Roadmap

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:

- Data & addressing
- Integers & floats
- Machine code & C
- x86 assembly programming
- 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
  - 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

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
- **Null is typically represented as 0**
- **Characters and strings**
- **Arrays**
- **Objects**

Data in Java

- **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

the string ‘CSE351’:

C: ASCII	43	53	45	33	35	31	\0

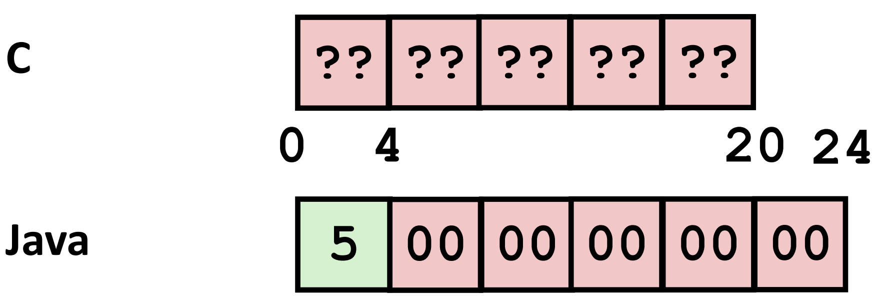
0 1 4 7 16

Java: Unicode	6	00	43	00	53	00	45	00	33	00	35	00	31

Data in Java

- **Arrays**
  - Every element initialized to 0
  - Bounds specified in hidden fields at start of array (int – 4 bytes)
    - *array.length* returns value of this field
    - *Hmm, since it has this info, what can it do?*

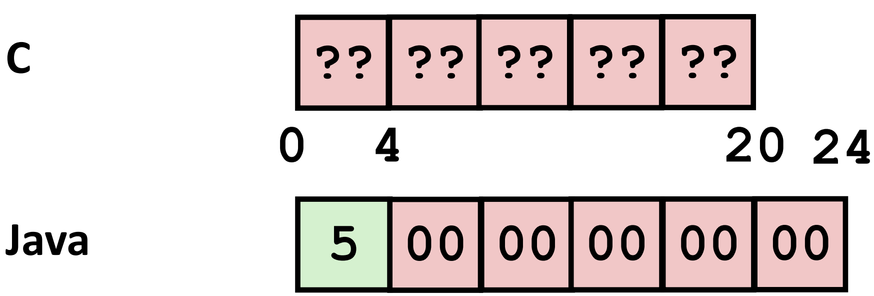
int array[5]:



Data in Java

- **Arrays**
  - Every element initialized to 0
  - Bounds specified in hidden fields 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]:



Data structures (objects) in Java

- **Objects (structs) can only include primitive data types**
  - Include complex data types (arrays, other objects, etc.) using *references*

C

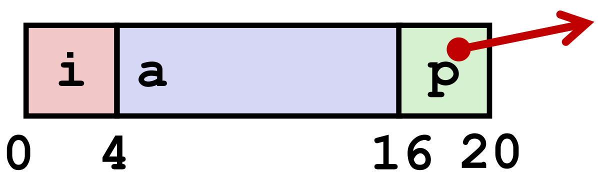
```
struct rec {
  int i;
  int a[3];
  struct rec *p;
};
```

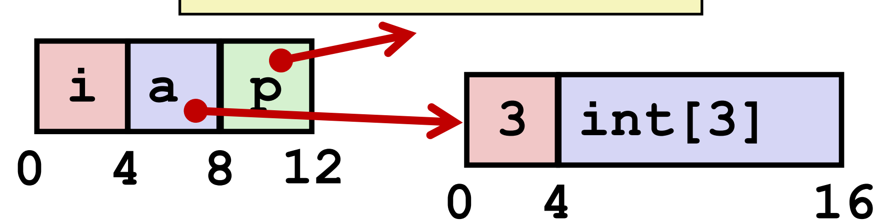
Java

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

```
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;
```



