Memory Bugs, Java and C

CSE 351 Winter 2019

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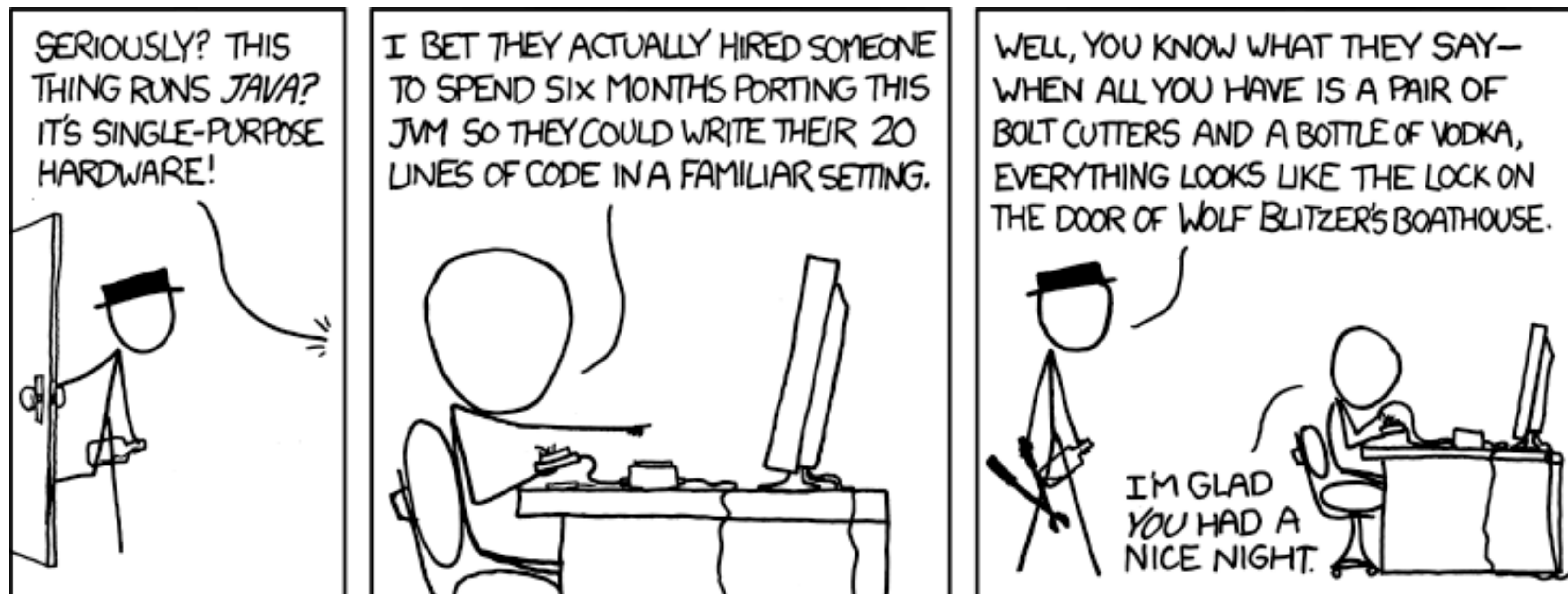


https://xkcd.com/801/

Administrivia

- Course evaluations now open
  - You should have received a link!
  - Participation is really important ☺
- **Final Exam:** Tue, 3/19, 8:30-10:20 pm in KNE 130
  - Structure:

Memory-Related Perils and Pitfalls in C

		Program stop possible?	Fixes:
A)	Dereferencing a non-pointer		
B)	Freed block – access again		
C)	Freed block – free again		
D)	Memory leak – failing to free memory		
E)	No bounds checking		
F)	Reading uninitialized memory		
G)	Dangling pointer		
H)	Wrong allocation size		

Find That Bug!

```
char s[8];
int i;

gets(s);   /* reads "123456789" from stdin */
```

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
int* foo() {
    int val;

    return &val;
}
```

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
int **p;

p = (int **)malloc( N * sizeof(int) );

for (int i = 0; i < N; i++) {
   p[i] = (int *)malloc( M * sizeof(int) );
}
```

