# Java and C

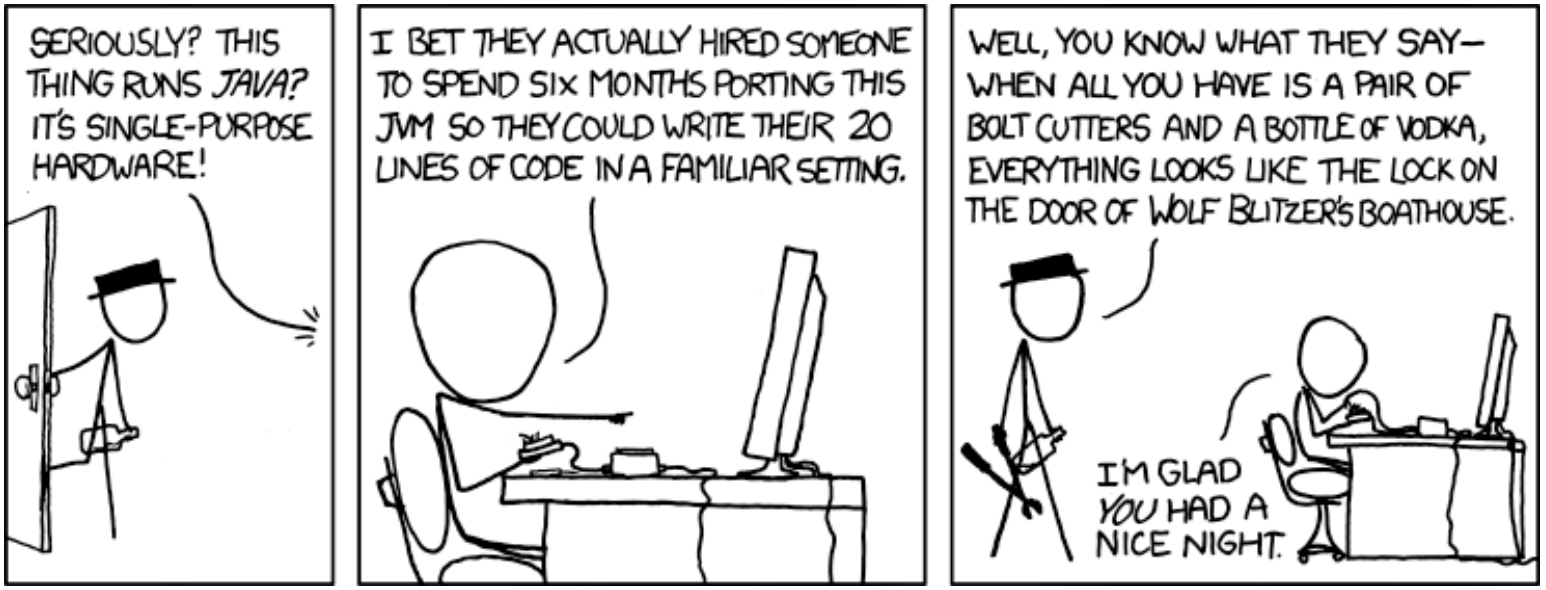
CSE 351 Spring 2019

**Instructor:**

Ruth Anderson

**Teaching Assistants:**

Gavin Cai
Britt Henderson
Sophie Tian
Casey Xing
Jack Eggleston
Richard Jiang
Connie Wang
Chin Yeoh
John Feltrup
Jack Skalitzky
Sam Wolfson




https://xkcd.com/801/

# Administrivia

- Lab 5, due Friday (6/7)
  - Memory Allocation
  - Recommended that you watch the Lab 5 helper videos
  - Sunday 6/9 is last day Lab 5 may be submitted (if one late day is used)
- **Final Exam:** Wed, 6/12, 12:30-2:20 pm in KNE 130
- Course evaluations now open, please fill out!

# 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();
```

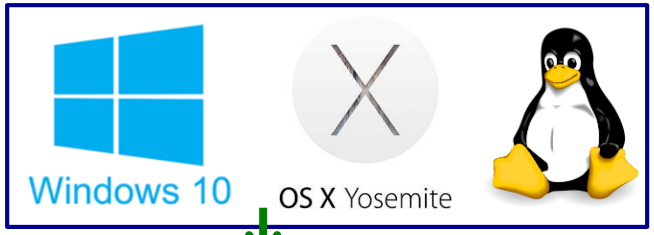
Assembly language:

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

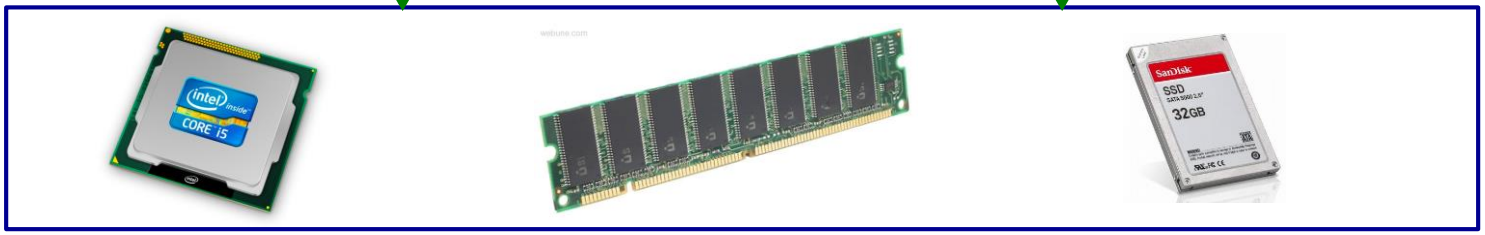
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
11000001111110100011111
```

OS:




Computer system:




Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

# 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

# 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

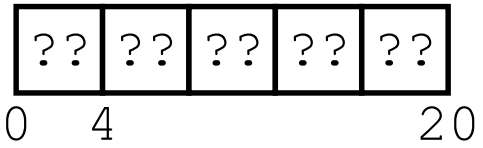
- Integers, floats, doubles, pointers – same as C
  - "Pointers" are called "references" in Java, but are much more constrained than C's general pointers
  - Java's portability-guarantee fixes the sizes of all types
    - Example: `int` is 4 bytes in Java regardless of machine
  - No unsigned types to 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` – 4 bytes)
  - `array.length` returns value of this field
- *Since it has this info, what can it do?*

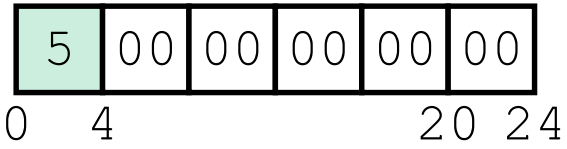
**C:**

**int** array[5];




**Java:**

int[] array = **new** int[5];

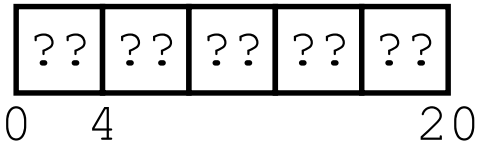


# Data in Java: Arrays

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

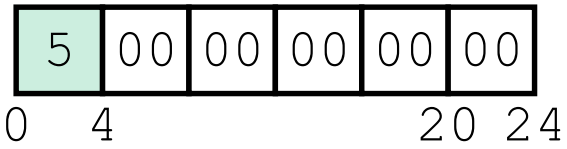
**C:**

**int** array[5];




**Java:**

int[] array = **new** int[5];




