Roadmap

C:

```c
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```java
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:

Memory & data
Integers & floats
Machine code & C
x86 assembly
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Java vs. C

- **Reconnecting to Java**
  - Back to 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
  - Runtime environment
  - Translation from high-level code to machine code

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*
- 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
    - just like caching, etc.

The Other Huge Point

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

- **We have occasionally contrasted to Java, but CSE143 and similar 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

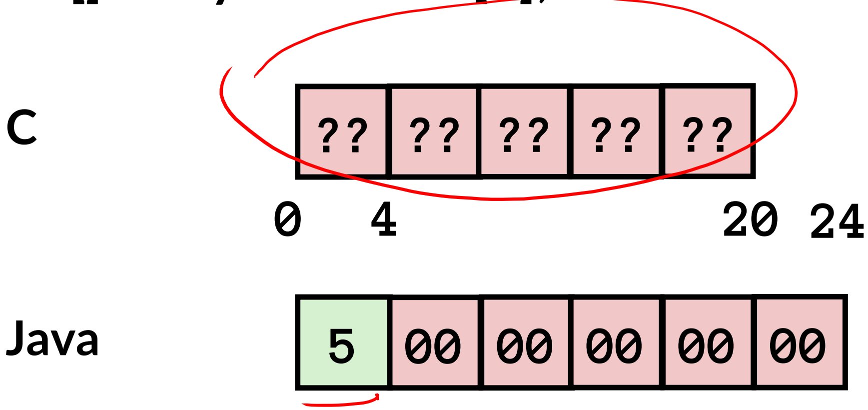
Data in Java

- **Integers, floats, doubles, pointers – same as C**
  - Yes, Java has pointers – they are called 'references' – however, Java references 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 implementation
  - 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

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

```
int array[5];              // C
int[] array = new int[5];  // Java
```



Data in Java: Arrays

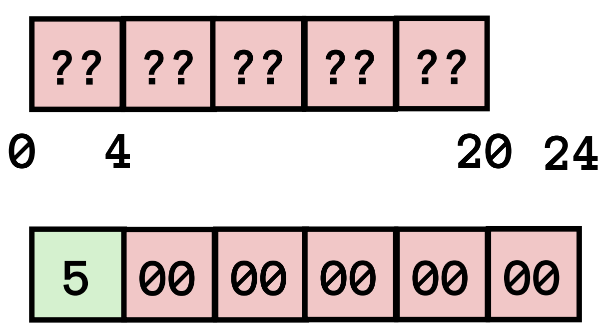
- **Arrays**
  - Every element initialized to 0 or null
  - Length specified in immutable field at start of array (int – 4 bytes)
    - array.length returns value of this field
  - Every access triggers a bounds-check
    - Code is added to ensure the index is within bounds
    - Exception if out-of-bounds

int array[5];   // C

int[] array = new int[5]; // Java

C

Java



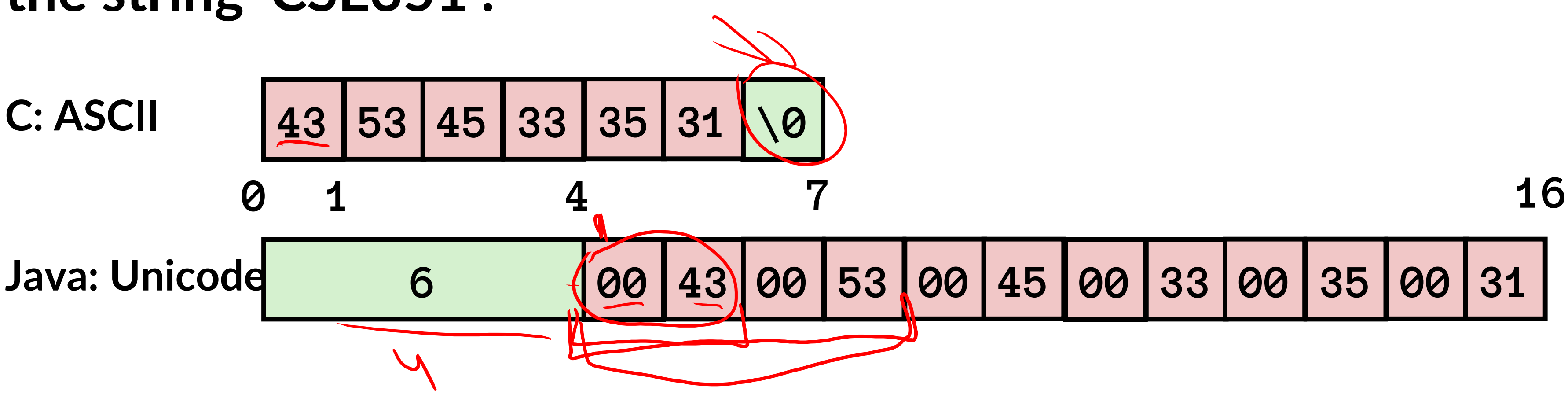
Bounds-checking sounds slow, but:

1. Length field is likely in cache
2. Compiler may store length field in register for loops
3. Compiler may prove that some checks are redundant

Data in Java: Characters & Strings

- **Characters and 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)

the string 'CSE351':



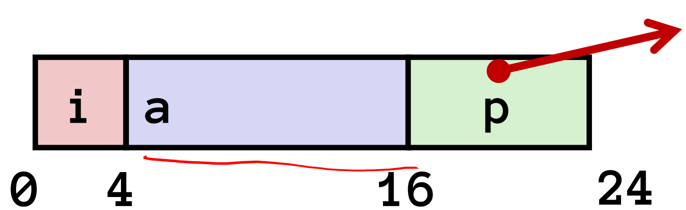
Data structures (objects) in Java

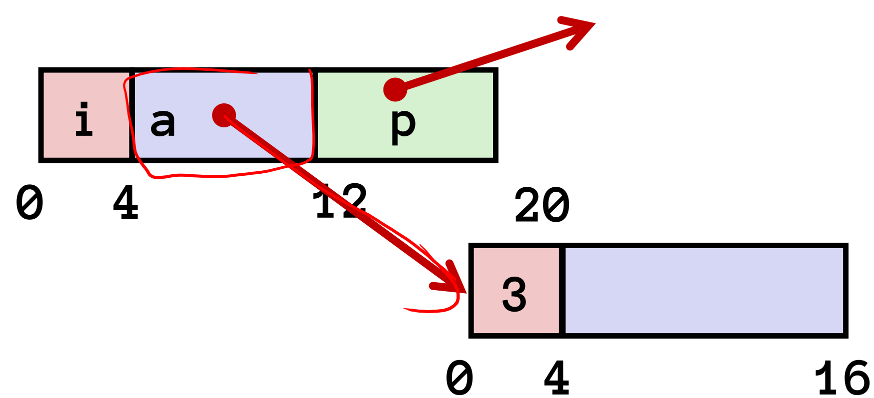
- **Objects are always stored by reference, never stored "inline".**
  - Include complex data types (arrays, other objects, etc.) using references

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

Java
```java
class Rec {
  int i;
  int[] a = new int[3];
  Rec p;
…
}
```

Example of array stored "inline"





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 C's `r->a`
  - So, no Java field needs more than 8 bytes

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

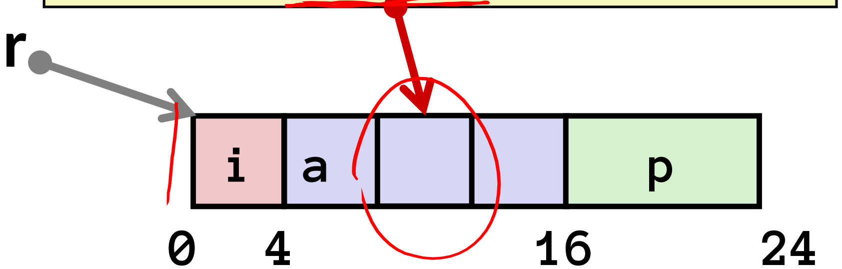
```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```