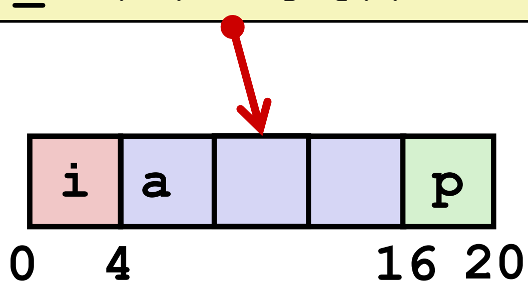


Pointers/References

- **Pointers in C can point to any memory address**
- **References in Java can only point to an object**
  - And only to its first element – not to the middle of it

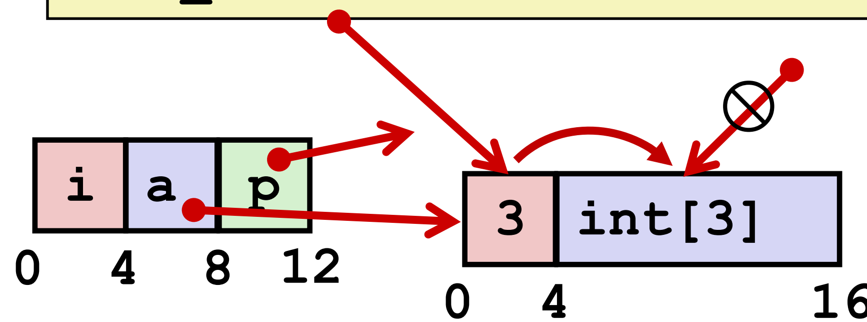
C

```
struct rec {
   int i;
   int a[3];
   struct rec *p;
};
some_fn(&(r.a[1]))  //ptr
```



Java

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



Pointers to fields

- **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 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

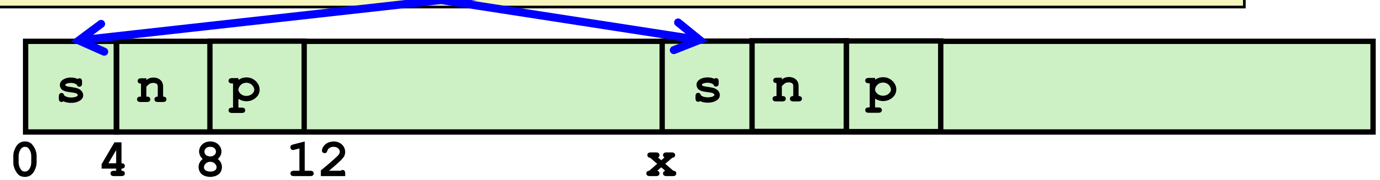
Casting in C

- We can cast any pointer into any other pointer

```
struct BlockInfo {
        int 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



Casting in Java

- **Can only cast compatible object references**

```
class Object{
  …
};
```

```
class Parent {
  int address;
};
```

```
class Sister extends Parent{
  int hers;
};
```

```
class Brother extends Parent{
  int his;
};
```

```
// Parent is a super class of Brother and Sister, which are siblings
Parent    a = new Parent();
Sister   xx = new Sister();
Brother  xy = new Brother();
Parent   p1 = new Sister();          // ok, everything needed for Parent
                                     // is also in Sister
Parent   p2 = p1;                    // ok, p1 is already a Parent
Sister  xx2 = new Brother();         // incompatible type – Brother and
                                     // Sisters are siblings
Sister  xx3 = new Parent();          // wrong direction; elements in Sister
                                     // not in Parent (hers)
Brother xy2 = (Brother) a;           // run-time error; Parent does not contain
                                     // all elements in Brother (his)
Sister  xx4 = (Sister) p2;           // ok, p2 started out as Sister
Sister  xx5 = (Sister) xy;           // inconvertible types, xy is Brother
```

How is this implemented / enforced?

Creating objects in Java

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

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

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

}
…
Point newPoint = new Point();
…
```