**To speed up bounds-checking:**

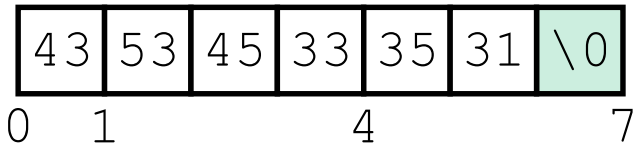
- Length field is likely in cache
- Compiler may store length field in register for loops
- Compiler may prove that some checks are redundant

# Data in Java: Characters & Strings

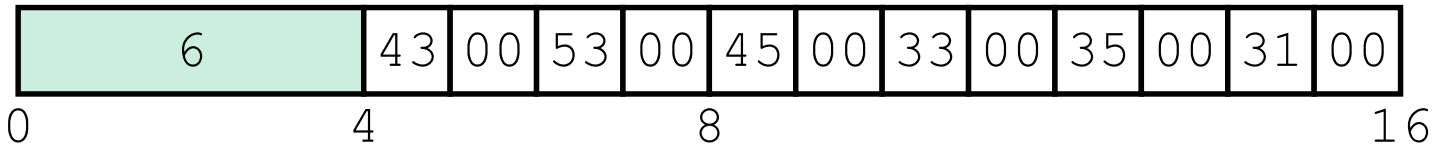
- Two-byte Unicode instead of ASCII
  - Represents most of the world's alphabets
- String not bounded by a '\0' (null character)
  - Bounded by hidden length field at beginning of string
- All String objects read-only (vs. StringBuffer)

Example: the string "CSE351"

**C:**
(ASCII)




**Java:**
(Unicode)



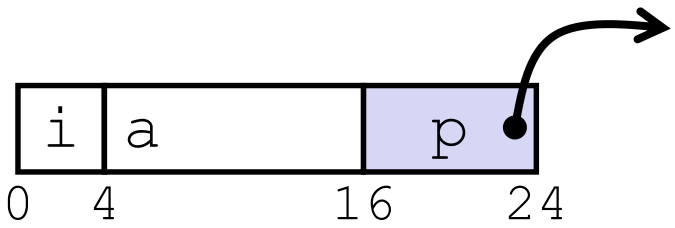
# Data in Java: Objects

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

**C:**

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

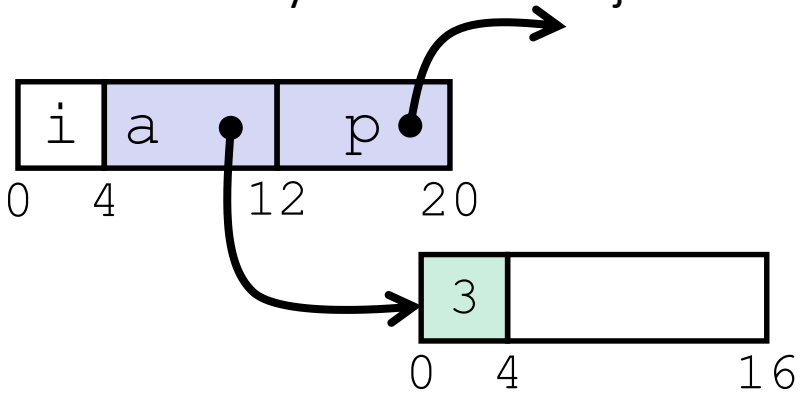
- `a[]` stored "inline" as part of struct




**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:**

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

**Java:**

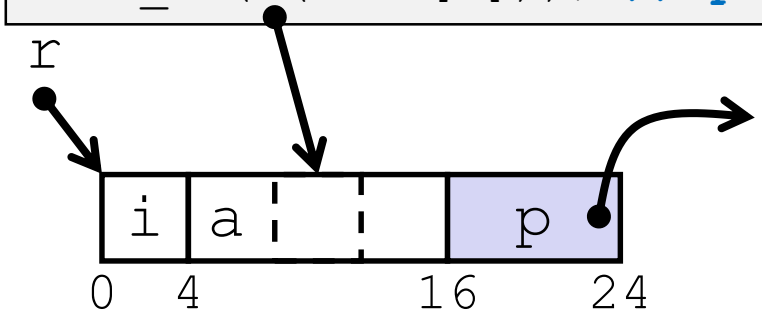
```
r = new Rec();
r2 = new Rec();
r.i = val;
r.a[2] = val;
r.p = r2;
```

# Pointers/References

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

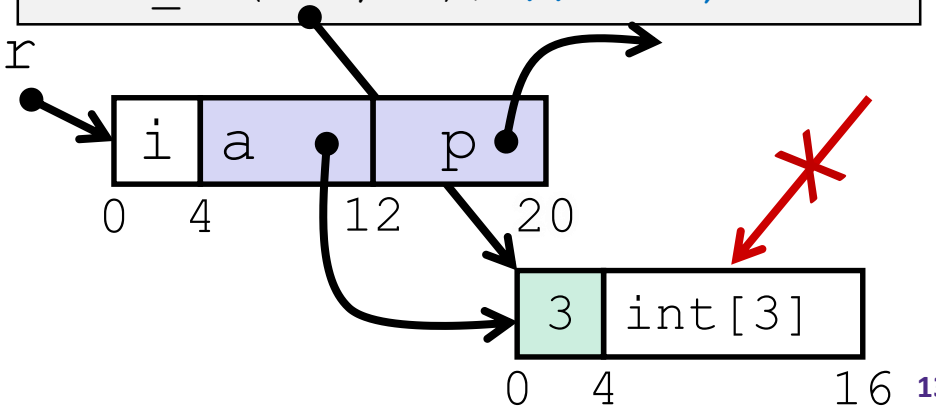
**C:**

```
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
```



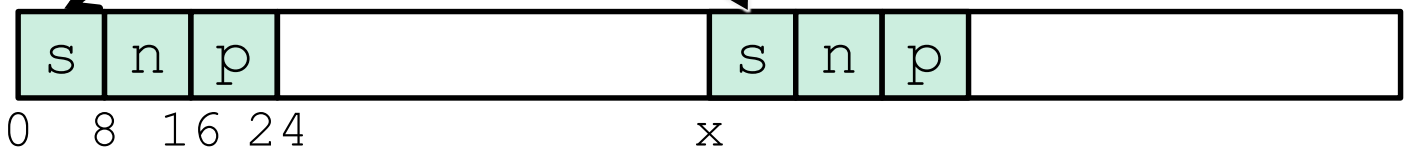
# Casting in C (example from Lab 5)

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

```
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 );
...
```

