Java and C (condensed)
CSE 351 Autumn 2022

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http://xkcd.com/801/
Relevant Course Information

❖ hw26 due Wednesday (12/7)
❖ Lab 5 due Friday (12/9)

❖ Course evaluations now open
  ▪ See Ed Discussion post for links (separate for Lec and Sec)

❖ **Final Exam: 12/12-14**
  ▪ **Review Session:** Friday 12/9 on Zoom, 2 hours TBD
  ▪ Final review section on 12/8
  ▪ Will be structured similarly to the Midterm
Java vs. C

❖ Reconnecting to Java (hello, 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 including dynamic dispatch
The Hardware/Software Interface

- **Topic Group 1: Data**
  - Memory, Data, Integers, Floating Point, Arrays, Objects

- **Topic Group 2: Programs**
  - x86-64 Assembly, Procedures, Stacks, Executables

- **Topic Group 3: Scale & Coherence**
  - Caches, Processes, Virtual Memory, Memory Allocation

Apply more generally than just C!!!

Even more applications

Applications

Programming Languages & Libraries

Operating System

Hardware

Transistors, Gates, Digital Systems

Physics

These apply to execution regardless of source language
Worlds Colliding

❖ CSE351 has given you a “really different feeling” about what computers do and how programs execute

❖ We have occasionally contrasted to Java, but CSE143 may still feel like “a different world”
  ▪ It’s not – it’s just a higher-level of abstraction
  ▪ Connect these levels via how-one-could-implement-Java in 351 terms
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** (Java language specification).
  - Tells us how code should behave for different language constructs, but 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
  - “Pointers” are called “references” in Java, but are much more constrained than C’s general pointers
  - Java’s portability-guarantee fixes the sizes of all types
    - Example: `int` is 4 bytes in Java regardless of machine
  - No unsigned types to avoid conversion pitfalls
    - Added some useful methods in Java 8 (also use bigger signed types)

- `null` is typically represented as 0 but “you can’t tell”

- Much more interesting:
  - Arrays
  - Characters and strings
  - Objects
Data in Java: Arrays

- Every element initialized to 0 or null
- Length specified in immutable field at start of array (int: 4B)
  - `array.length` returns value of this field
- *Since it has this info, what can it do?*

C:
```c
int array[5];
```

Java:
```java
int[] array = new int[5];
```
Data in Java: Arrays

- Every element initialized to 0 or null
- Length specified in immutable field at start of array (int: 4B)
  - `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

C:
```
int array[5];
```

Java:
```
int[] array = new int[5];
```

To speed up bounds-checking:
- Length field is likely in cache
- Compiler may store length field in register for loops
- Compiler may prove that some checks are redundant
Data in Java: Characters & 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
❖ All String objects read-only (vs. StringBuffer)

Example: the string “CSE351”

C: (ASCII) | 43 53 45 33 35 31 \0 |
0 1 4 7

Java: (Unicode) | 6 43 00 53 00 45 00 33 00 35 00 31 00 |
0 4 8 16
Data in Java: Objects

- Data structures (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;
};
```

- `a[]` stored “inline” as part of `struct`

**Java:**

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

- `a` stored by reference in object
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 r→a in C
  - So no Java field needs more than 8 bytes

C:

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

Java:

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

- **Pointers** in C can point to any memory address
- **References** in Java can only point to [the starts of] objects
  - Can only be dereferenced to access a field or element of that object

### C:
```c
struct rec {  
  int i;  
  int a[3];  
  struct rec* p;
};
struct rec* r = malloc(...);
some_fn(&(r->a[1])); // ptr
```

### Java:
```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)

- Can cast any pointer into any other pointer
  - Changes dereference and arithmetic behavior

```c
struct block_info {
    size_t size_and_tags;
    struct block_info* next;
    struct block_info* prev;
};
typedef struct block_info block_info;
...
int x;
block_info* b;
block_info* new_block;
...
new_block = (block_info*) ( (char*) b + x );
...```

- Cast `b` into `char*` to do unscaled addition
- Cast back into `block_info*` to use as `block_info` struct

```
snp
0 8 16 24 x
```

x
Type-safe casting in Java

- Can only cast compatible object references
  - Based on class hierarchy

```java
Vehicle  v = new Vehicle(); // super class of Boat and Car
Boat    b1 = new Boat();   // |--> sibling
Car     c1 = new Car();   // |--> sibling

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
  - Based on class hierarchy

```
Vehicle v = new Vehicle();  // super class of Boat and Car
Boat b1 = new Boat();       // |--> sibling
Car c1 = new Car();         // |--> sibling
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;
```

- Everything needed for Vehicle also in Car
- v1 is declared as type Vehicle
- Compiler error: Incompatible type – elements in Car that are not in Boat (siblings)
- Compiler error: Wrong direction – elements Car not in Vehicle (wheels)
- Runtime error: Vehicle does not contain all elements in Boat (propellers)
- v2 refers to a Car at runtime
- Compiler error: Unconvertable types – b1 is declared as type Boat
Java Object Definitions

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

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

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

- How might we represent Java objects in memory based on what we’ve learned in C?
Java Objects and Method Dispatch

- **Object header**: GC info, hashing info, lock info, etc.

