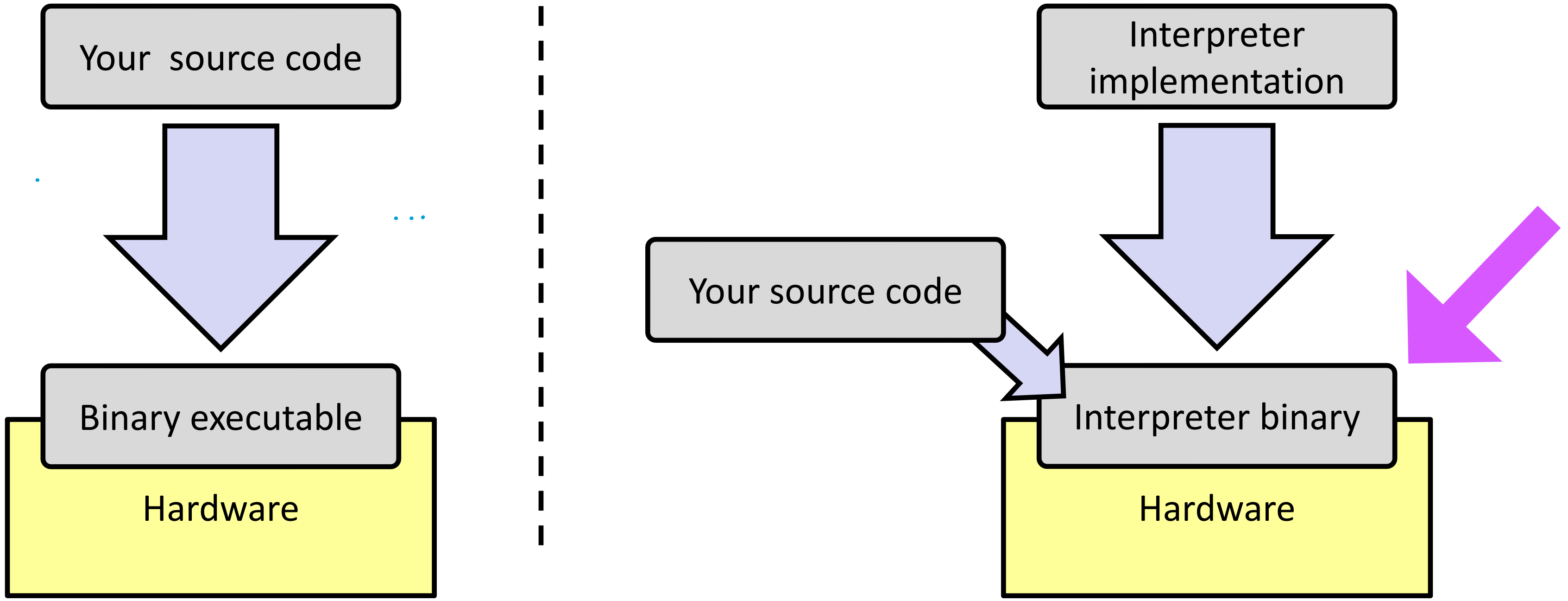
- The "trick" in the implementation is this part:

```
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

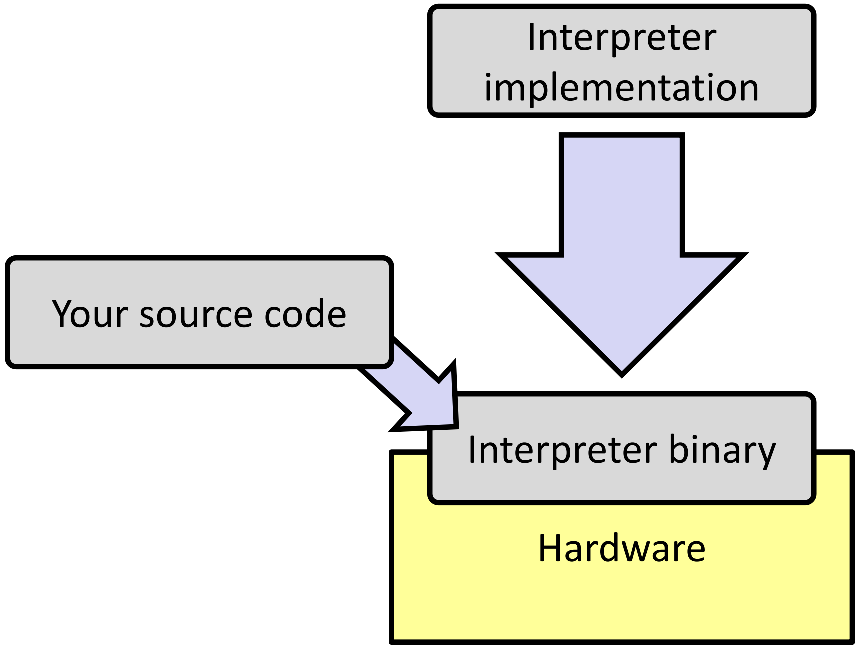
Implementing Programming Languages

- 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 <u>slower</u> to execute and <u>harder</u> 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 <u>some</u> validation in the real world (*e.g.*, JavaScript vs. C)
- Some modern language implementations are a mix (Java)