Pointers/References

- **Pointers in C can point to any memory address**
- **References in Java can only point to [the starts of] objects**
  - And can only be dereferenced to access a field or element of thaXt object

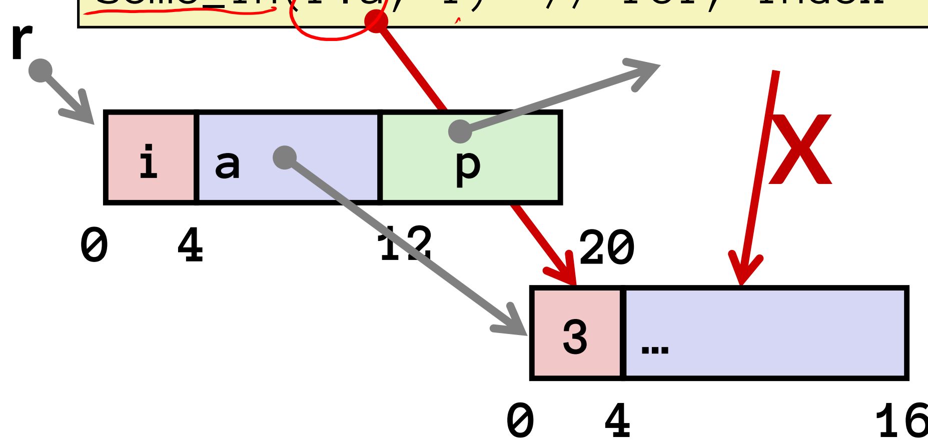
C

```
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
```



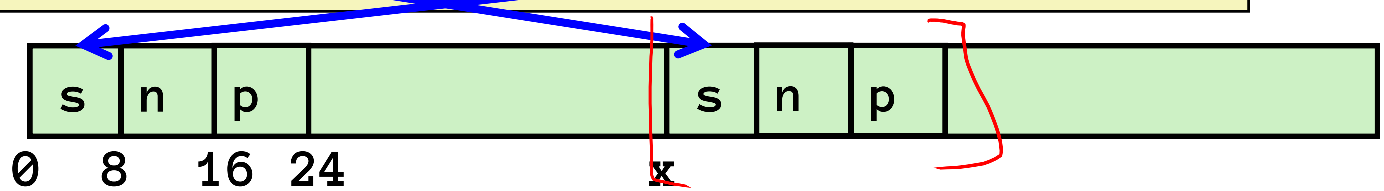
Casting in C (example from Lab 5)

- **We can cast any pointer into any other pointer; just look at the same bits differently**

```
struct BlockInfo {
        size_t sizeAndTags;
        struct BlockInfo* next;
        struct BlockInfo* prev;
};
typedef struct BlockInfo BlockInfo;
…
int x;
BlockInfo *b;
BlockInfo *newBlock;
…
newBlock = (BlockInfo *) ( (char *) b + x );
…
```

Cast b into char pointer so that you can add byte offset without scaling

Cast back into BlockInfo pointer so you can use it as BlockInfo struct



Type-safe casting in Java

- **Can only cast compatible object references**

```
class Object {
  …
}
```

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

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

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

```
// Vehicle is a super class of Boat and Car, which are siblings
Vehicle  v = new Vehicle();
Car     c1 = new Car();
Boat    b1 = new Boat();
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**

```
class Object {
  …
}
```

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

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

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

```
// Vehicle is a super class of Boat and Car, which are siblings
Vehicle  v  = new Vehicle();
Car      c1 = new Car();
Boat     b1 = new Boat();
Vehicle v1 = new Car();     // OK, everything needed for Vehicle
                            //   is also in Car
Vehicle v2 = v1;            // OK, v1 is declared as type Vehicle
Car      c2 = new Boat();   // Compiler error - Incompatible type - elements
                            //  in Car that are not in Boat (classes are siblings
Car      c3 = new Vehicle();// Compiler error - Wrong direction; elements in Car
                            //  not in Vehicle (wheels)
Boat     b2 = (Boat) v;     // Run-time error; Vehicle does not contain
                            //  all elements in Boat (propellers)
Car      c4 = (Car) v2;     // OK, v2 refers to a Car at runtime
Car      c5 = (Car) b1;     // Compiler error - Unconvertible types,
                            //  b1 is declared as type Boat
```

How is this implemented/ enforced?

Java objects