fields

constructor

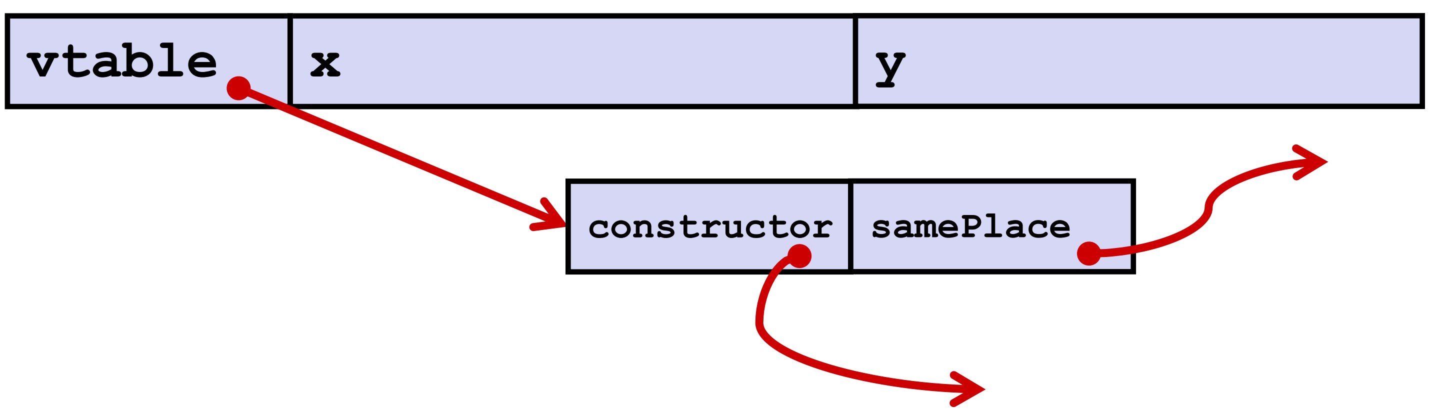
method

creation

Creating objects in Java

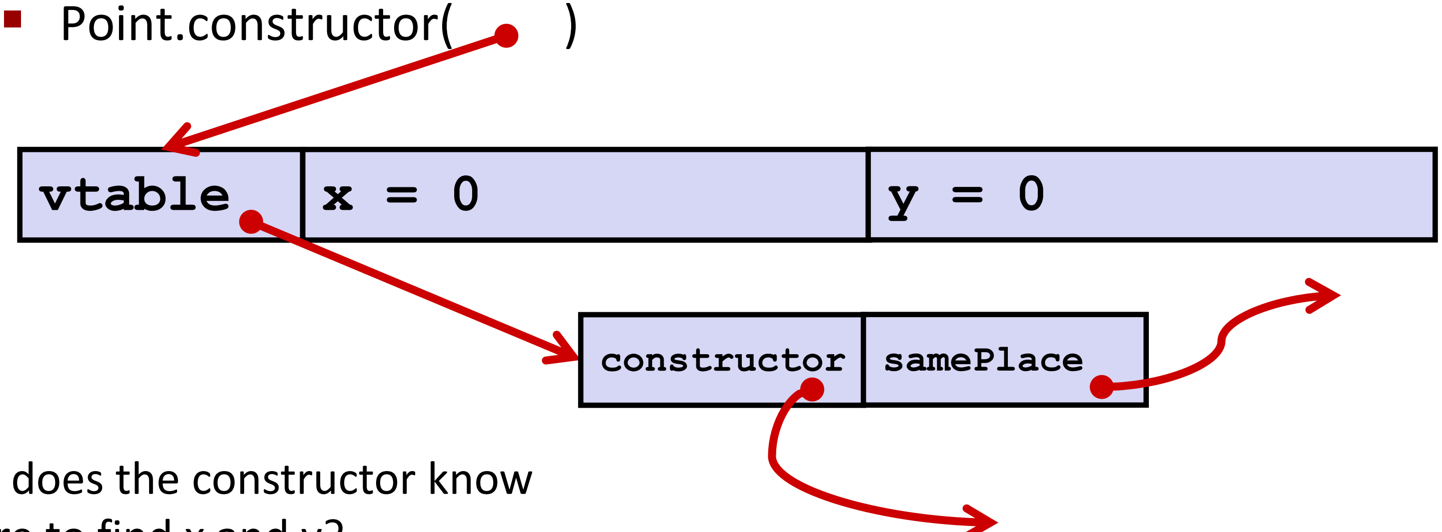
- **“new”**
  - Allocates space for data fields
  - Adds pointer in object to “virtual table” or “vtable” for class
    - vtable is shared across all objects in the class!
    - Includes space for “static fields” and pointers to methods’ code
  - Returns reference (pointer) to new object in memory
  - Runs “constructor” method
- **The new object is eventually garbage collected if all references to it are discarded**

Point object:



Initialization

- newPoint's fields are initialized starting with the vtable pointer to the vtable for this class
- The next step is to call the 'constructor' for this object type
- Constructor code is found using the 'vtable pointer' and passed a pointer to the newly allocated memory area for newPoint so that the constructor can set its x and y to 0
  - Point.constructor( )



How does the constructor know where to find x and y?