- N and M defined elsewhere (#define)

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = (int *)malloc( N*sizeof(int) );
   int i, j;

   for (i = 0; i < N; i++)
      for (j = 0; j < N; j++)
         y[i] += A[i][j] * x[j];

   return y;
}
```

- A is NxN matrix, x is N-sized vector (so product is vector of size N)
- N defined elsewhere (#define)

Error Type: ☐ **Prog stop Possible?** ☐ **Fix:**

Find That Bug!

- The classic `scanf` bug
  - `int scanf(const char *format)`

```
int val;
...
scanf("%d", val);
```

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
   // manipulate y
free(x);
```

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
x = (int*)malloc( N * sizeof(int) );
   // manipulate x
free(x);

   ...

y = (int*)malloc( M * sizeof(int) );
for (i=0; i<M; i++)
   y[i] = x[i]++;
```

Error Type:

Prog stop Possible?

Fix:

Find That Bug!

```
typedef struct L {
   int val;
   struct L *next;
} list;

void foo() {
   list *head = (list *) malloc( sizeof(list) );
   head->val = 0;
   head->next = NULL;
      // create and manipulate the rest of the list
      ...
   free(head);
   return;
}
```

Error Type:

Prog stop Possible?

Fix:

Dealing With Memory Bugs

- Conventional debugger (`gdb`)
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- Debugging `malloc` (UToronto CSRI `malloc`)
  - Wrapper around conventional `malloc`
  - Detects memory bugs at `malloc` and `free` boundaries
    - Memory overwrites that corrupt heap structures
    - Some instances of freeing blocks multiple times
    - Memory leaks
  - Cannot detect all memory bugs
    - Overwrites into the middle of allocated blocks
    - Freeing block twice that has been reallocated in the interim
    - Referencing freed blocks

Dealing With Memory Bugs (cont.)

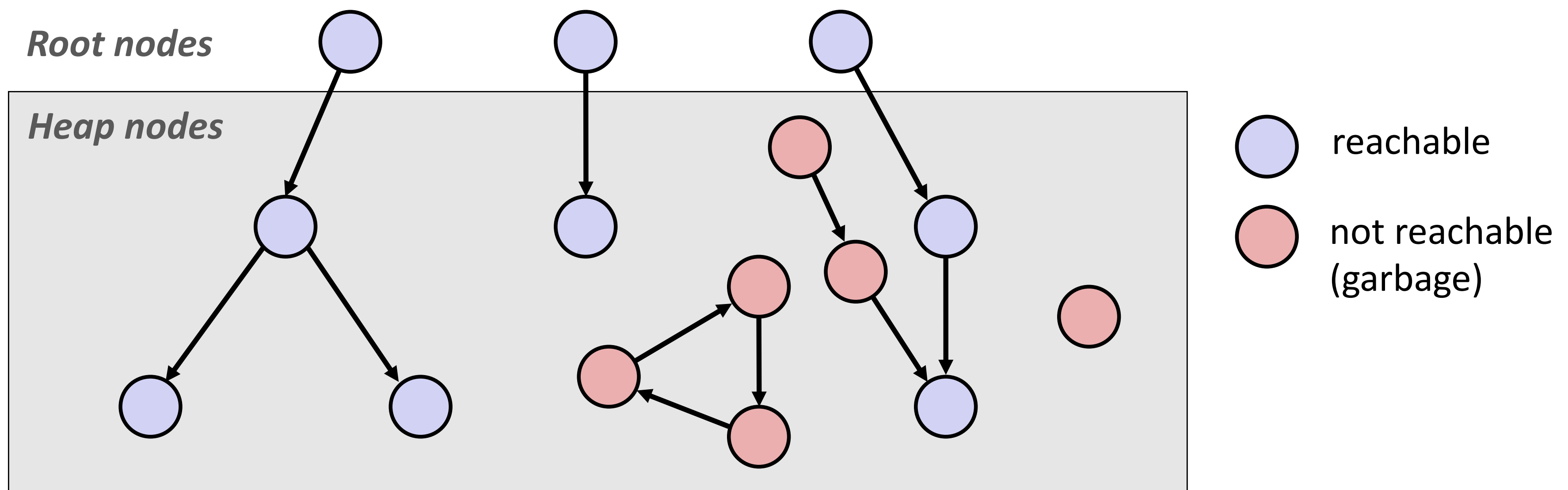
- Some `malloc` implementations contain checking code
  - Linux glibc malloc: **`setenv MALLOC_CHECK_ 2`**
  - FreeBSD: **`setenv MALLOC_OPTIONS AJR`**
- Binary translator: valgrind (Linux), Purify
  - Powerful debugging and analysis technique
  - Rewrites text section of executable object file
  - Can detect all errors as debugging **`malloc`**
  - Can also check each individual reference at runtime
    - Bad pointers
    - Overwriting
    - Referencing outside of allocated block

What about Java or ML or Python or …?

- In *memory-safe languages*, most of these bugs are impossible
  - Cannot perform arbitrary pointer manipulation
  - Cannot get around the type system
  - Array bounds checking, null pointer checking
  - Automatic memory management
- But one of the bugs we saw earlier is possible. Which one?

Memory Leaks with GC

- Not because of forgotten `free` — we have GC!
- Unneeded "leftover" roots keep objects reachable
- *Sometimes* nullifying a variable is not needed for correctness but is for performance
- Example: Don't leave big data structures you're done with in a static field



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();
```

