Today

- **Reconnecting to Java – the last unit of the course**
  - Back to CSE143!
  - But now you know a lot more about what really happens when we execute programs
- **Java running native (compiled to C/assembly)**
  - Object representations: arrays, strings, etc.
  - Bounds checking
  - Memory allocation, constructors
  - Garbage collection
- **Java on a virtual machine**
  - Virtual processor
  - Another language: byte-codes

Meta-point to this lecture

- **None of this data representation we are going to talk about is *guaranteed* by Java**
- **In fact, the language simply provides an *abstraction***
- **We can't easily tell how things are really represented**
- **But once you understand lower levels of abstraction it is worth seeing the *most straightforward way* to implement Java's basic features since it may be useful in thinking about your program**
- **We'll be focusing on this "straightforward" implementation**

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**

University of Washington

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**
  - 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
    - Trap if out-of-bounds
  - Every element initialized to 0

int array[5]:

C	??	??	??	??	??	
	0	4			20	24
Java	5	00	00	00	00	00

Structure of an (object) array

- **In C, an array is a contiguous series of structs**
  - Accessed by index, pointer value incremented by size of object in array

```
struct pt { float x; float y; };
struct pt *array = (struct pt *) malloc (100 * sizeof(struct pt));
        …array[index]…
```

- **In Java, an array is a contiguous series of primitive objects**
  - Can be ints, doubles, references (pointers),
  - Accessed by index, pointer value incremented by size of element
  - Before access check "0 <= index < length" – throw bounds exception if not

```
class Pt { float x; float y; };
Pt[] array = new Pt[100];
for (i=0; i<100; i=i+1) { array[i] = new Pt(); }
        …array[index]…
```

- **Array of structs vs. array of references to objects**

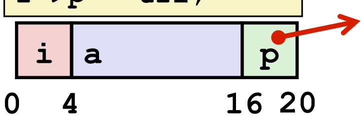
Data structures (objects) in Java

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

C

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

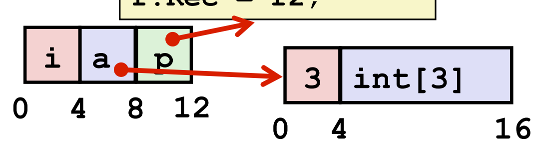
```
struct rec r;
struct rec r2;
r->i = val;
r->a[2] = val;
r->p = &r2;
```



Java

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

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

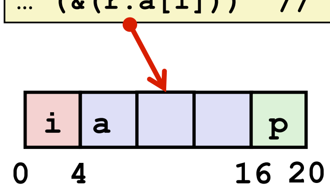


Pointers/References

- **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

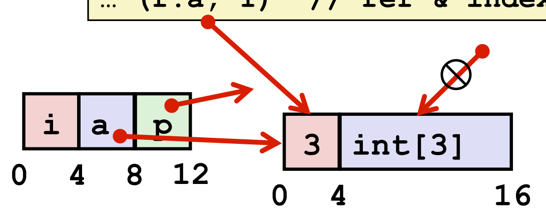
C

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



Java

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

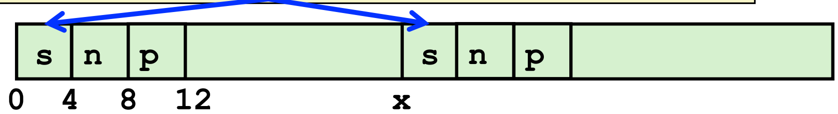
Casting in C

- **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 *p;
BlockInfo *newBlock;
…
newBlock = (BlockInfo *) ( (char *) p + x );
…
```

Cast p 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
```