  - *e.g.*, Java compiles to bytecode that is <u>then</u> 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

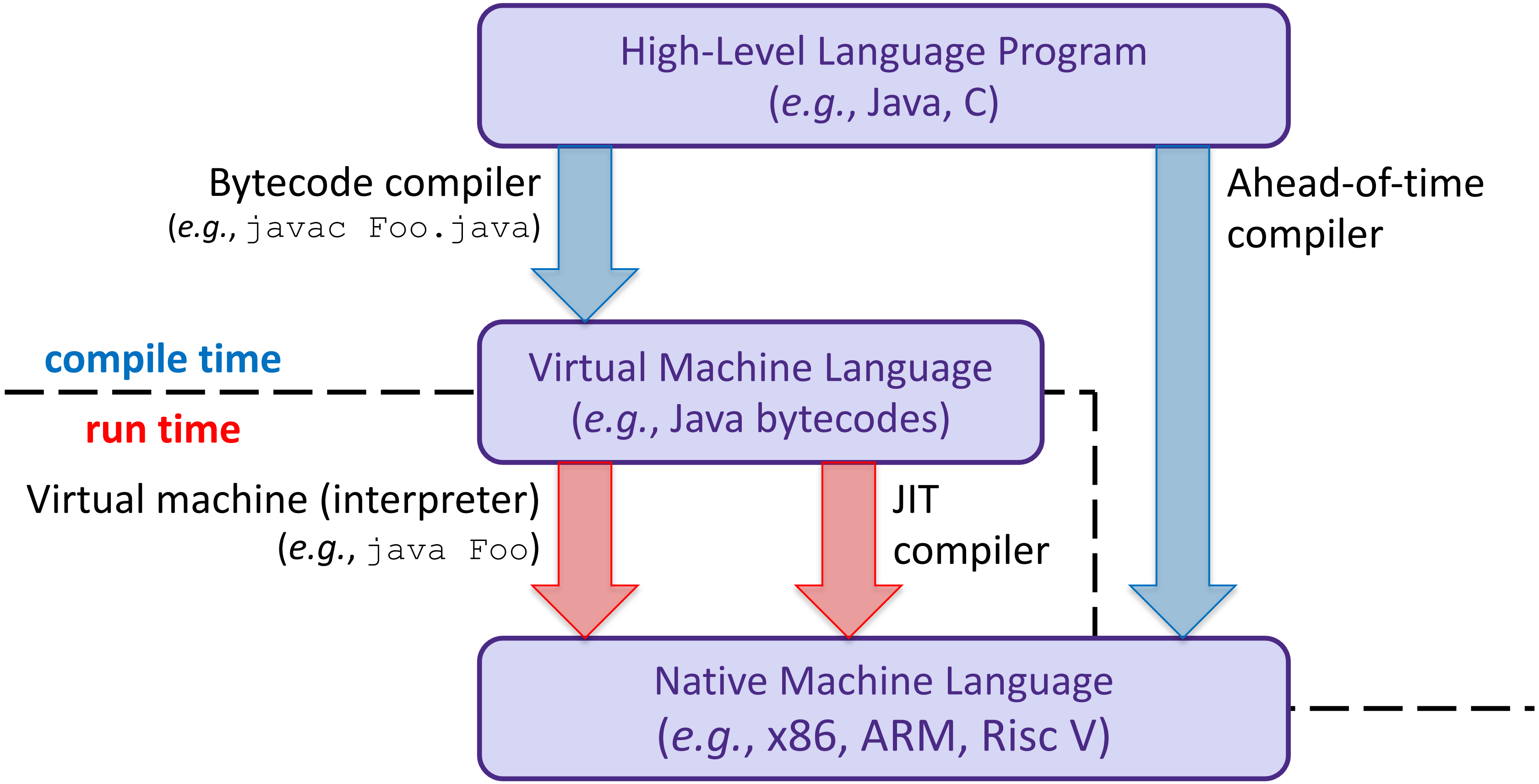
3. To execute the program stored in the bytecodes, these can be interpreted by the Java Virtual Machine (JVM)
   - Running the virtual machine: `java Foo`
   - Loads `Foo.class` and interprets the bytecodes

"The JVM"

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

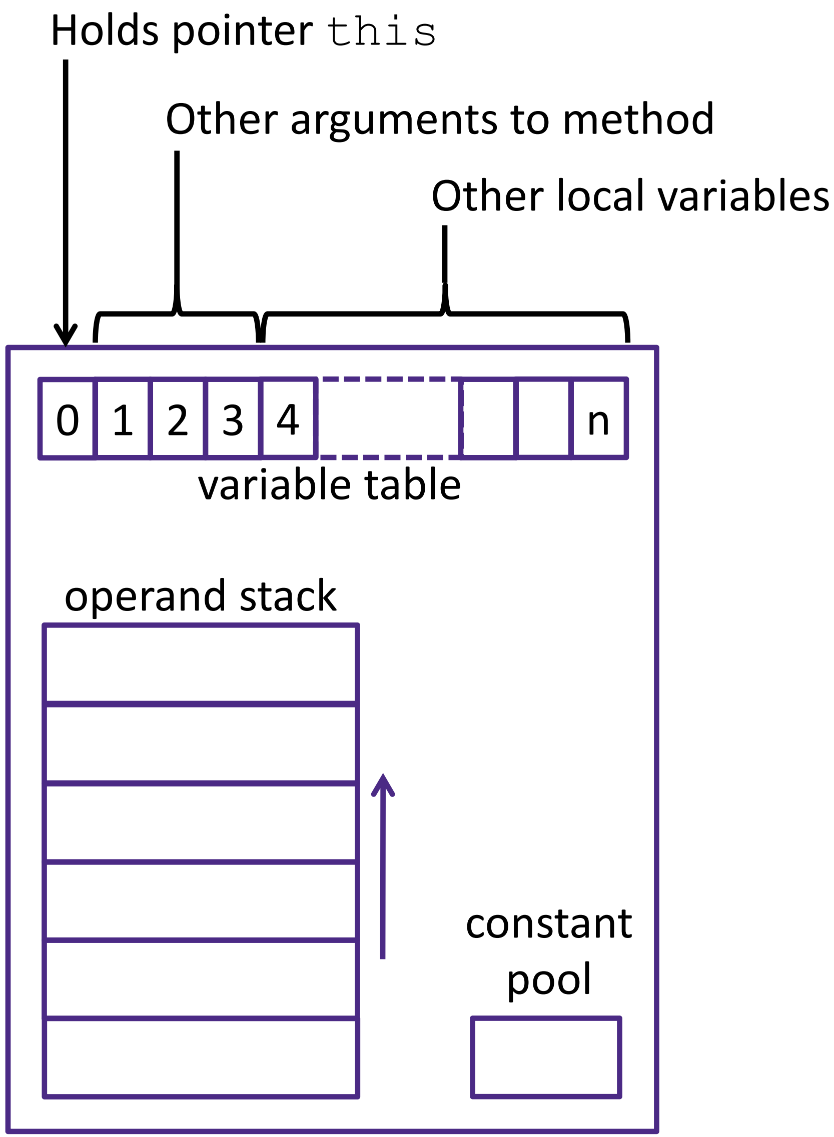
- Java programs are usually run by a ***Java virtual machine*** *(JVM)*