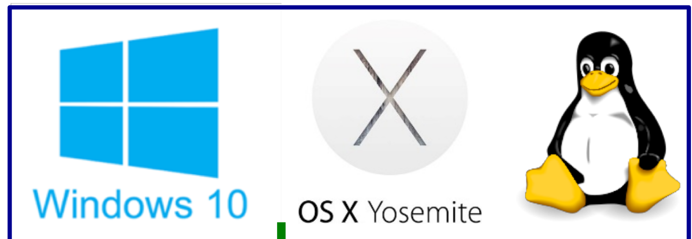
Assembly language:

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

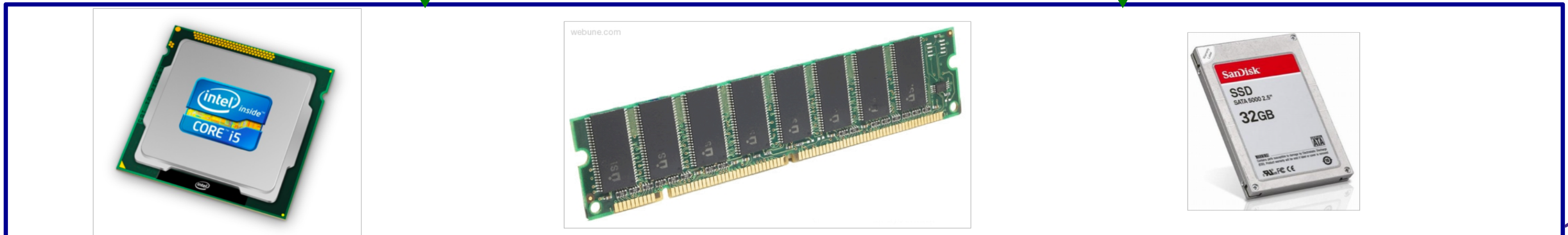
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