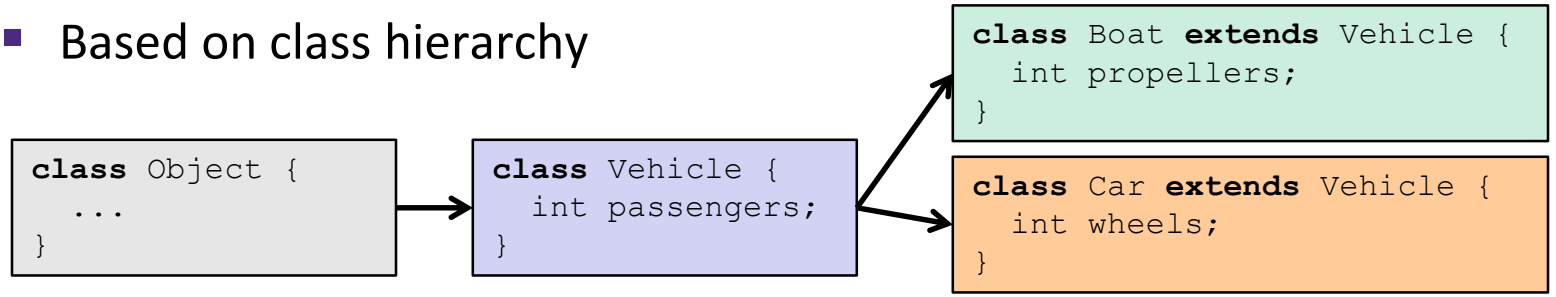
Cast `b` into `char *` to do unscaled addition

Cast back into `BlockInfo *` to use as `BlockInfo` struct



# Type-safe casting in Java

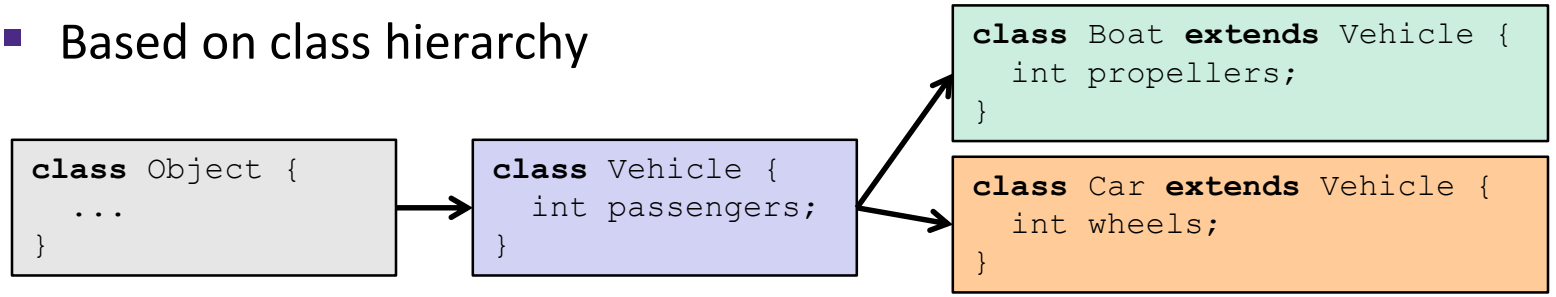
- Can only cast compatible object references
  - Based on class hierarchy




```
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;
```

