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
1100000111110100001111

OS:
Windows 8
Mac

Computer system:

Java vs. C

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

Java vs. C

Autumn 2015
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

**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?*

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

<table>
<thead>
<tr>
<th>C</th>
<th>Java</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 4</td>
<td>5 00</td>
</tr>
<tr>
<td>20 24</td>
<td>00 00</td>
</tr>
</tbody>
</table>

Autumn 2015
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

```java
int array[5]; // C
int[] array = new int[5]; // 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.
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

```
0 1 4 7
43 53 45 33 35 31 \0
```

Java: Unicode

```
6 00 43 00 53 00 45 00 33 00 35 00 31
```

Java vs. C
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;
};
```

Example of array stored “inline”

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

Java vs. C
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(...);
```

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

**Java vs. C**
Casting in C (example from Lab 5)

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

```c
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

```java
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

```java
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 - Incovertible types,
    // b1 is declared as type Boat
```

How is this implemented/enforced?
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(); ...

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?)

- When we call “*new*”: allocate space for object; zero/null fields; run constructor
  - compiler actually resolves constructor like a static method

---

Point object

- header
- vtable pointer
- x
- y

Point class vtable

- code for `Point()`
- code for `samePlace()`

Point object

- header
- vtable pointer
- x
- y
Java Methods

- **Static** methods are just like functions.
- **Instance** methods
  - can refer to `this`;
  - have an implicit first parameter for `this`;
  - 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:

```java
Point p = new Point();
return p.samePlace(q);
```

C pseudo-translation:

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

---

**Subclassing**

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

PtSubclass object

<table>
<thead>
<tr>
<th>header</th>
<th>vtable</th>
<th>x</th>
<th>y</th>
<th>aNewField</th>
</tr>
</thead>
</table>

- **vtable for PtSubClass (not Point)**
- **Pointer to old code for constructor**
- **Pointer to new code for samePlace**
- **Pointer to code for sayHi**

aNewField tacked on at end
Dynamic dispatch

Point object

Java:
Point p = ???;
return p.samePlace(q);

C pseudo-translation:
// works regardless of what p is
return p->vtable[1](p, q);
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 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 (there is no compile time!)
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 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
Virtual Machine Model

High-Level Language Program (e.g. Java, C)

Virtual Machine Language (e.g. Java bytecodes)

Native Machine Language (e.g. x86, MIPS)

Bytecode compiler (e.g. javac Foo.java)

Virtual machine (interpreter) (e.g. java Foo)

JIT compiler

Ahead-of-time compiler

compile time
run time

Java vs. C
Java bytecode

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

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

No registers or stack locations; all operations use operand stack.

`i` stands for integer, `a` for reference, `b` for byte, `c` for char, `d` for double, ...

compiled to x86:

bytecode:

machine:

variable table

constant pool

Holds pointer ‘this’
Other arguments to method
Other local variables

iload 1  // push 1\textsuperscript{st} argument from table onto stack
iload 2  // push 2\textsuperscript{nd} 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

Java vs. C
A Simple Java Method

Method `java.lang.String getEmployeeName()`

```java
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
```

In the `.class` file: `2A B4 00 05 B0`

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: 0xCAFEBAEBE (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

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:

```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:

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

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

- Windows 8
- macOS
- Linux

Computer system:

- Intel Core i5
- RAM
- SSD