Java Methods

- **Methods in Java are just functions (as in C) but with an extra argument: a reference to the object whose method is being called**
  - E.g., newPoint.samePlace calls the samePlace method with a pointer to newPoint (called ‘this’) and a pointer to the argument, p – in this case, both of these are pointers to objects of type Point
  - Method becomes Point.samePlace(Point this, Point p)
    - return x==p.x && y==p.y;   becomes something like:
      return (this->x==p->x) && (this->y==p->y);

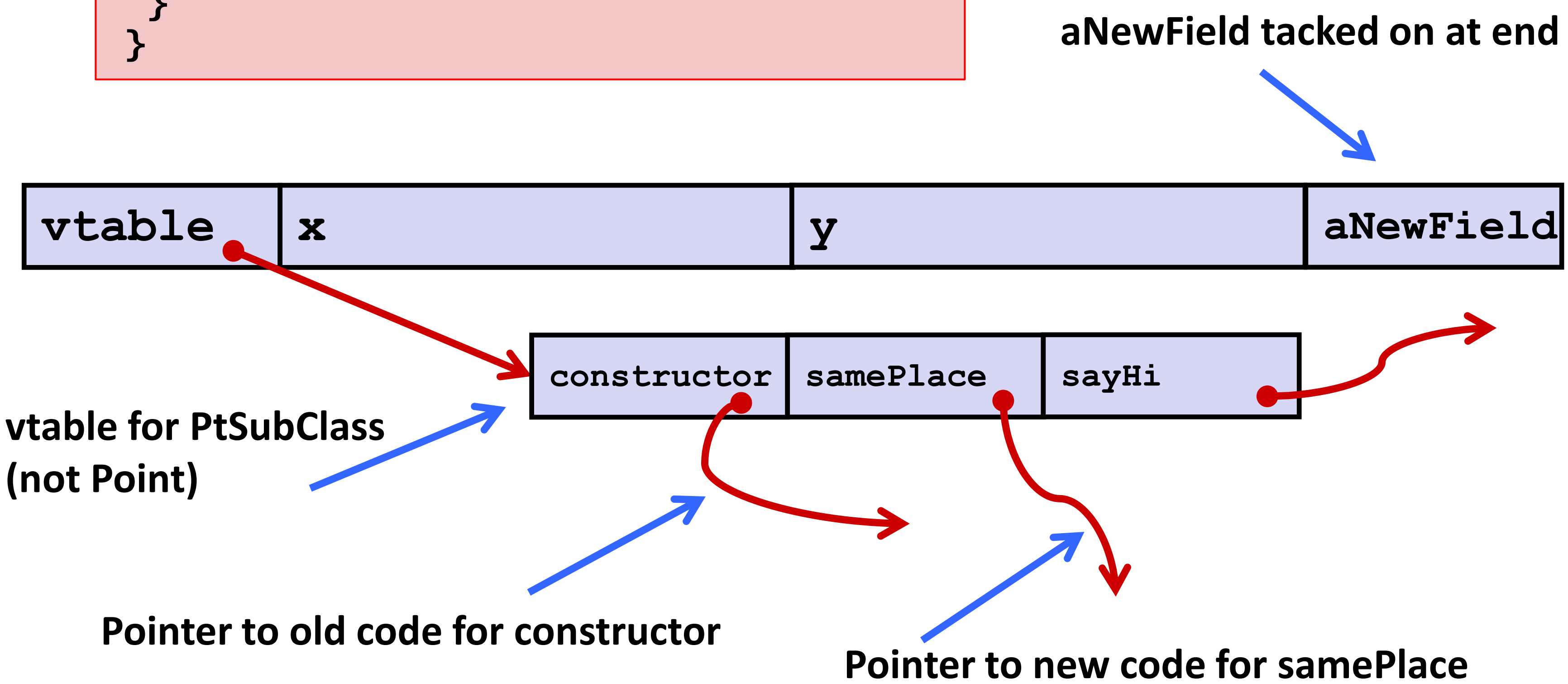
Subclassing

```
class PtSubClass extends Point{
   int aNewField;
   boolean samePlace(Point p2) {
       return false;
   }
   void sayHi() {
      System.out.println("hello");
   }
 }
```