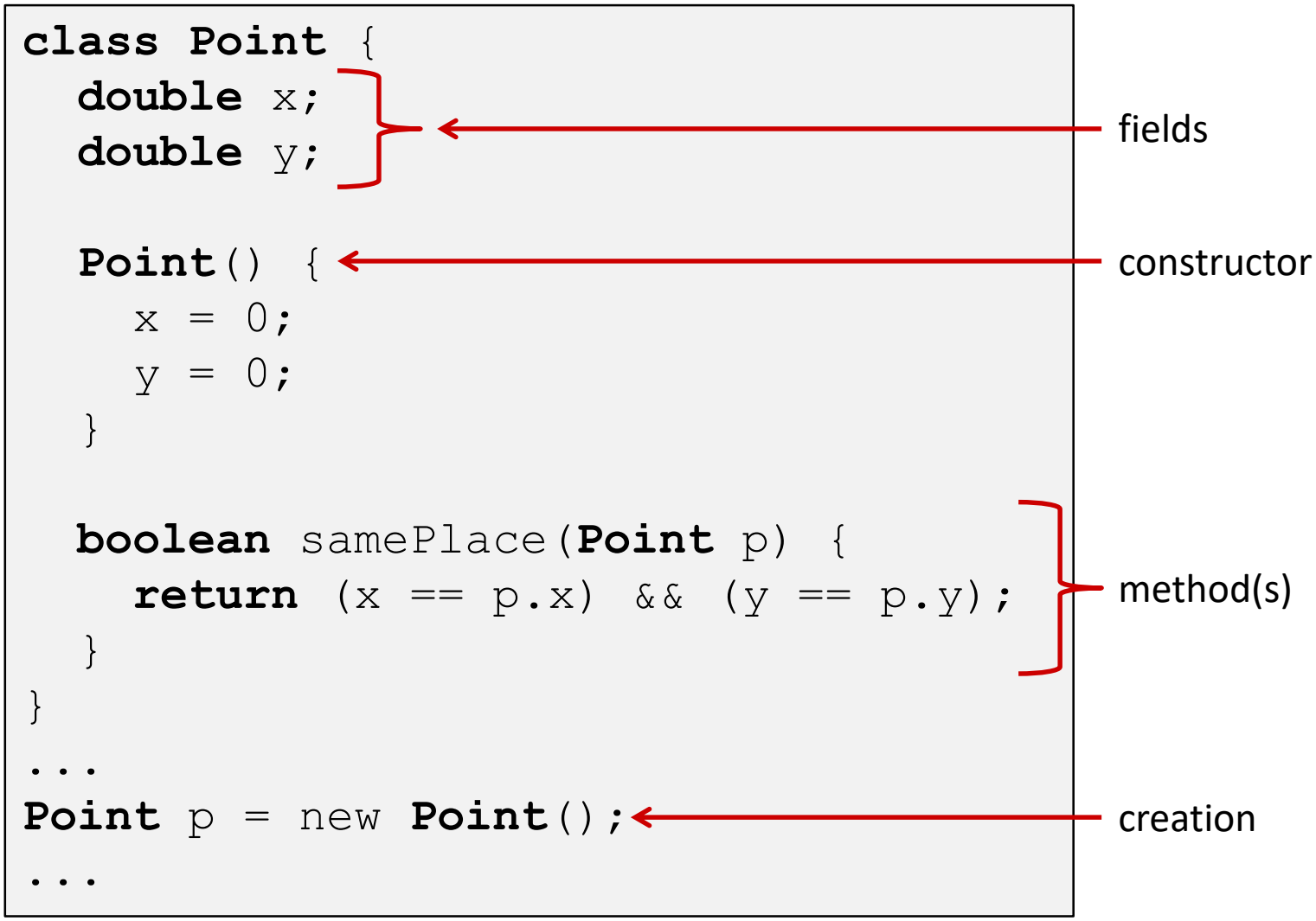
# Type-safe casting in Java

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

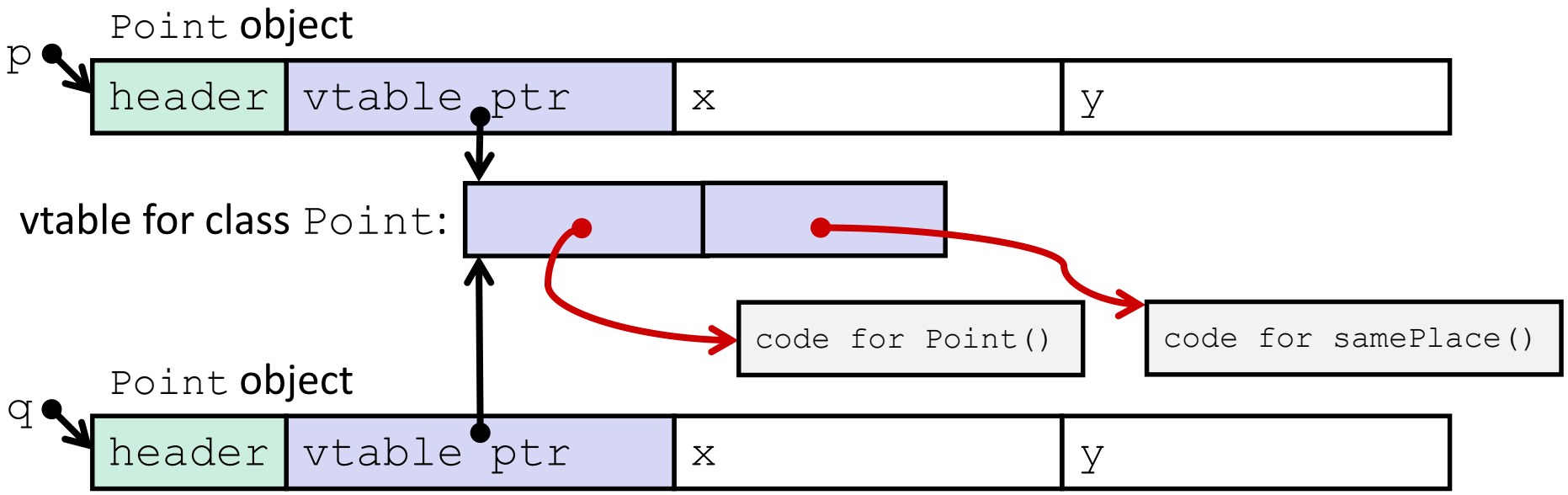



```
Vehicle  v = new Vehicle(); // super class of Boat and Car
Boat    b1 = new Boat();    // |--> sibling
Car     c1 = new Car();     // |--> sibling

Vehicle v1 = new Car();     <-- ✓ Everything needed for Vehicle also in Car
Vehicle v2 = v1;            <-- ✓ v1 is declared as type Vehicle
Car     c2 = new Boat();    <-- ✗ Compiler error: Incompatible type – elements in
                                  Car that are not in Boat (siblings)
Car     c3 = new Vehicle(); <-- ✗ Compiler error: Wrong direction – elements in Car
                                  not in Vehicle (wheels)
Boat    b2 = (Boat) v;      <-- ✗ Runtime error: Vehicle does not contain all
                                  elements in Boat (propellers)
Car     c4 = (Car) v2;      <-- ✓ v2 refers to a Car at runtime
Car     c5 = (Car) b1;      <-- ✗ Compiler error: Unconvertable types – b1 is
                                  declared as type Boat
```

# Java Object Definitions



# Java Objects and Method Dispatch




- *Virtual method table* (*vtable*)
  - 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.
  - Why no size?

# Java Constructors

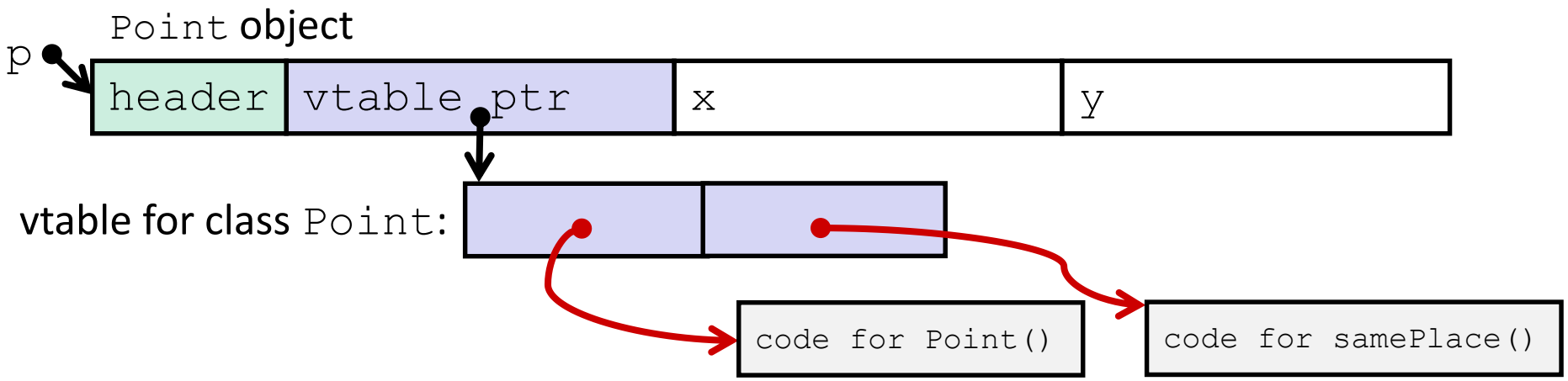
- **When we call `new`:** allocate space for object (data fields and references), initialize to zero/null, and run constructor method

**Java:**

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

**C pseudo-translation:**

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



# Java Methods

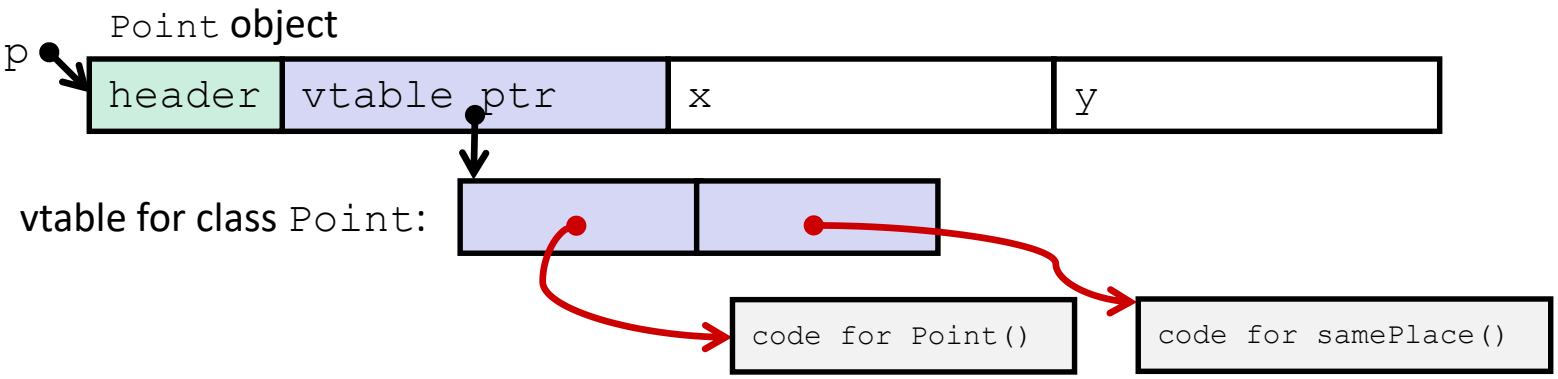
- Static methods are just like functions
- Instance methods:
  - Can refer to *this;*
  - Have an implicit first parameter for *this;* and
  - Can be overridden in subclasses
- The code to run when calling an instance method is chosen *at runtime* by lookup in the vtable

