

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 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’:

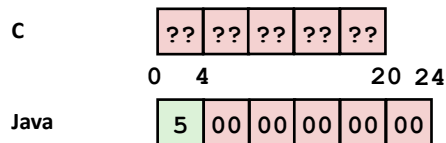
C: ASCII	43	53	45	33	35	31	\0										
	0	1		4			7										16
Java: Unicode	6		00	43	00	53	00	45	00	33	00	35	00	31			

Data in Java

■ Arrays

- 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]:



Structure of an 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

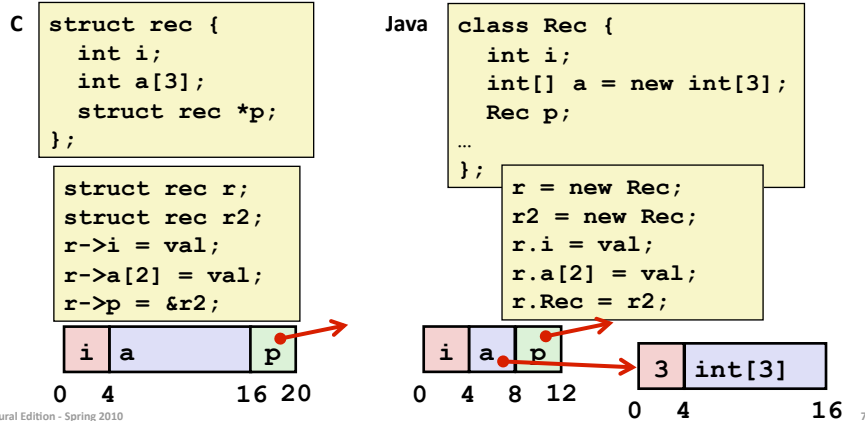
- Can be ints, doubles, references (pointers),
- Accessed by index, pointer value incremented by size of element
- Before access check “0 <= index < length” – throw bounds exception if not

```
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

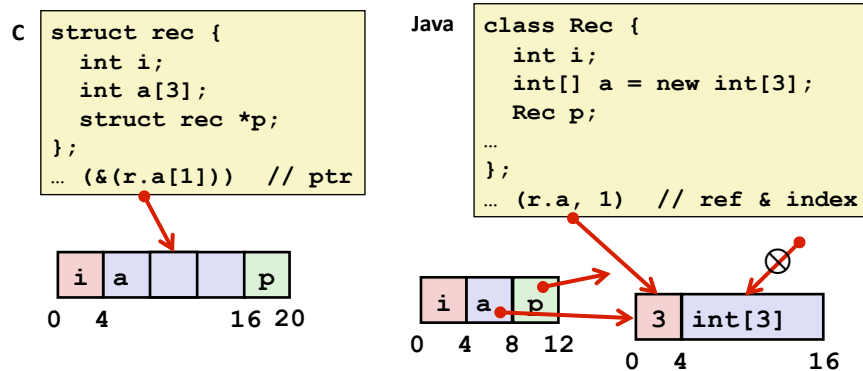
Data structures (objects) in Java

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



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



Pointers to fields

- In C, we have “->” and “.” depending on
 - (*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

Casting in C

- We can cast any pointer into any other pointer

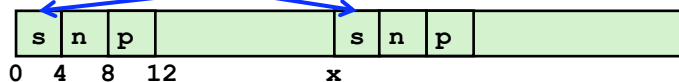
```

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 );
...

```

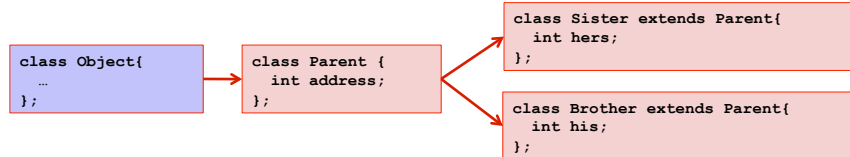
Cast p into char pointer so that you can add byte offset without scaling

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



Casting in Java

- Can only cast compatible object references



```

// 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; // ok, but run-time error when accessing
                          // what that is not in a Parent (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