- **Where does "aNewField" go?**
  - At end of fields of Point – allows easy casting from subclass to parent class!
- **Where does pointer to code for two new methods go?**
  - To override "samePlace", write over old pointer
  - Add new pointer at end of table for new method "sayHi"

Subclassing

```
class PtSubClass extends Point{
   int aNewField;
   boolean samePlace(Point p2) {
       return false;
   }
   void sayHi() {
      System.out.println("hello");
   }
 }
```

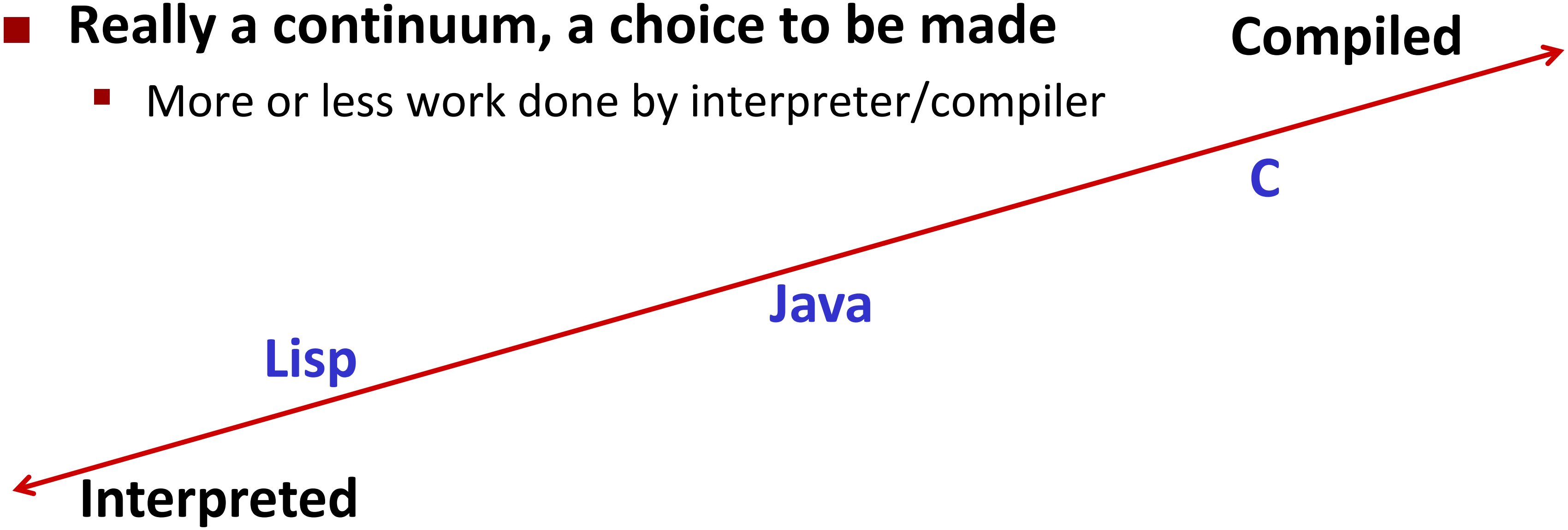


Implementing Programming Languages

- **Many choices in how to implement programming models**
- **We've talked about compilation, can also *interpret***
  - Execute line by line in original source code
  - Less work for compiler – all work done at run-time
  - Easier to debug – less translation
  - Easier to run on different architectures – runs in a simulated environment that exists only inside the *interpreter* process
- **Interpreting languages has a long history**
  - Lisp – one of the first programming languages, was interpreted
- **Interpreted implementations are very much with us today**
  - Python, Javascript, Ruby, Matlab, PHP, Perl, …