**Java:**

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

**C pseudo-translation:**

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



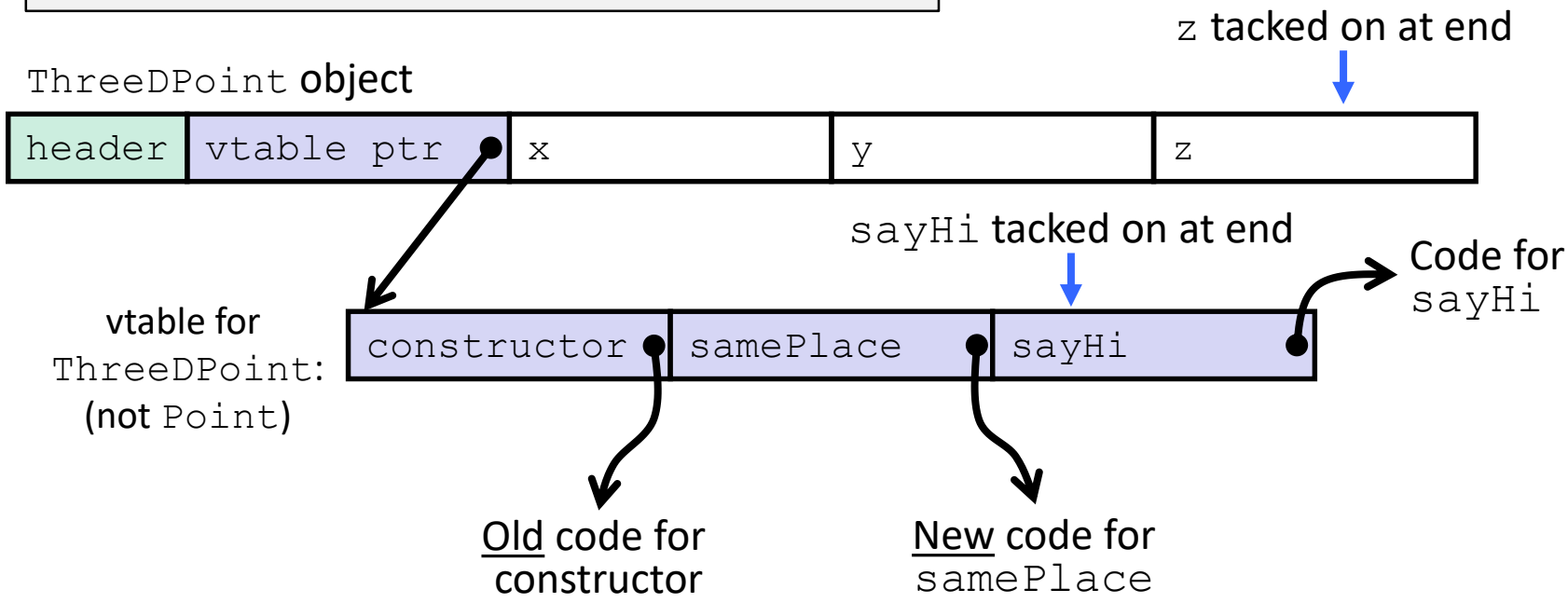
# Subclassing

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

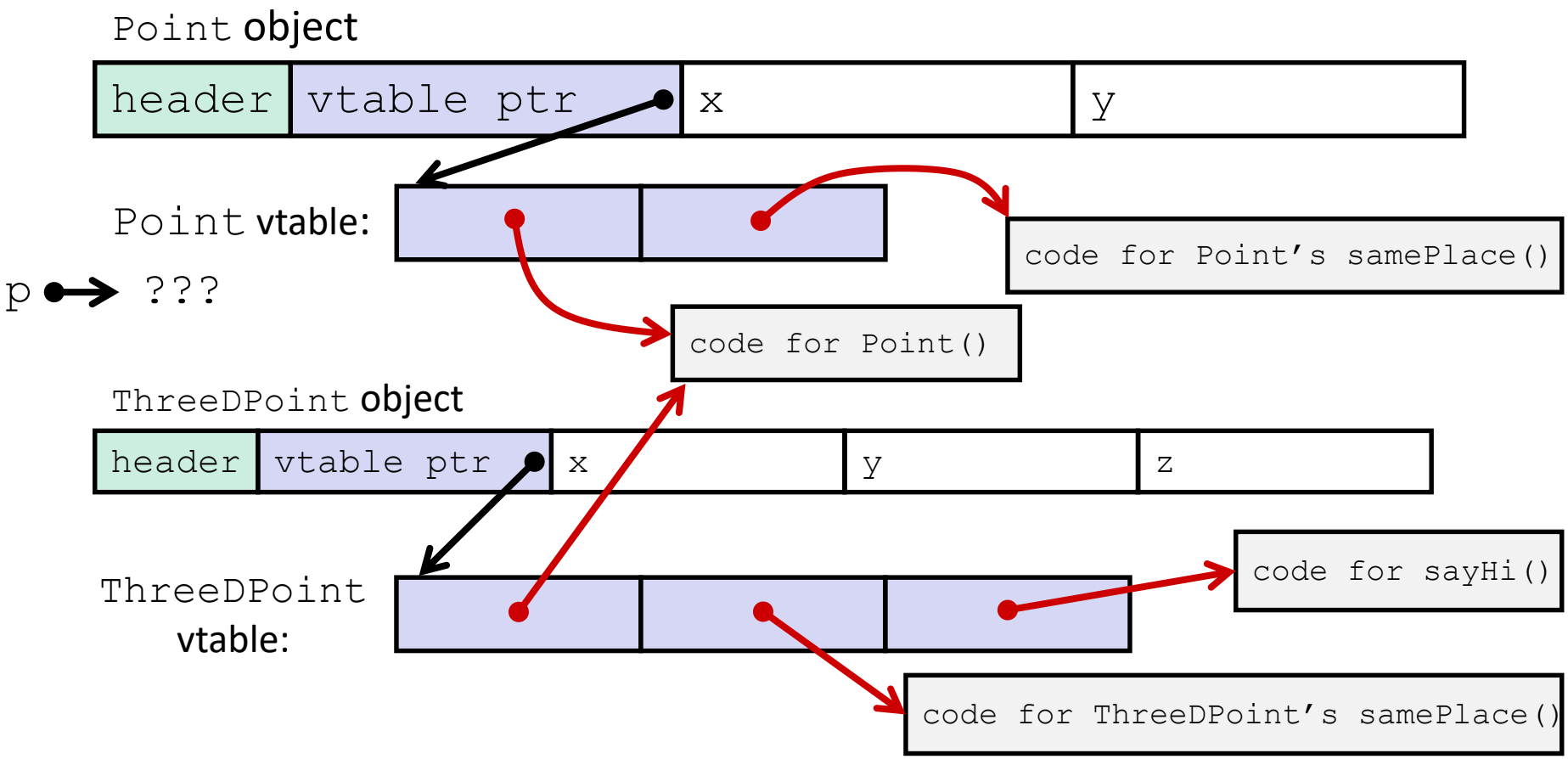
- Where does "`z`" go? At end of fields of `Point`
  - `Point` fields are always in the same place, so `Point` code can run on `ThreeDPoint` objects without modification
- Where does pointer to code for two new methods go?
  - No constructor, so use default `Point` constructor
  - To override "`samePlace`",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