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

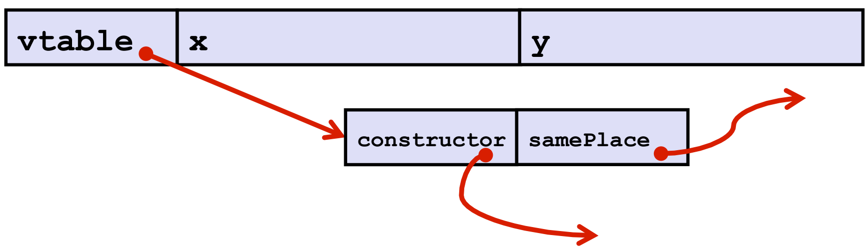
constructor

method

creation

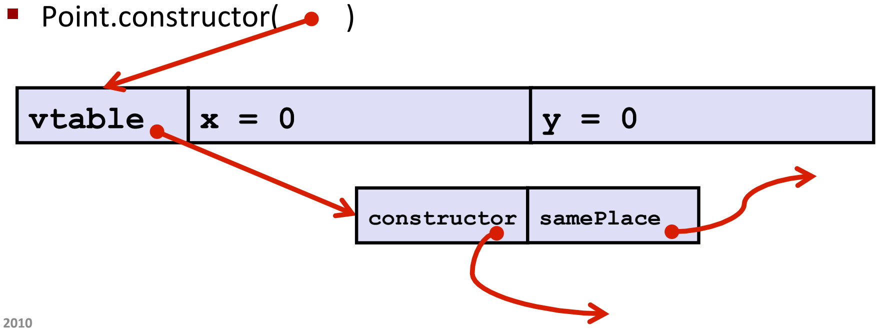
Creating objects in Java

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



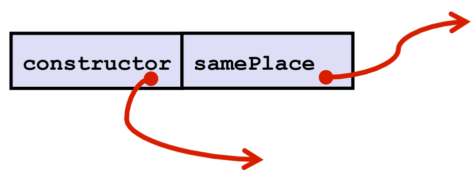
Initialization

- **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**
  - This can be resolved statically, so does’t require vtable lookup
  - Point.constructor(   )



What about the vtable itself?

- **Array of pointers to every method defined for the object Point**
- **Compiler decided in which element of the array to put each pointer and keeps track of which it puts where**
- **Methods are just C functions but with an extra argument – the pointer to the allocated memory for 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)



Calling a method

- **newPoint.samePlace(p2) is a call to the samePlace method of the object of type Point with the arguments newPoint and p2 which are both pointers to Point objects**
- **In C**
  - CodePtr = (newPoint->vtable)[theRightIndexForSamePlace]
    - Gets address of method’s code
  - CodePtr(this, p2)
    - Calls method with references to object and parameter
- **We need ‘this’ so that we can read the x and y of our object and execute**
  - return x==p.x && y==p.y; which becomes
  - return (this->x==p2->x) && (this->y==p2->y)