```
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();
…
```

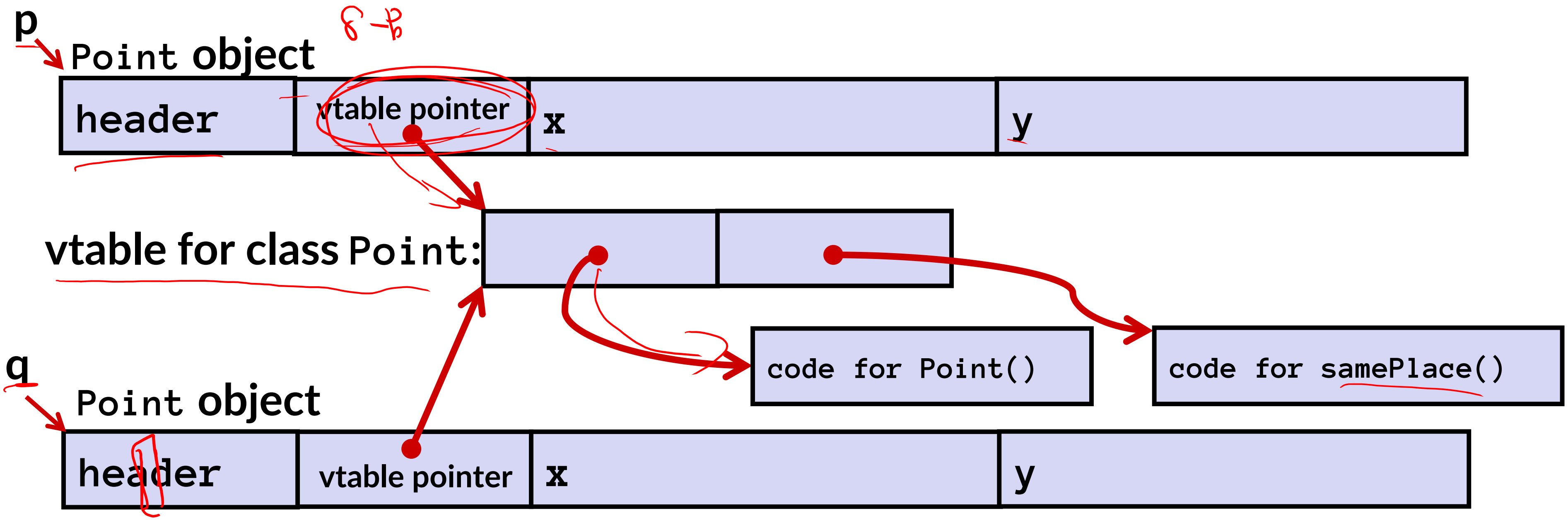
fields

constructor

method

creation

Java objects



- ***vtable* pointer : points to *virtual method table***
  - like a jump table for instance ("virtual") methods plus other class info
  - one table per class
- ***Object header* : GC info, hashing info, lock info, etc.** (no size – why?)

Java Constructors

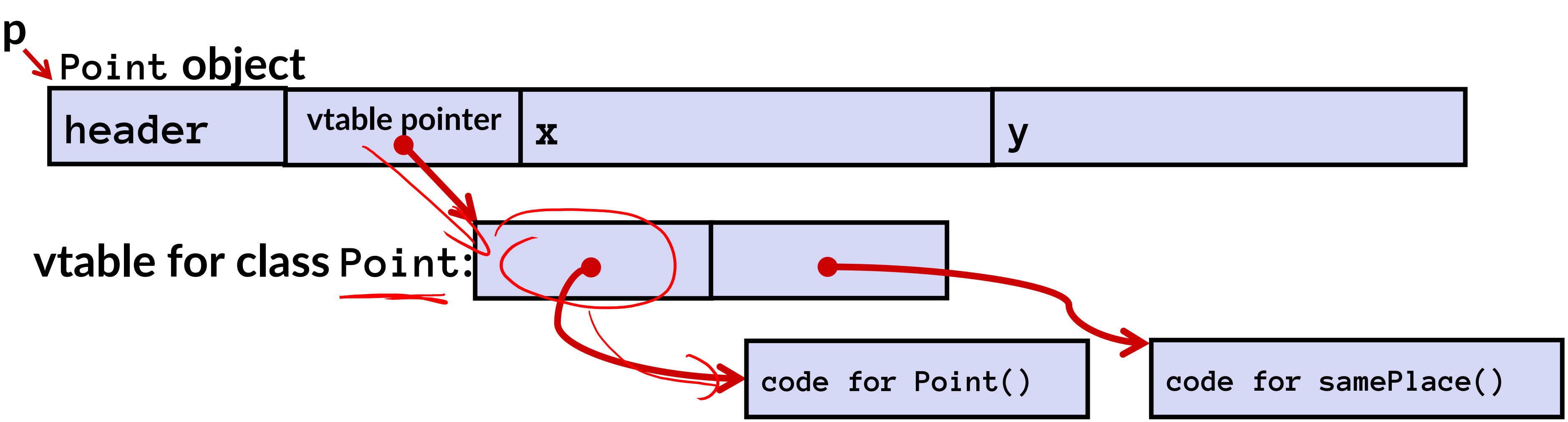
- When we call `new`: allocate space for object, zero/null fields, and run constructor

Java:

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

C pseudo-translation:

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



Java Methods

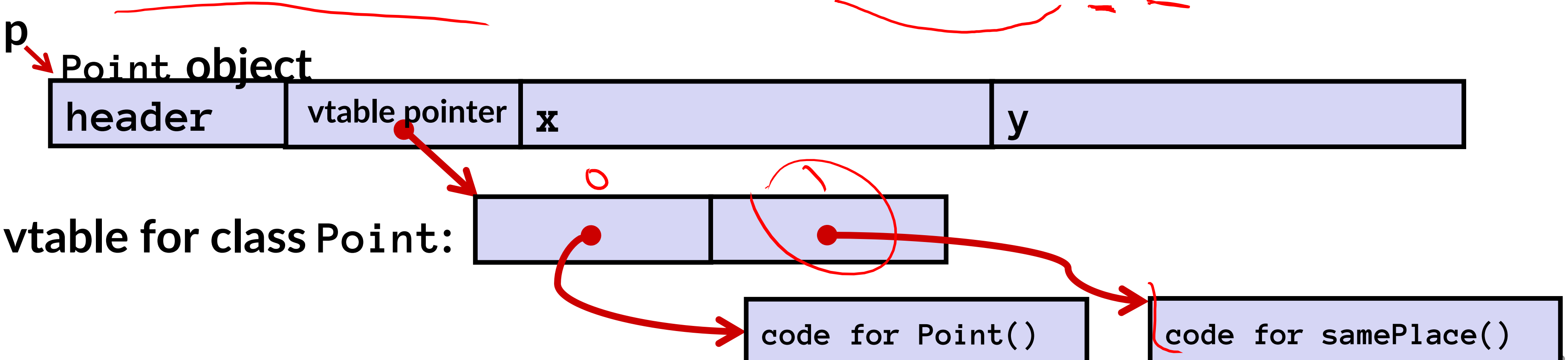
- Static methods are just like functions
- Instance methods
  - can refer to *this;*
  - have an implicit first parameter for *this; and*
  - can be overridden in subclasses
- **The code to run when calling an instance method (e.g., *p.samePlace(q)*) is chosen *at run-time* by lookup in the vtable.**

Java:

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

C pseudo-translation:

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



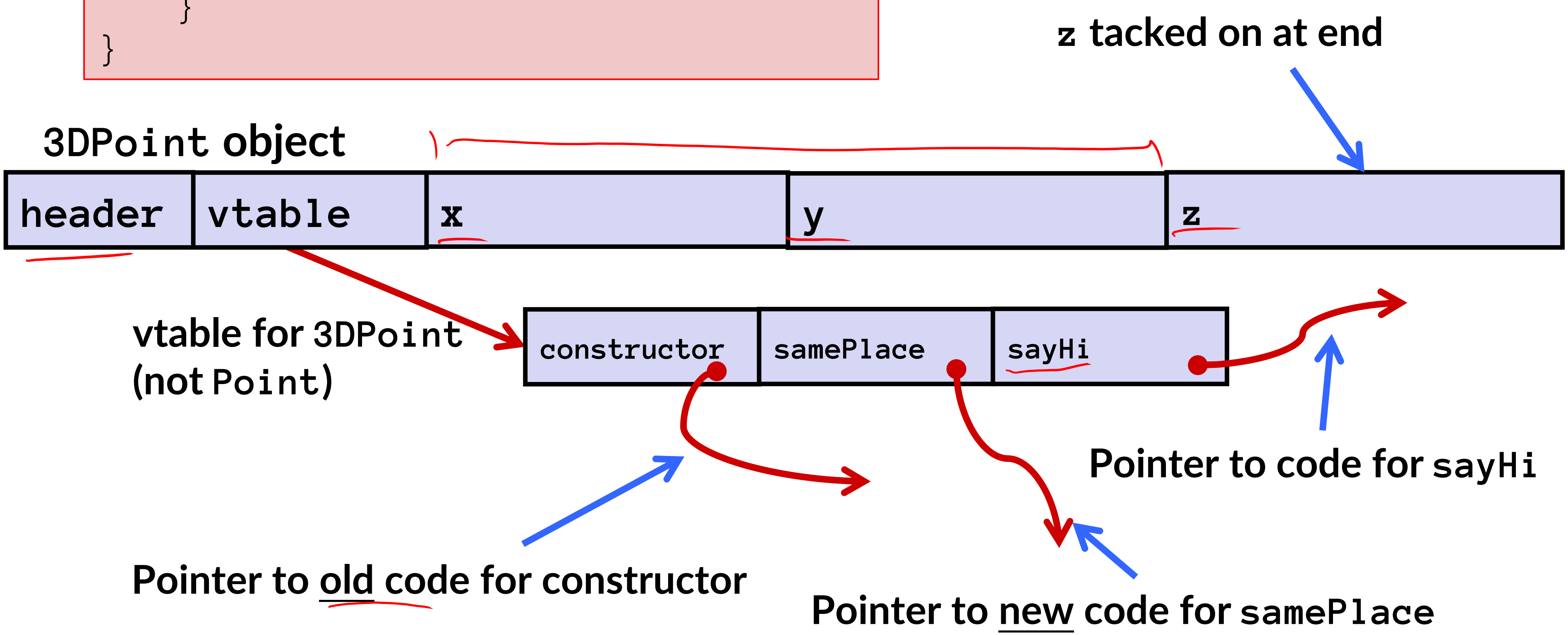
Subclassing