# Dynamic Dispatch




**Java:**

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

**C pseudo-translation:**

```
// works regardless of what p is
return p->vtable[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:

```
p->vtable[i](p,q)
```

  - In the body of the pointed-to code, any calls to (other) methods of `this` will use p->vtable
  - Dispatch determined by `p`, not the class that defined a method

# Practice Question

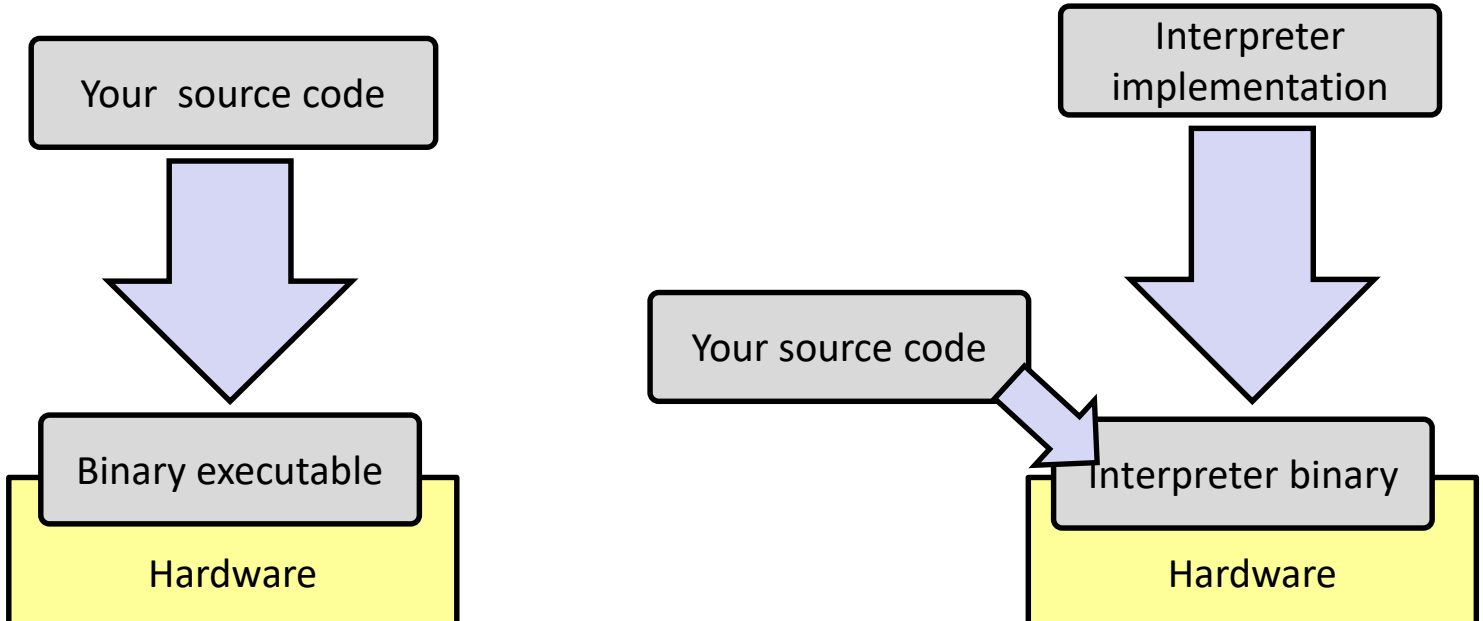
- Assume: 64-bit pointers and that a Java object header is 8 B
- What are the sizes of the things being pointed at by `ptr_c` and `ptr_j`?

```
struct c {
  int i;
  char s[3];
  int a[3];
  struct c *p;
};
struct c* ptr_c;
```