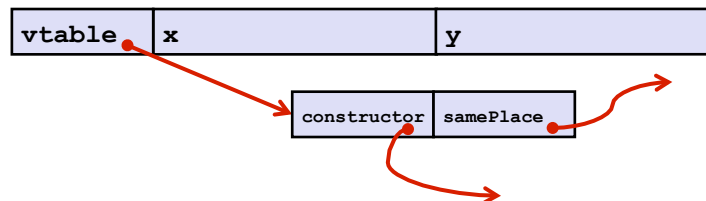
constructor

method

creation

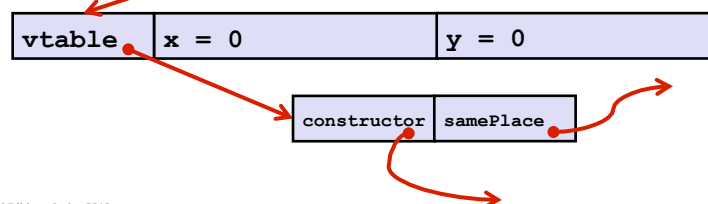
Creating objects in Java

- **“new”**
 - Allocates space for data fields
 - Adds pointer 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**



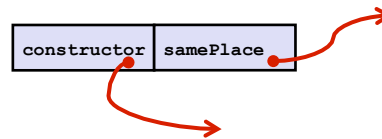
Initialization

- **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 doesn’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)`

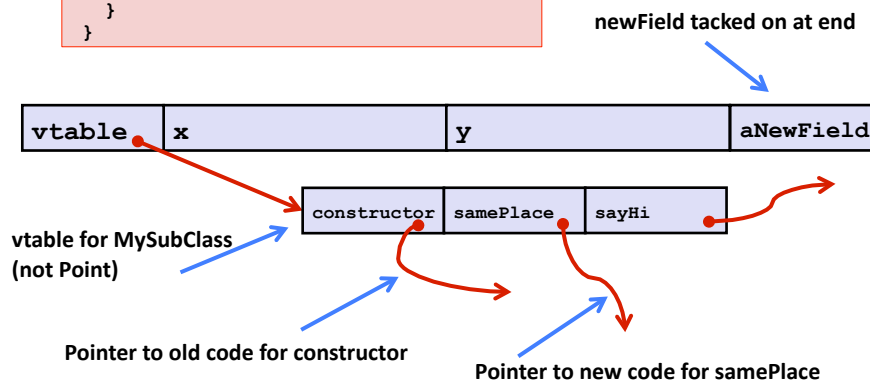
Subclassing

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



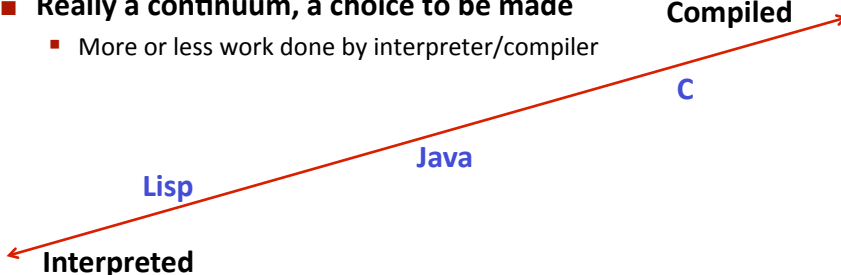
Some Java Optimizations

- **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

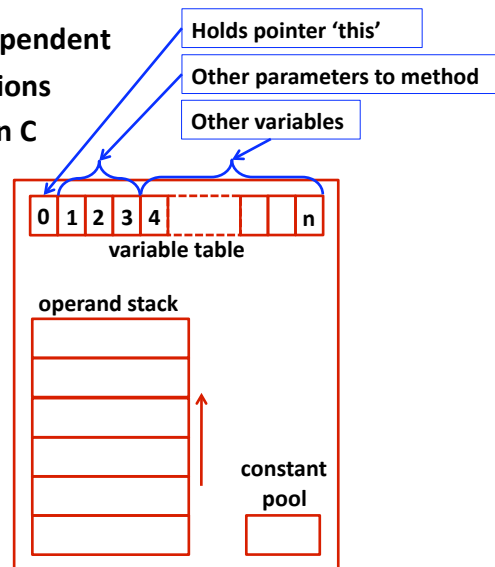
- **Many choices in how to implement programming models**
- **We've talked about compilation, can also *interpret***
 - Execute line by line in original source code
 - Less work for compiler – all work done at run-time
 - Easier to debug – less translation
 - Easier to protect other processes – runs 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)

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**