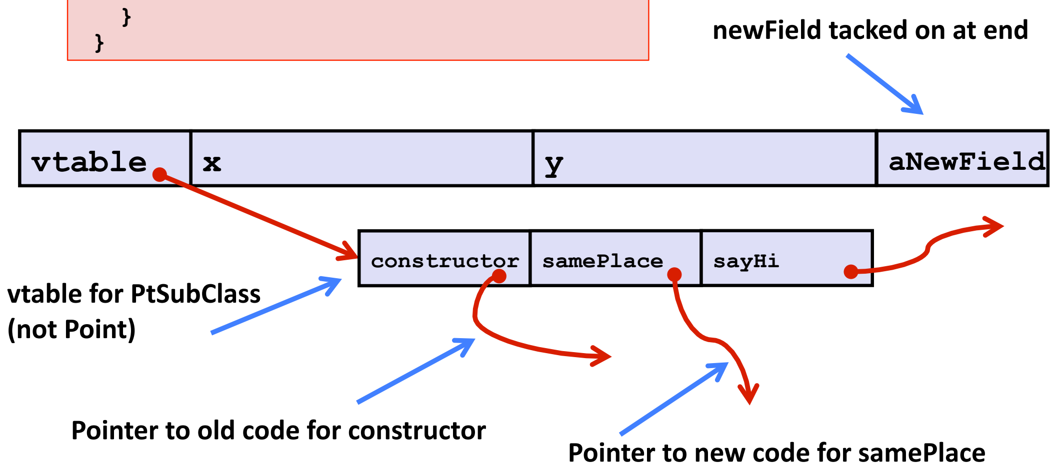
Subclassing

```
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
- **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”
  - This necessitates “dynamic” vtable

Subclassing

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



Some Java Optimizations

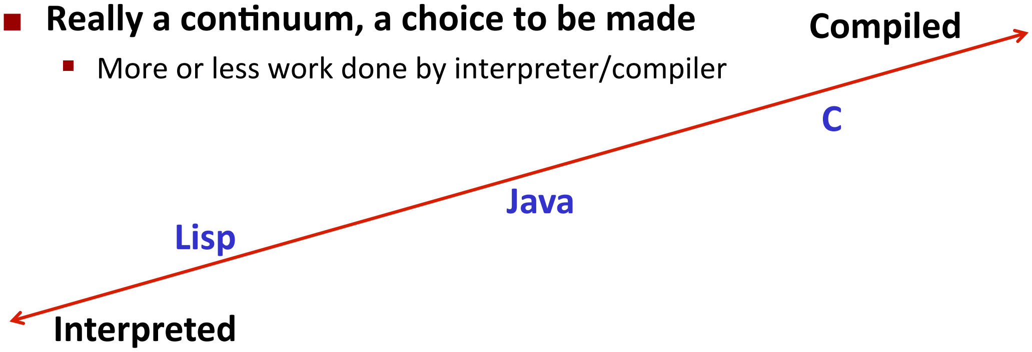
- **Don't have to do every check**
  - analyze the code or change representation
- **Don't check for null**
  - install handler for segmentation faults and then check if pointer was null in that code
- **Use vtable pointers to check runtime casts**
  - If objects point to same vtable, then they are the same type
  - Address of vtable serves as "run-time name for the class"

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 protect other processes – runs in an 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, …

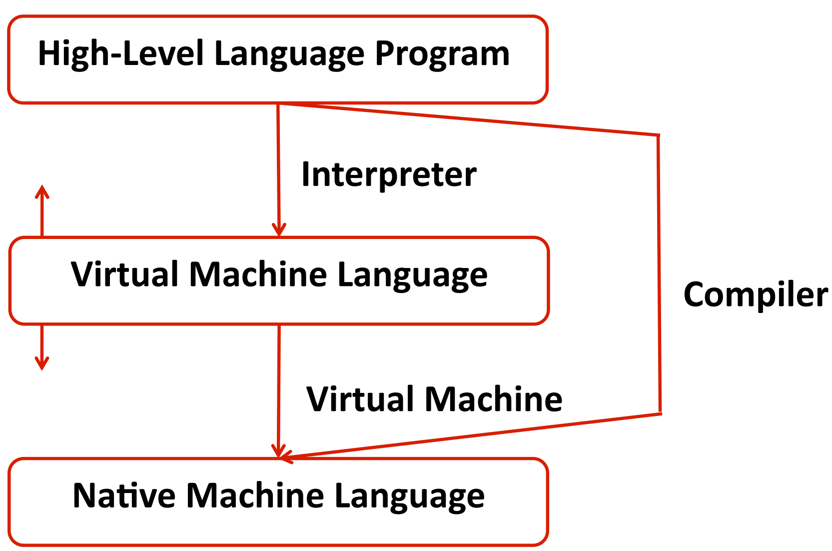
Interpreted vs. Compiled

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



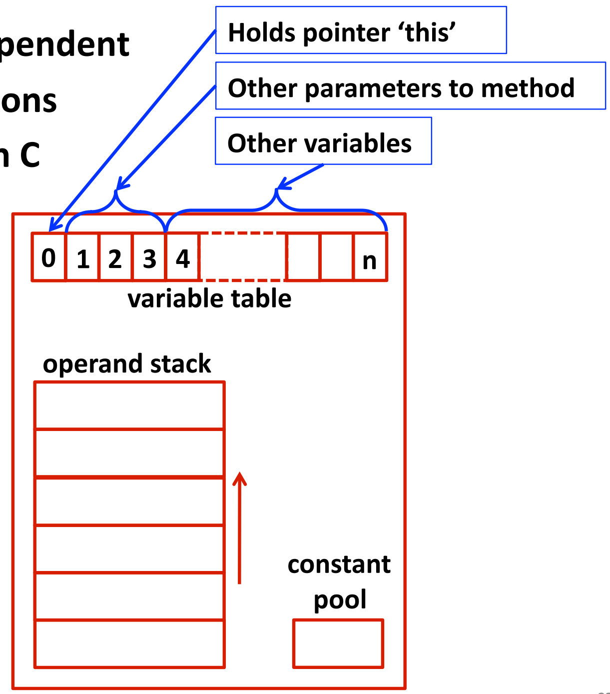
- **Java programs are usually run by a *virtual machine***
  - VMs interpret an intermediate language – partly compiled
- **Java can also be compiled (just as a C program is) or at run-time by a *just-in-time (JIT) compiler* (as opposed to an ahead-of-time (AOT) compiler)**

Virtual Machine Model



Java Virtual Machine

- Making Java machine-independent
- Providing stronger protections
- VM usually implemented in C
- Stack execution model
- There are many JVMs
  - Some interpret
  - Some compile into assembly



A Basic JVM 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 – byte-code)

```
iload 1     // push 1st argument from table onto stack
iload 2     // push 2nd argument from table onto stack
iadd        // add and pop top 2 element, push result
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 employeeName()

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 the
                 // 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

- **10 sections to 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: Pool of constants 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 sourcefile, etc)

Example

```
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 employeeName();
public int employeeNumber();
}

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 employeeName()
0 aload_0
1 getfield #5 <Field java.lang.String name>
4 areturn

Method int employeeNumber()
0 aload_0
1 getfield #4 <Field int idNumber>
4 ireturn

Method void storeData(java.lang.String, int)
…
```


Other languages for JVMs

- **Apart from the Java language itself, The most common or well-known JVM languages are:**
  - 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 (CLR)
- Common Intermediate Language (CLI) is C#'s byte-code