```
class 3DPoint extends Point {
    double z;
    boolean samePlace(Point p2) {
        return false;
    }
    void sayHi() {
        System.out.println("hello");
    }
}
```

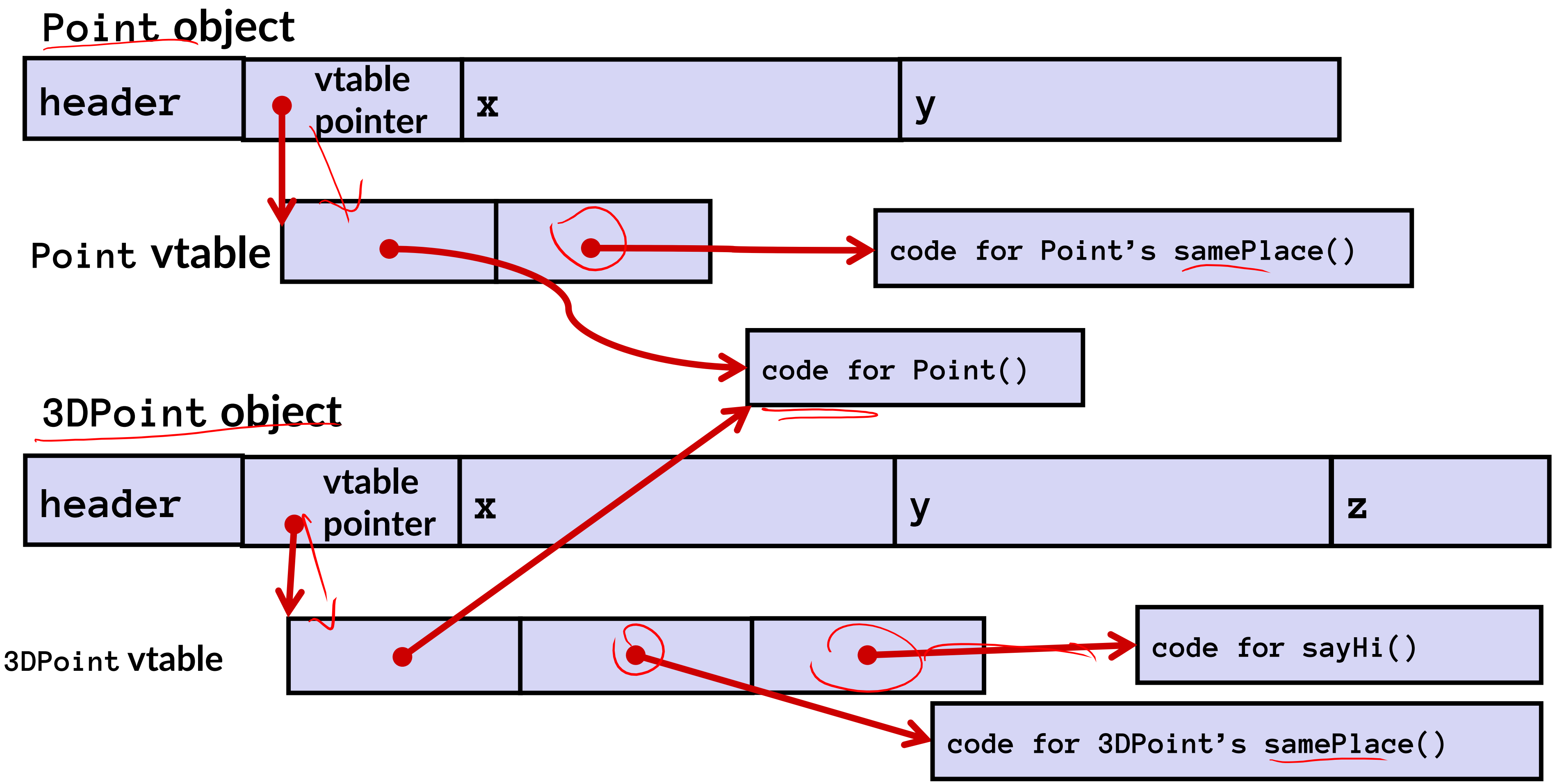
- **Where does "`z`" go? At end of fields of `Point`**
  - `Point` fields are always in the same place, so `Point` code can run on `3DPoint` objects without modification
- **Where does pointer to code for two new methods go?**
  - No constructor, so use default `Point` constructor
  - To override "`samePlace`", use same vtable position
  - Add new pointer at end of table for new method "`sayHi`"

Subclassing