```
class jobj {
  int i;
  String s = "hi";
  int[] a = new int[3];
  jobj p;
}
jobj ptr_j = new jobj();
```

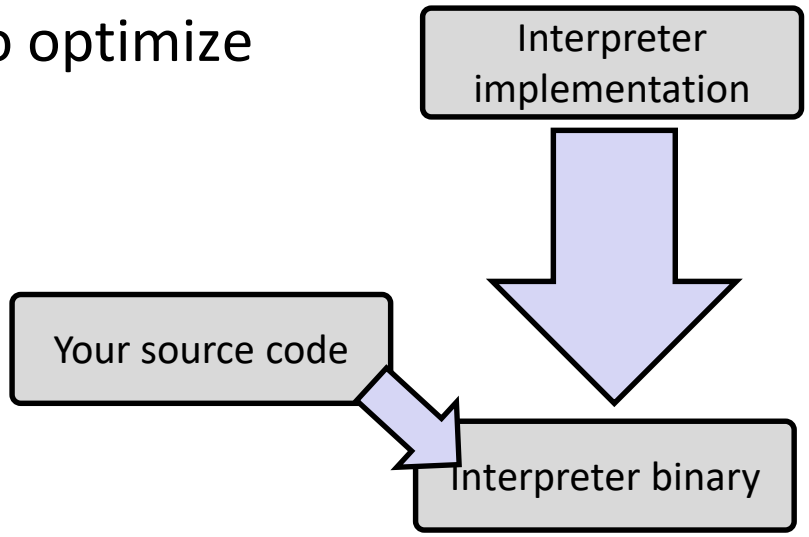
# Implementing Programming Languages

- 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 (something close to) the *source code* directly
- 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
  - Just port the interpreter (program), not the program-being-interpreted
- Slower and harder to optimize



# Interpreter vs. Compiler

- An aspect of a language implementation
  - A language can have multiple implementations
  - Some might be compilers and other interpreters

- "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)

- Also, as about to see, modern language implementations are often a mix of the two. E.g. :
  - Compiling to a bytecode language, then interpreting
  - Doing just-in-time compilation of parts to assembly for performance

# "The JVM"

**Note:** The JVM is different than the CSE VM running on VMWare. Yet *another* use of the word "virtual"!

- 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**
    - http://en.wikipedia.org/wiki/Just-in-time_compilation
  - Java is sometimes compiled ahead of time (AOT) like C

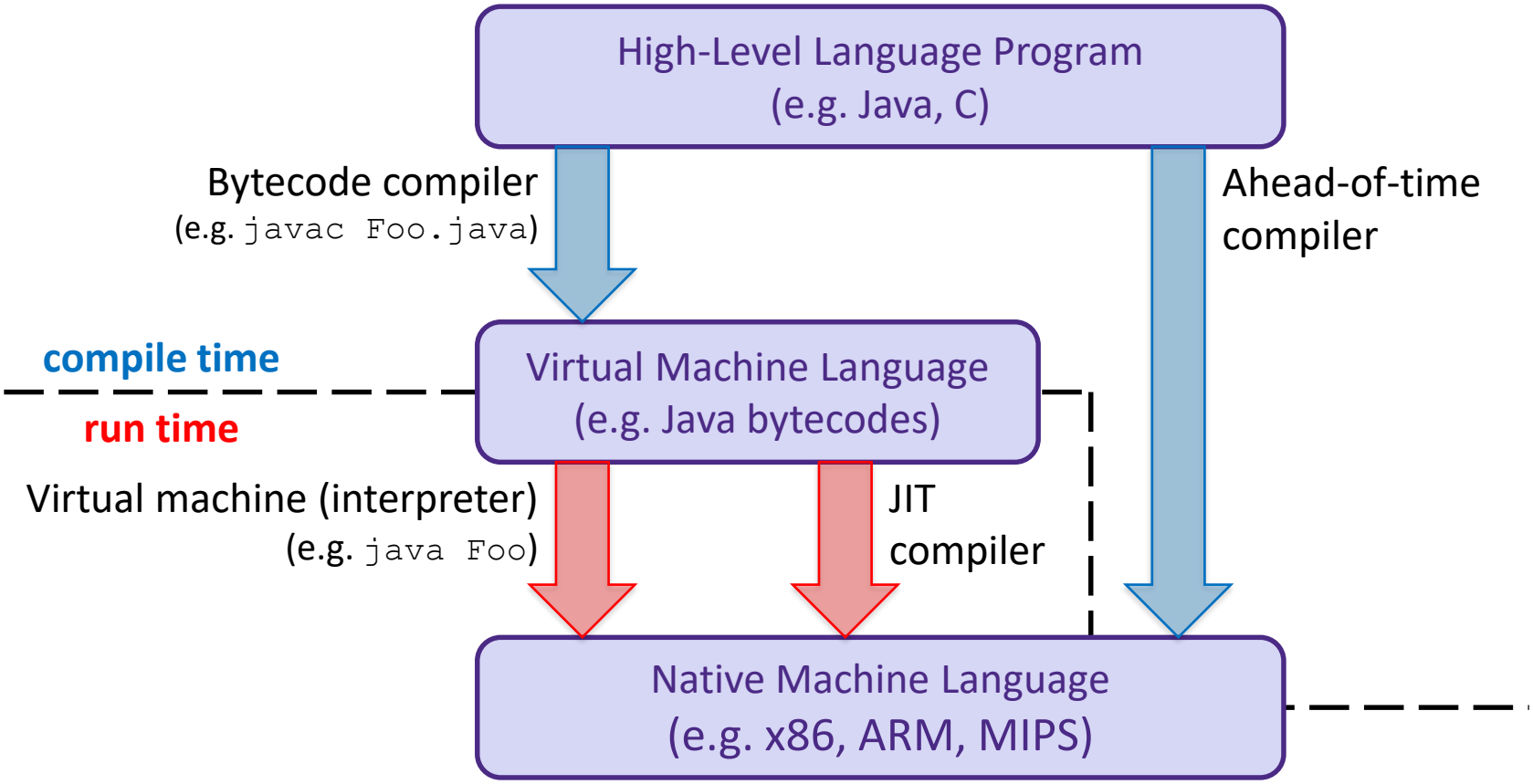
# Compiling and Running Java

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

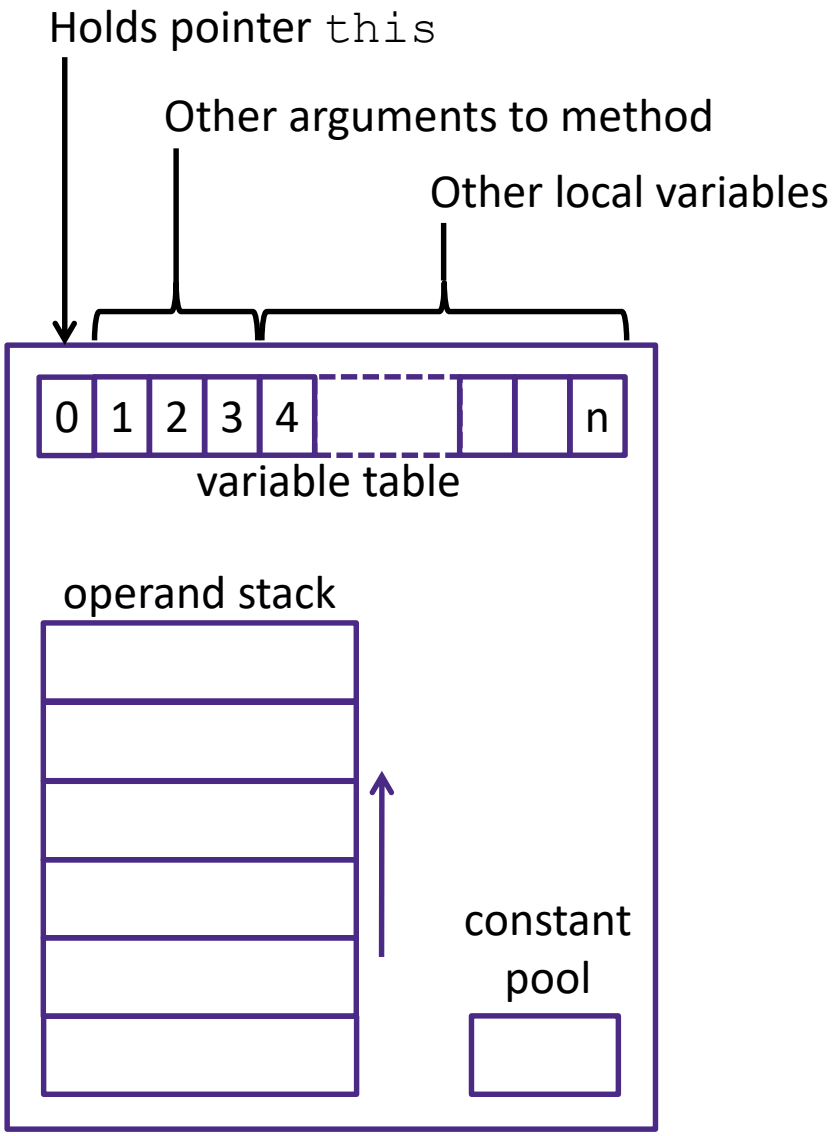
3. To execute the program stored in the bytecodes, Java bytecodes can be interpreted by a program (an interpreter)
   - For Java, this interpreter is called the Java Virtual Machine (the JVM)
   - To run the virtual machine:
   - `java Foo`
   - This Loads the contents of `Foo.class` and interprets the bytecodes

# Virtual Machine Model

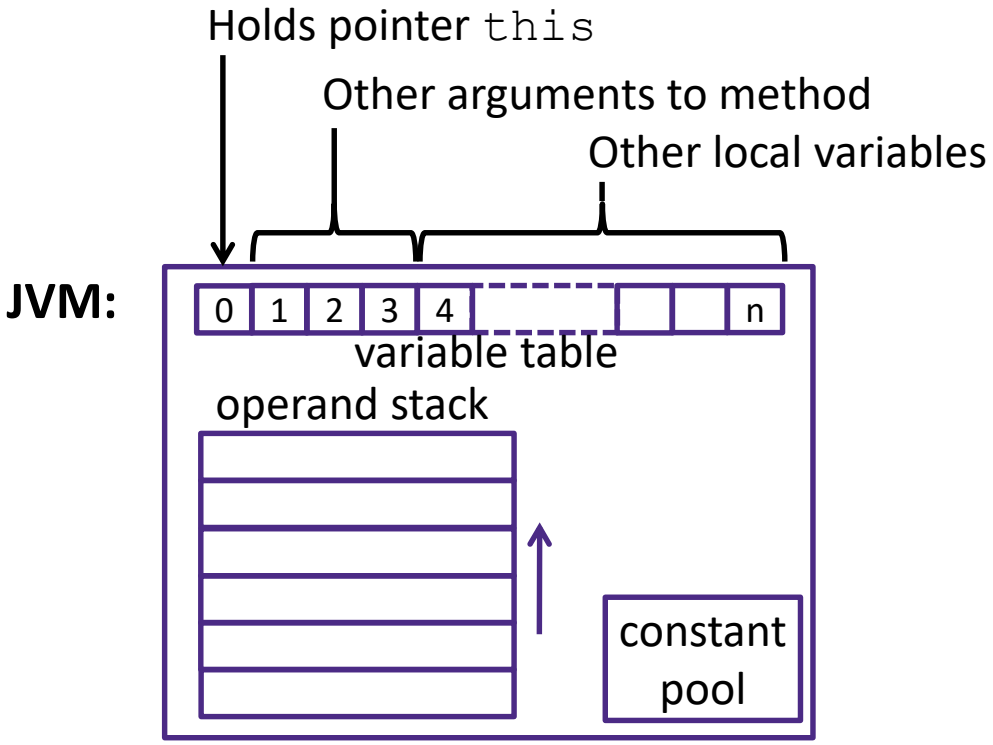


# Java Bytecode

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



# JVM Operand Stack




'i' = integer,
'a' = 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 (IA32) x86:**

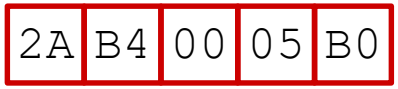
```
mov 8(%ebp),  %eax
mov 12(%ebp), %edx
add %edx, %eax
mov %eax, -8(%ebp)
```

# 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>
                   // getfield instruction has a 3-byte encoding
                   // 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
```