  - JVMs interpret an intermediate language, Java bytecode
  - Many JVMs compile bytecode to native machine code
    - **Just-in-time (JIT) compilation**
    - http://en.wikipedia.org/wiki/Just-in-time_compilation
  - Java is sometimes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

Virtual Machine Model



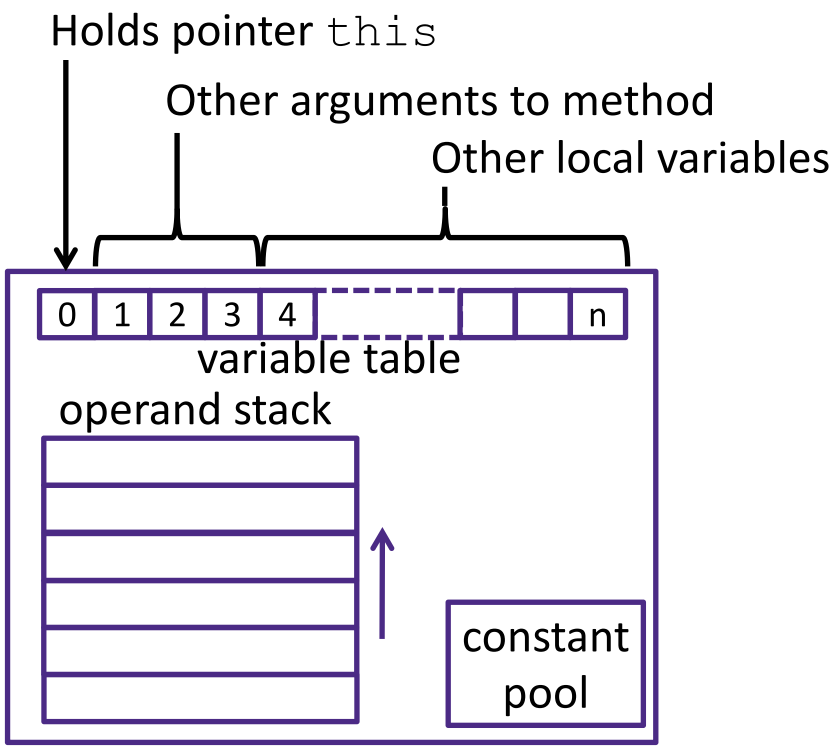
Java Bytecode

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



JVM Operand Stack

JVM:



'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

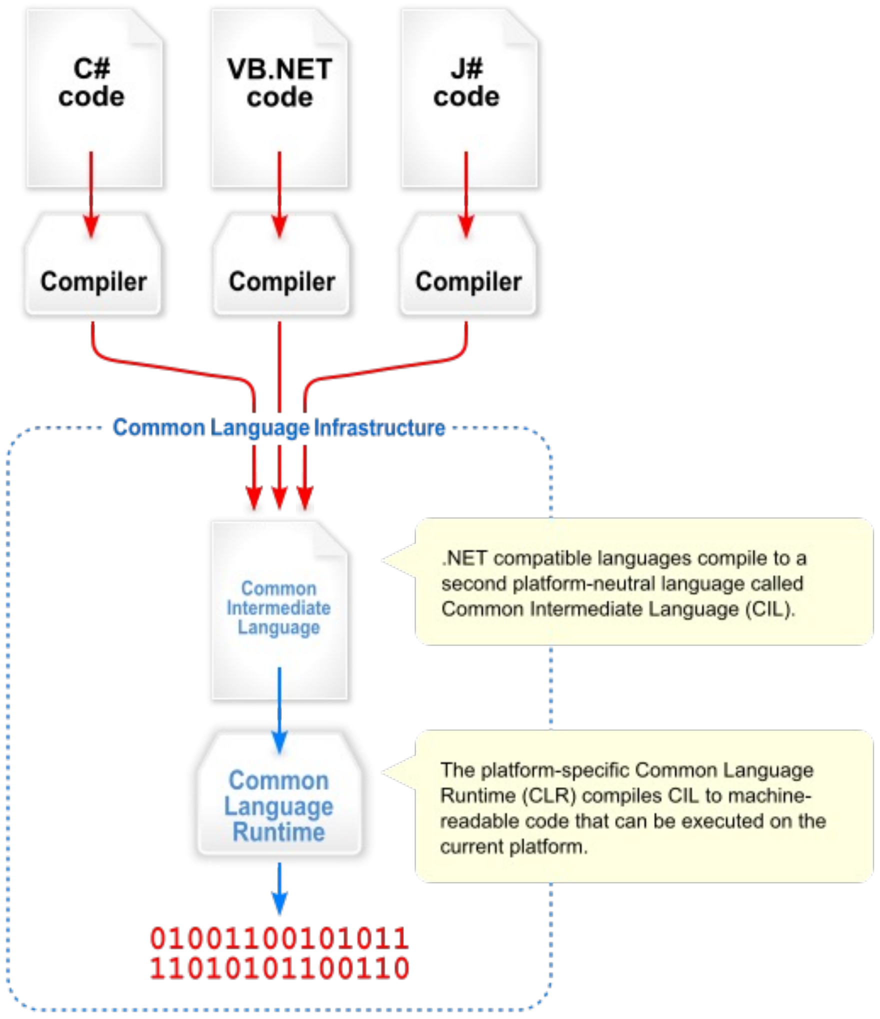
```
Compiled from Employee.java
class Employee extends java.lang.Object {
  public Employee(java.lang.String,int);
  public java.lang.String getEmployeeName();
  public int getEmployeeNumber();
}

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 & readily usable 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! ☺️ 😎 😂

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  - Memory, Data, Integers, Floating Point, Arrays, Structs
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  - Caches, Processes, Virtual Memory, Memory Allocation