```
class 3DPoint 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->vtable[1](p, q);
```

That's the "magic"

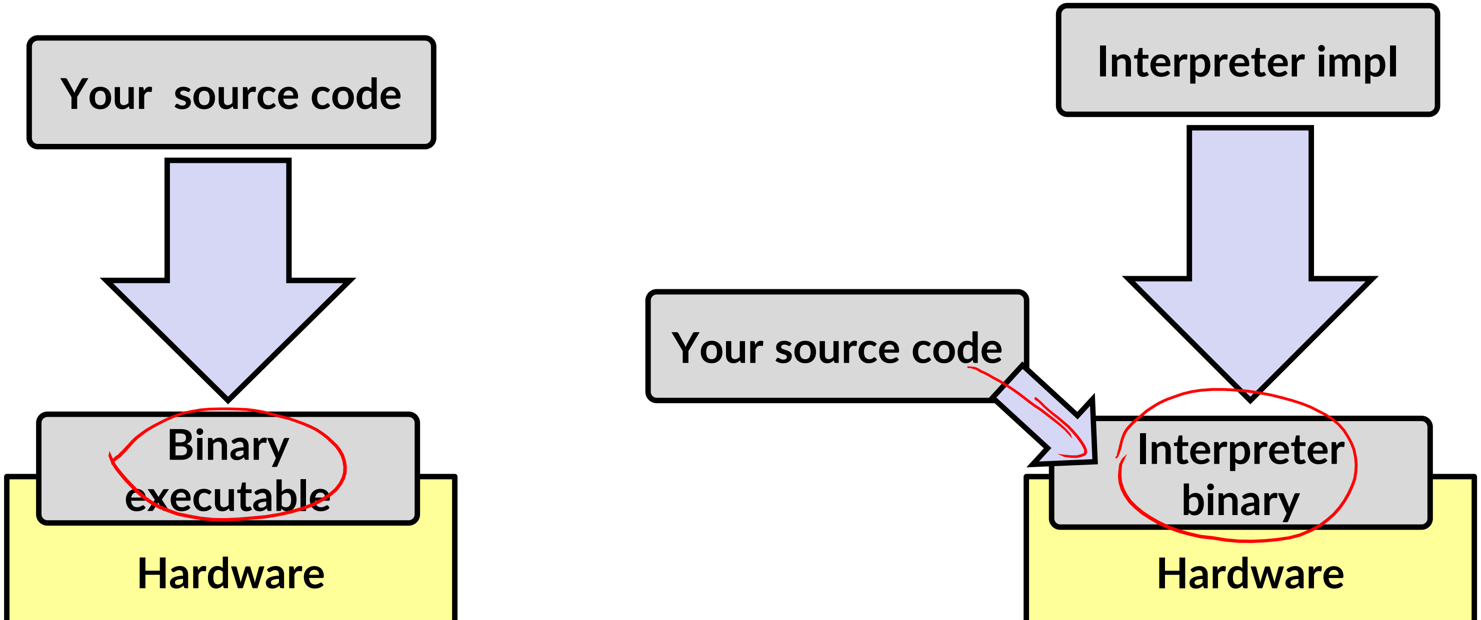
- In CSE143, it may have seemed "magic" that an *inherited* method could call an *overridden* method
  - You were tested on this endlessly ☺
- The "trick" in the implementation is this part:

```
p->vtable[i](p, q)
```

  - In the body of the pointed-to code, any calls to (other) methods of this will use `p->vtable`
  - Dispatch determined by `p`, not the class that defined a method

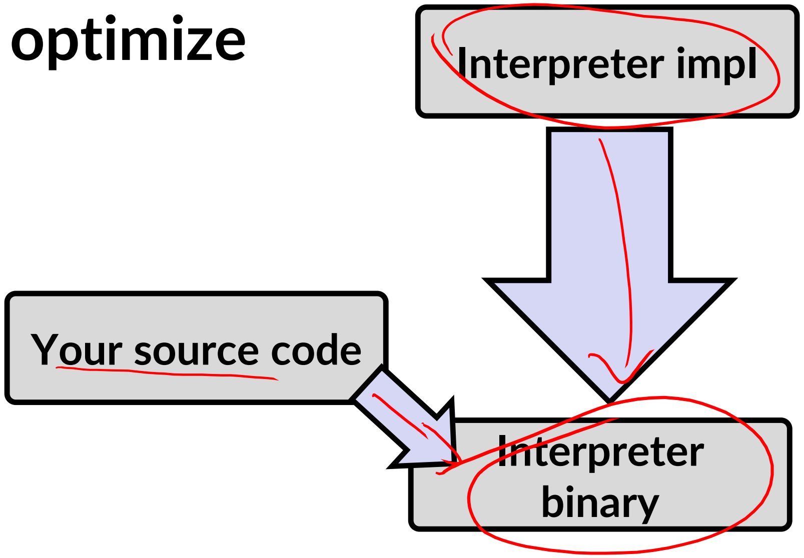
Implementing Programming Languages

- **Many choices in how to implement programming models**
- **We've talked about compilation, can also *interpret***
- **Interpreting languages has a long history**
  - Lisp, an early programming language, was interpreted
- **Interpreters are still in common use:**
  - Python, Javascript, Ruby, Matlab, PHP, Perl, …



An Interpreter is a Program

- **Execute the *source code* directly (or something close)**
- **Simpler/no compiler – less translation**
- **More transparent to debug – less translation**
- **Easier to run on different architectures – runs in a simulated environment that exists only inside the *interpreter* process**
  - Just port the interpreter
- **Slower and harder to optimize**



Interpreter vs. Compiler

- **An aspect of a language implementation**
  - A language can have multiple implementations
  - Some might be compilers and other interpreters
- **"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)
- **Also, as about to see, modern language implementations are often a mix of the two**
  - Compiling to a bytecode language, then interpreting
  - Doing just-in-time compilation of parts to assembly for performance