- **Virtual method table (vtable)**
  - Like a jump table for instance ("virtual") methods plus other class info
  - One table per class
  - Each object instance contains a **vtable pointer (vptr)**

- **Virtual method table**:
  - One table per class
  - Each object instance contains a vtable pointer (vptr)

---

Diagram:

- `Point object p` has a header, vptr, x, y
- `Point object q` has a header, vptr, x, y
- **vtable for class Point**:
  - Point object p's vptr points to the vtable for Point
  - Point object q's vptr points to the vtable for Point
  - Code for `Point()`: code for `samePlace()`
Java Constructors

- **When we call** `new`: allocate space for object (data fields and references), initialize to zero/null, and run constructor method

**Java:**

```java
Point p = new Point();
```

**C pseudo-translation:**

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

---

![Diagram of Point object and vtable for class Point]

- `Point object`: `p`
- `vtable for class Point`: `header`, `vptr`, `x`, `y`
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 is chosen *at runtime* by lookup in the vtable

**Java:**

```java
p.samePlace(q);
```

**C pseudo-translation:**

```c
p->vptr[1](p, q);
```

![Diagram showing vtable for class Point](image)
Subclassing

```java
class ThreeDPoint extends Point {
    double z;
    boolean samePlace(Point p2) {
        return false;
    }
    void sayHi() {
        System.out.println("hello");
    }
}
```

❖ Where does “z” go? At end of fields of Point
  ▪ Point fields are always in the same place, so Point code can run on ThreeDPoint objects without modification

❖ Where does pointer to code for two new methods go?
  ▪ No constructor, so use default Point constructor
  ▪ To override “samePlace”, use same vtable position
  ▪ Add new pointer at end of vtable for new method “sayHi”
Subclassing

class ThreeDPoint extends Point {
    double z;
    boolean samePlace(Point p2) {
        return false;
    }
    void sayHi() {
        System.out.println("hello");
    }
}

ThreeDPoint object

vtable for ThreeDPoint: constructor, samePlace, sayHi

Code for sayHi

vtable for (not Point)

Old code for constructor
New code for samePlace

z tacked on at end

sayHi tacked on at end
Dynamic Dispatch

**Point object**

- header
- vptr
- x
- y

**Point vtable:**

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

**ThreeDPoint object**

- header
- vptr
- x
- y
- z

**ThreeDPoint vtable:**

- code for `sayHi()`
- code for 3DPoint’s `samePlace()`

---

**Java:**

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

**C pseudo-translation:**

```
// works regardless of what p is
return p->vptr[1](p, q);
```
Ta-da!

- In CSE143, it may have seemed “magic” that an *inherited* method could call an *overridden* method
  - You were tested on this endlessly

- The “trick” in the implementation is this part:
  
  ```c
  p->vptr[i](p,q)
  ```
  
  - In the body of the pointed-to code, any calls to (other) methods of *this* will use `p->vptr`
  - Dispatch determined by `p`, not the class that defined a method
Implementing Programming Languages

- Many choices in programming model implementation
  - We’ve previously discussed compilation
  - One can also *interpret*

- **Interpreters** have a long history and are still in use
  - *e.g.*, Lisp, an early programming language, was interpreted
  - *e.g.*, Python, Javascript, Ruby, Matlab, PHP, Perl, ...
Interpreters

❖ Execute (something close to) the source code directly, meaning there is less translation required
  ▪ This makes it a simpler program than a compiler and often provides more transparent error messages

❖ Easier to run on different architectures – runs in a simulated environment that exists only inside the interpreter process
  ▪ Just port the interpreter (program), and then interpreting the source code is the same

❖ Interpreted programs tend to be slower to execute and harder to optimize
Interpreters vs. Compilers

- Programs that are designed for use with particular language implementations
  - You can choose to execute code written in a particular language via either a compiler or an interpreter, if they exist

- “Compiled languages” vs. “interpreted languages” a misuse of terminology
  - But very common to hear this
  - And has some validation in the real world (e.g., JavaScript vs. C)

- Some modern language implementations are a mix
  - e.g., Java compiles to bytecode that is then interpreted
  - Doing just-in-time (JIT) compilation of parts to assembly for performance
Compiling and Running Java

1. Save your Java code in a .java file

2. To run the Java compiler:
   - `javac Foo.java`
   - The Java compiler converts Java into *Java bytecodes*
     - Stored in a .class file

3. To execute the program stored in the bytecodes, these can be interpreted by the Java Virtual Machine (JVM)
   - Running the virtual machine: `java Foo`
   - Loads `Foo.class` and interprets the bytecodes
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
Virtual Machine Model

- **High-Level Language Program** (e.g., Java, C)
- **Virtual Machine Language** (e.g., Java bytecodes)
- **Native Machine Language** (e.g., x86, ARM, Risc V)

- **Bytecode compiler** (e.g., javac Foo.java)
- **Virtual machine (interpreter)** (e.g., java Foo)
- **JIT compiler**
- **Ahead-of-time compiler**
Java Bytecode

- Like assembly code for JVM, but works on all JVMs
  - Hardware-independent!
- Typed (unlike x86 assembly)
- Strong JVM protections
JVM Operand Stack

Bytecode:

```java
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
```

Compiled to (IA32) x86:

```assembly
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.
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!

- Originally, JVMs were designed and built for Java (still the major use) but JVMs are also viewed as a safe, GC’ed platform
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! 😊 😎 😂

- **Topic Group 1:** Data  
  - Memory, Data, Integers, Floating Point, Arrays, Structs

- **Topic Group 2:** Programs  
  - x86-64 Assembly, Procedures, Stacks, Executables

- **Topic Group 3:** Scale & Coherence  
  - Caches, Processes, Virtual Memory, Memory Allocation

We’ll explore the OUTSIDE of the House of Computing next lecture!