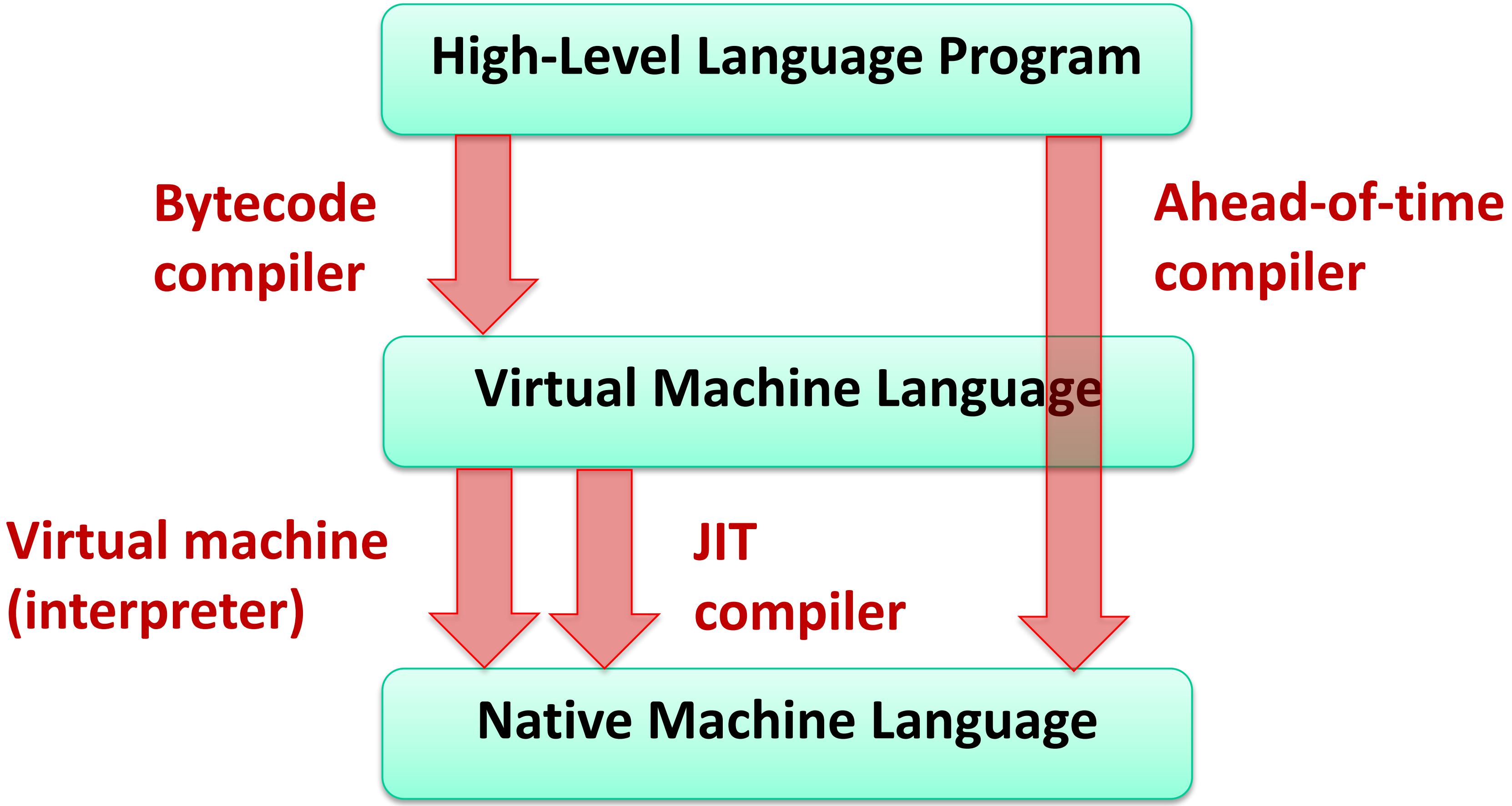
Interpreted vs. Compiled

- **Really a continuum, a choice to be made**
  - More or less work done by interpreter/compiler