"The JVM"

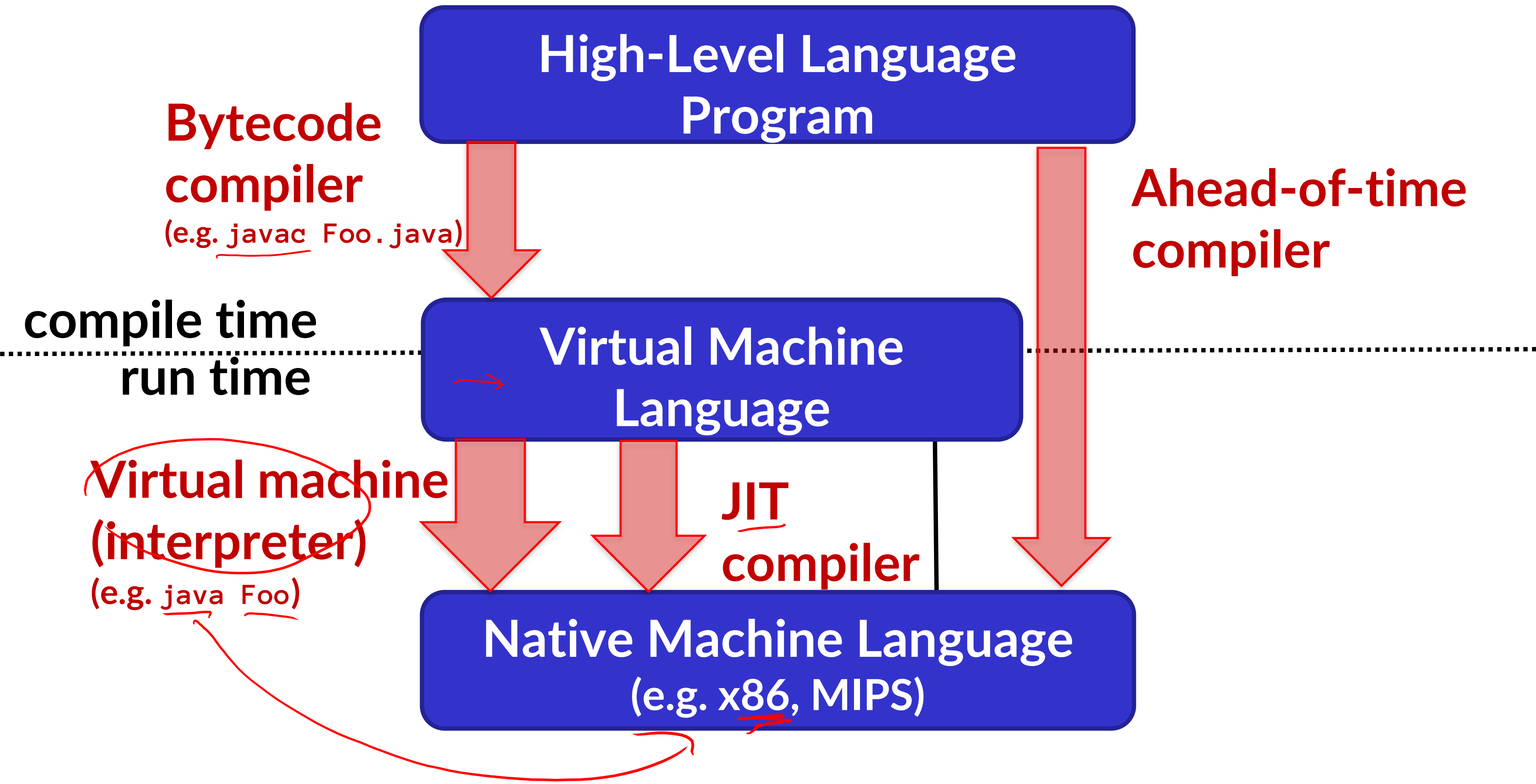
- **Java programs are usually run by a Java *virtual machine (JVM)***
  - JVMs interpret an intermediate language called *Java bytecode*
  - Many JVMs compile bytecode to native machine code
    - ***just-in-time (JIT) compilation***
  - Java is sometimes compiled ahead of time (AOT) like C

Compiling and Running Java

- The Java compiler converts Java into **Java bytecodes**
- **Java bytecodes** are stored in a .class file
- To run the Java compiler:
  - `javac Foo.java`
- To execute the program stored in the bytecodes, Java bytecodes can be interpreted by a program (an interpreter)
- For Java, this interpreter is called the Java Virtual Machine
- To run the Java virtual machine:
  - `java Foo`
  - This loads the contents of `Foo.class` and interprets the bytecodes

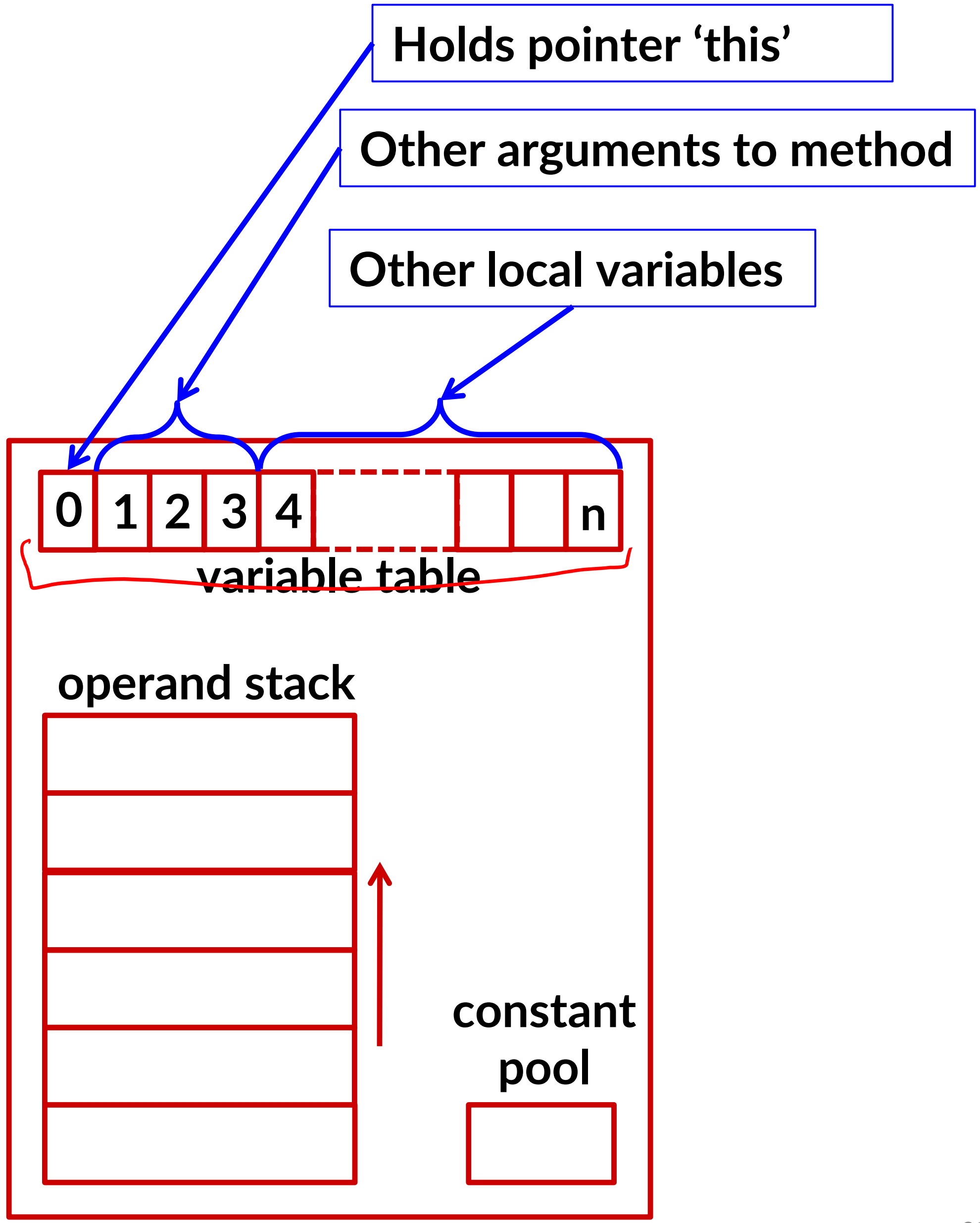
Note: The Java virtual machine is different than the CSE VM running on VMWare. *Another* use of the word "virtual"!

Virtual Machine Model



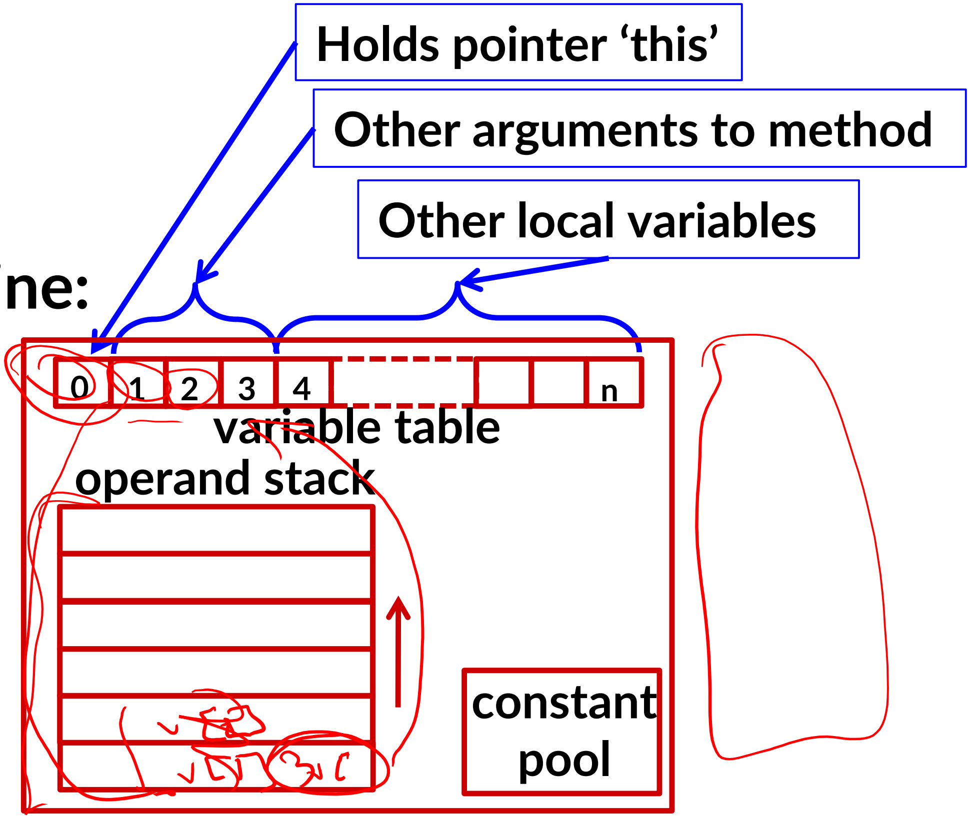
Java bytecode

- like assembly code for JVM, but works on *all* JVMs: hardware-independent
- typed (unlike x86 assembly)
- strong JVM protections



JVM Operand Stack

machine:



'i' stands for integer,
'a' for 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 x86:

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

A Simple Java Method

