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
```

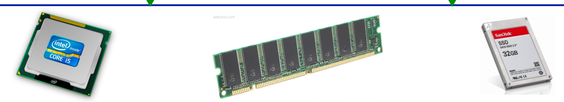
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 8 Mac

Computer system:



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**
  - just like caching, etc.

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

- **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	??	??	??	??	??	
	0	4			20	24
Java	5	00	00	00	00	00

Data in Java

- **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	??	??	??	??	??	
	0	4			20	24
Java	5	00	00	00	00	00

Bounds-checking sounds slow, but:

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

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 structures (objects) in Java

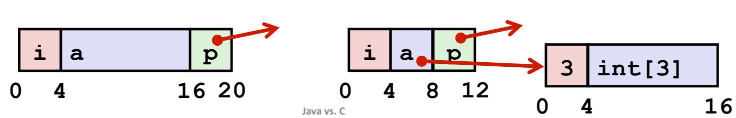
- **Objects are always stored by reference, never stored inline.**
  - Include complex data types (arrays, other objects, etc.) using *references*

C

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

Java

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



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

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

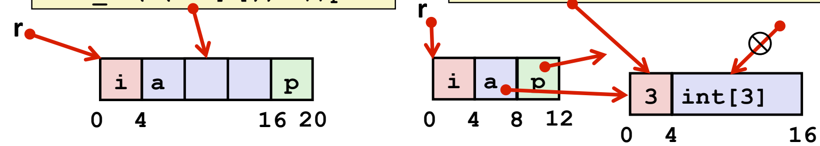
```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```


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 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
```



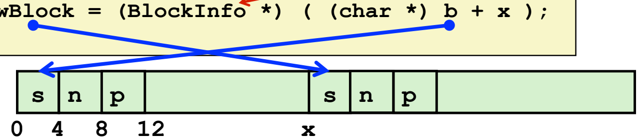
Casting in C (example from Lab 5)

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

```
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



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 already a Vehicle
Car      c2 = new Boat();      // incompatible type – Boat and
                               // Car are siblings
Car      c3 = new Vehicle();   // 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 started out as Car
Car      c5 = (Car) b1;        // incompatible types, b1 is Boat
```

Why are these problematic?

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();
…
```

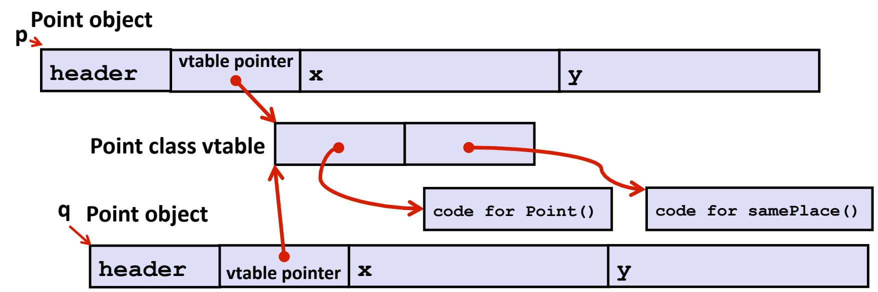
fields

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
- ***header* : GC info, hashing info, lock info, etc.**
  - no size – why?
- ***new* : allocate space for object; zero/null fields; run constructor**
  - compiler actually resolves constructor like a static method

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.**

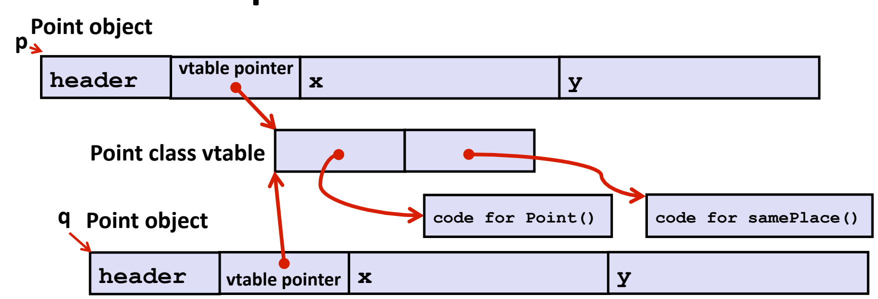
Java:

```
Point p = new Point();

return p.samePlace(q);
```

C pseudo-translation:

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

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


Method dispatch



Java:

```
Point p = new Point();

return p.samePlace(q);
```

C pseudo-translation:

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

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

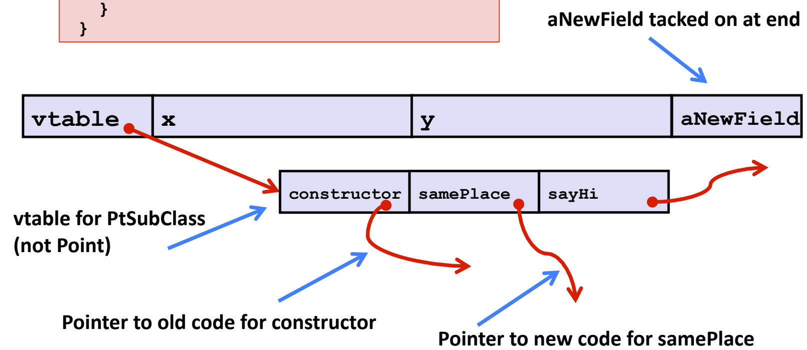
Subclassing

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

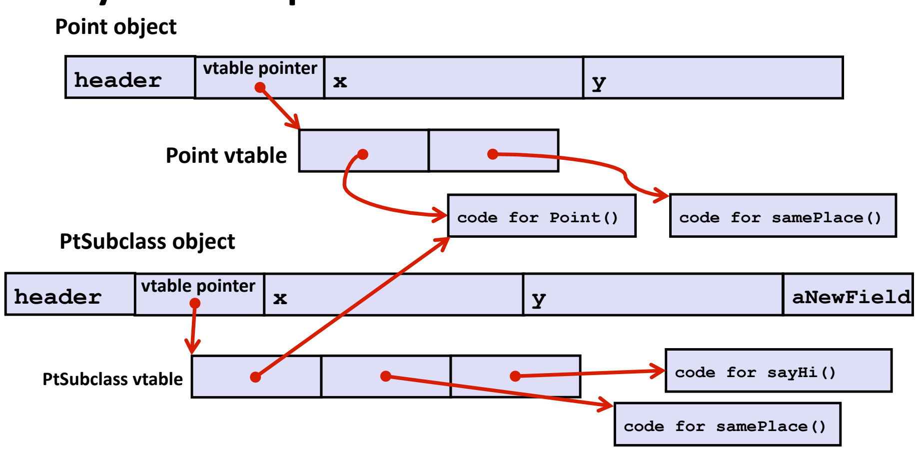
- **Where does "aNewField" go? At end of fields of Point**
  - Point fields are always in the same place, so Point code can run on PtSubClass objects without modification.
- **Where does pointer to code for two new methods go?**
  - No constructor, so use default Point constructor
  - To override "samePlace",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



Dynamic dispatch



Java:

```
Point p = ???;
return p.samePlace(q);
```

C pseudo-translation:

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


Agenda

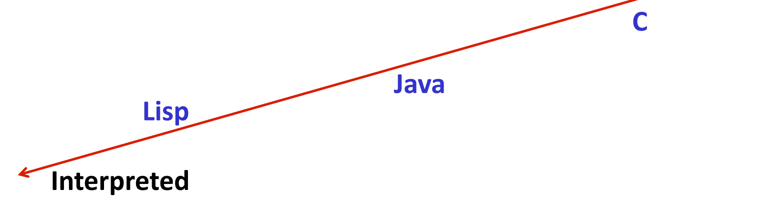
- **Inside**
- **HW4 grades/feedback are up**
- **Lab 5 due tonight! Go, go, go!**
  - If I'm not in the office today, I might be in the basement labs
- **Tomorrow: Review Session**
  - bring your own questions
- **Final exam topics/materials**
  - See past exams (website)
  - See topic manifest (website: last Friday's slides)
- **Today**
  - Finish up Java
  - Brief tour of Parallel Processing
  - 351 Conclusions :(

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
  - 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
  - Slower and harder to optimize
  - All errors at run time
- **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, …

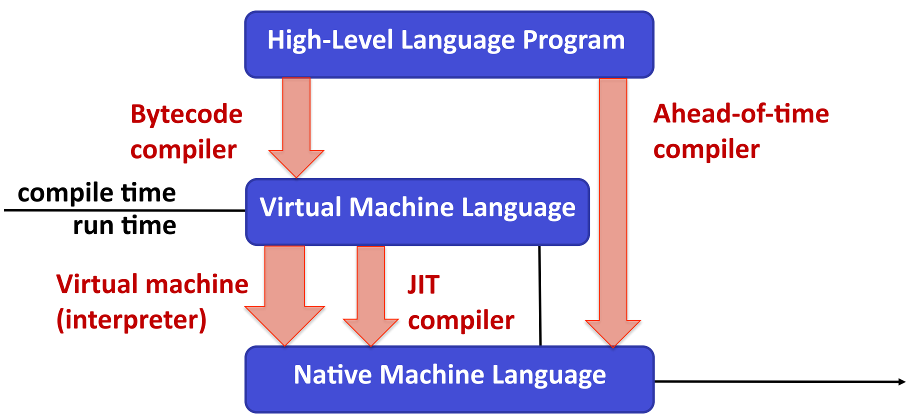
Interpreted vs. Compiled in practice

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



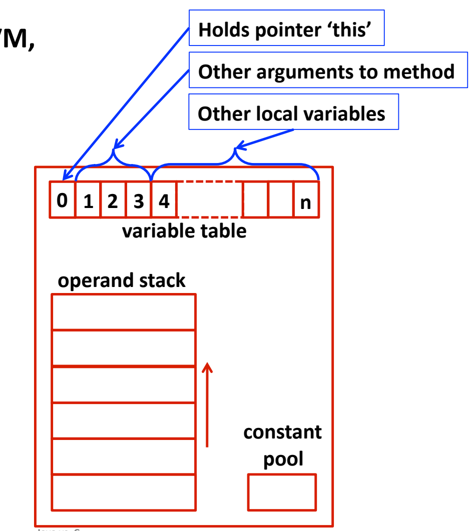
- **Java programs are usually run by a *virtual machine***
  - JVMs interpret an intermediate language called *Java bytecode*
  - Many JVMs compile bytecode to native machine code
    - ***just-in-time (JIT) compilation***
  - Java is sometimes compiled ahead of time (AOT) like C

Virtual Machine Model



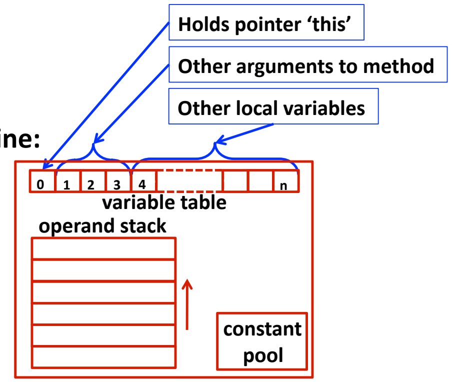
Java bytecode

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