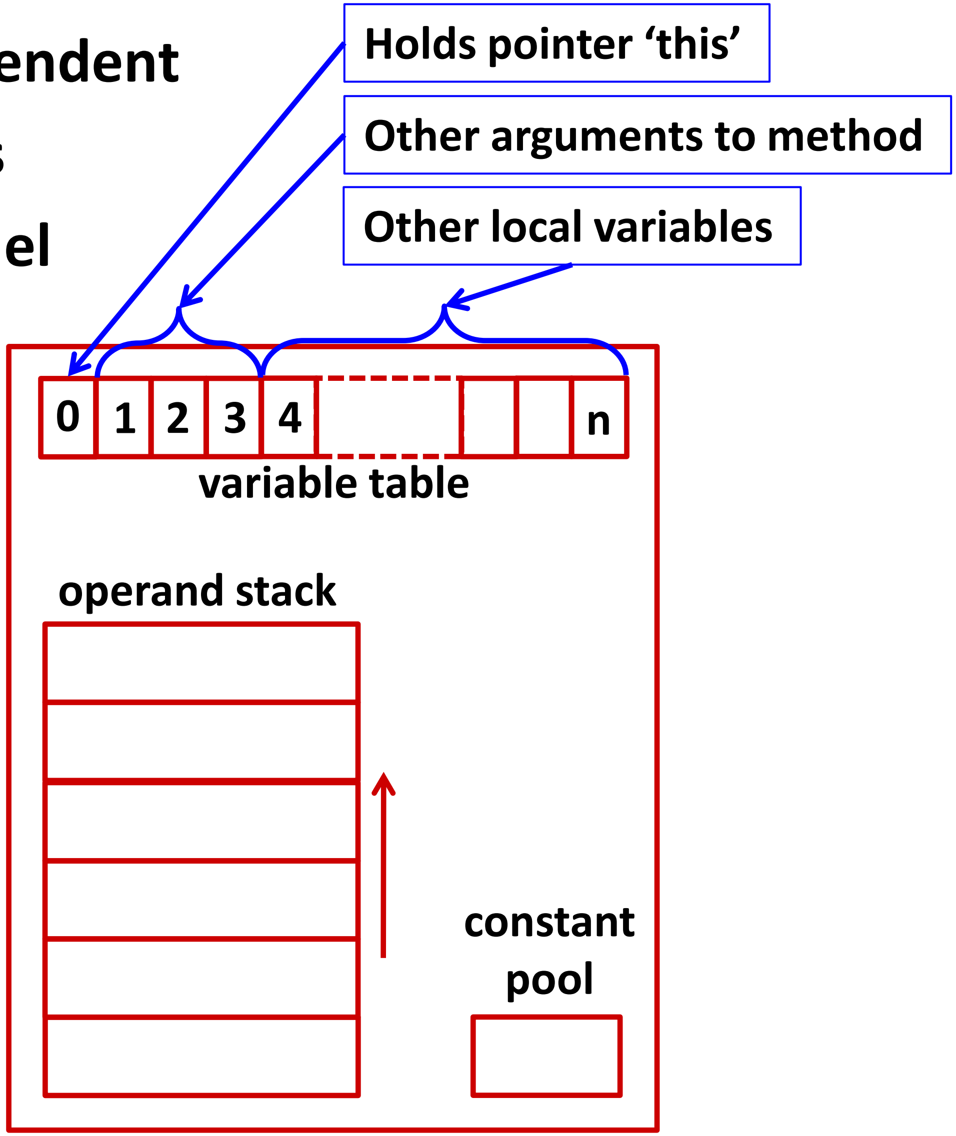
- **Java programs are usually run by a *virtual machine***
  - VMs interpret an intermediate, "partly compiled" language called *bytecode*
- **Java can also be compiled ahead of time (just as a C program is) or at runtime by a *just-in-time (JIT) compiler***

Virtual Machine Model



Java Virtual Machine

- Makes Java machine-independent
- Provides strong protections
- Stack-based execution model
- There are many JVMs
  - Some interpret
  - Some compile into assembly
  - Usually implemented in C



JVM Operand Stack Example

‘i’ stands for integer,
‘a’ for reference,
‘b’ for byte,
‘c’ for char,
‘d’ for double, …

No knowledge of registers or memory locations (each instruction is 1 byte – 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
```

```
mov 0x8001, %eax
mov 0x8002, %edx
add %edx, %eax
mov %eax, 0x8003
```

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 field and push the value onto stack.
                      // "name" field is the fifth field of the class

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, 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 the name of the 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 > Employee.bc
```

```
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 targeting the Rich Internet Application domain
  - 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