```
Method java.lang.String getEmployeeName()

0 aload 0        // "this" object is stored at 0 in the var table

1 getfield #5 <Field java.lang.String name> // takes 3 bytes
                 // pop an element from top of stack, retrieve its
                   // specified instance field and push it onto stack.
                   // "name" field is the fifth field of the object

4 areturn        // Returns object at top of stack
```

0	1			4
aload_0	getfield	00	05	areturn

In the .class file:

2A	B4	00	05	B0

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

Class File Format

- **Every class in Java source code is compiled to its own class file**
- **10 sections in the Java class file structure:**
  - **Magic number**: 0xCAFEBABE (legible hex from James Gosling – Java's inventor)
  - **Version of class file format**: the minor and major versions of the class file
  - **Constant pool**: set of constant values for the class
  - **Access flags**: for example whether the class is abstract, static, final, etc.
  - **This class**: The name of the current class
  - **Super class**: The name of the super class
  - **Interfaces**: Any interfaces in the class
  - **Fields**: Any fields in the class
  - **Methods**: Any methods in the class
  - **Attributes**: Any attributes of the class (for example, name of source file, etc.)
- **A *.jar* file collects together all of the class files needed for the program, plus any additional resources (e.g. images)**

Disassembled Java Bytecode

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

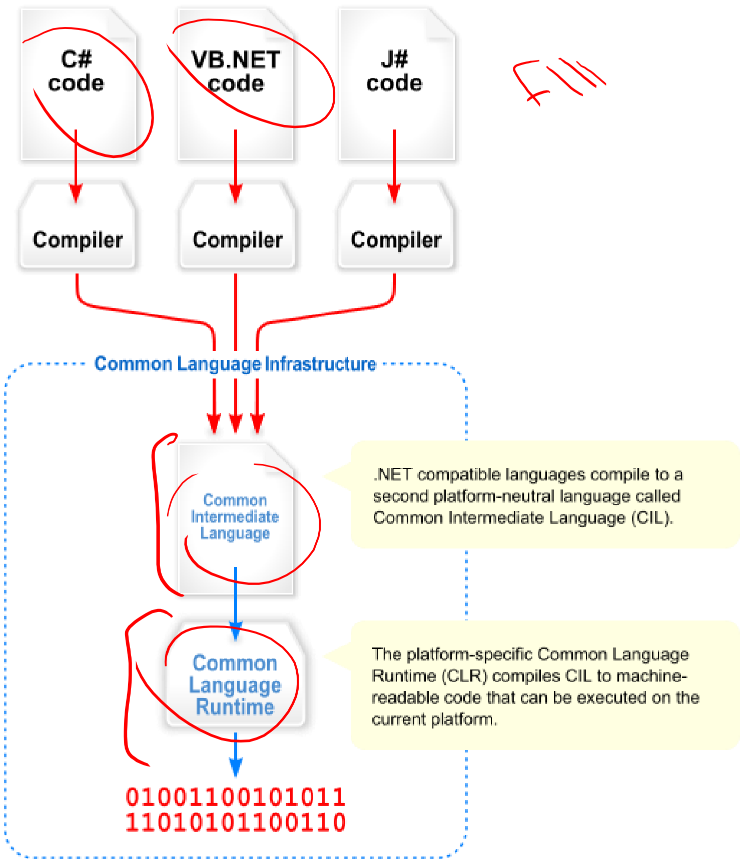
```
Compiled from Employee.java
class Employee extends java.lang.Object {
  public Employee(java.lang.String,int);
  public java.lang.String getEmployeeName();
  public int getEmployeeNumber();
}

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!

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! ☺

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:

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