Byte number: 0 1 4


As stored in the `.class` file:




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
```

http://en.wikipedia.org/wiki/Java_bytecode_instruction_listings

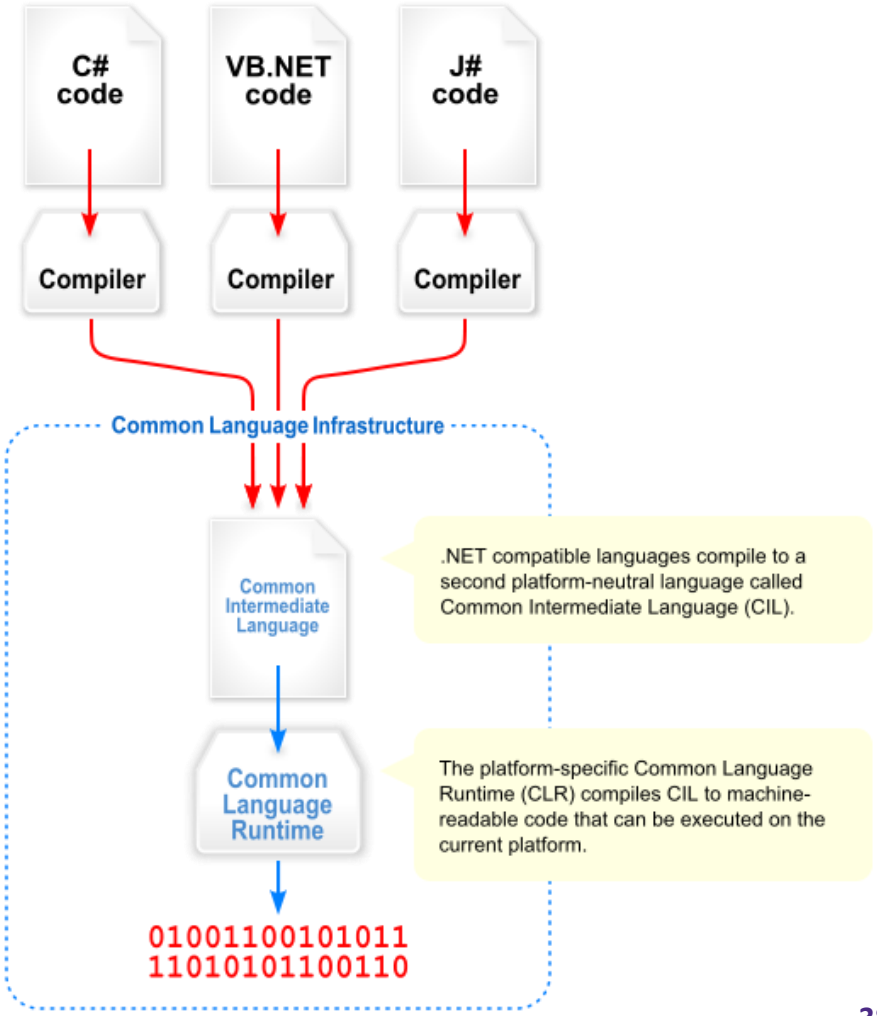
```
Compiled from Employee.java
class Employee extends java.lang.Object {
  public Employee(java.lang.String,int);
  public java.lang.String getEmployeeName();
  public int getEmployeeNumber();
}

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! ☺ 😎 😂

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();
```

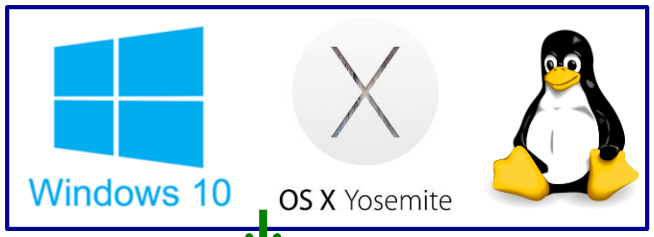
Assembly language:

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

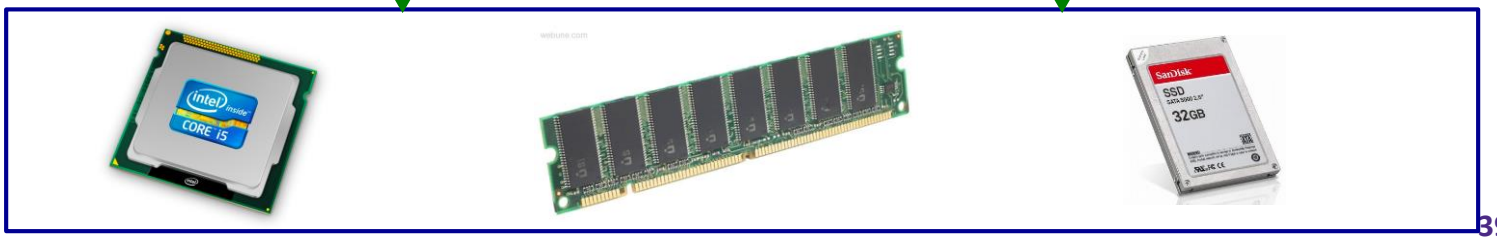
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
11000001111110100011111
```

OS:




Computer system:




- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C