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

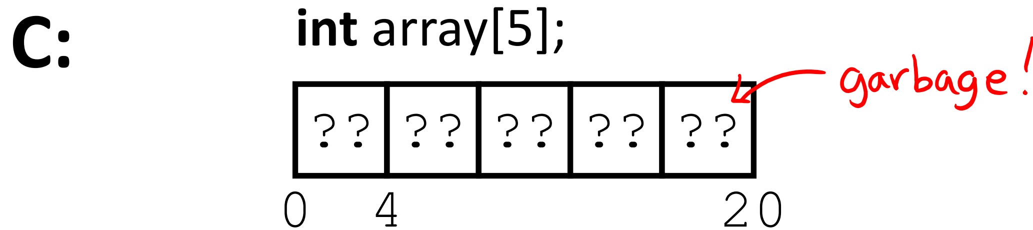
Data in Java

- 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**

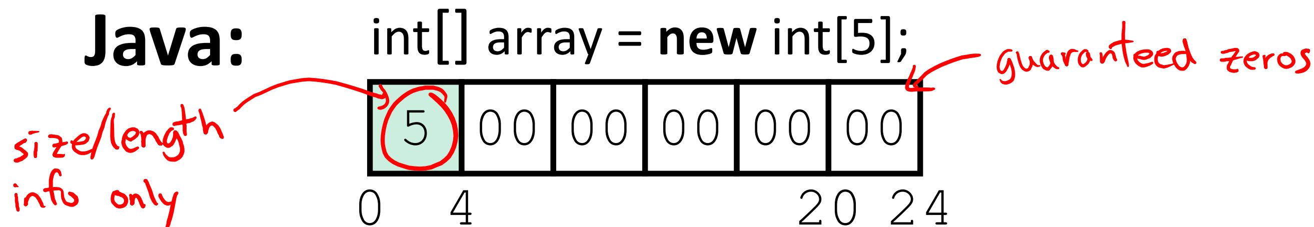
Data in Java: Arrays

- 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];

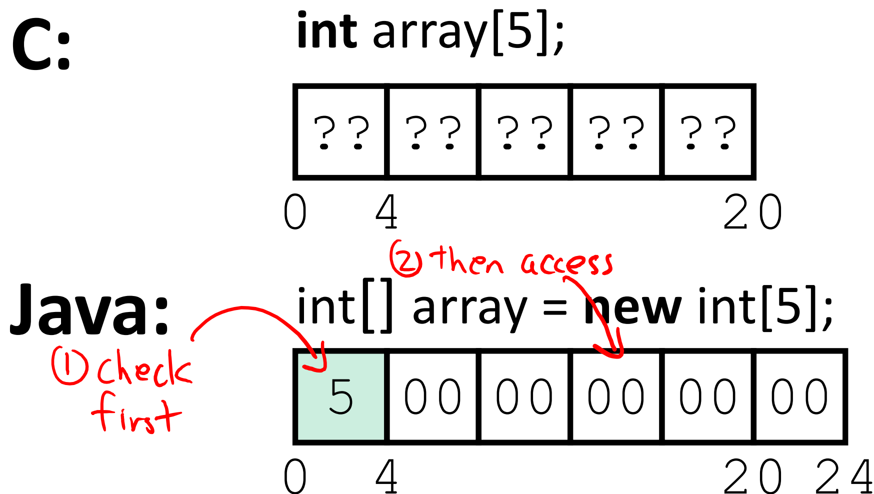


Java: int[] array = **new** int[5];



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



To speed up bounds-checking:

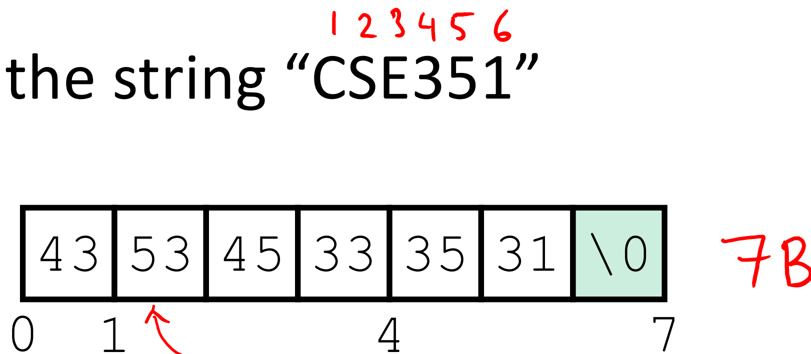
- Length field is likely in cache
- Compiler may store length field in register for loops
- Compiler may prove that some checks are redundant

Data in Java: Characters & Strings

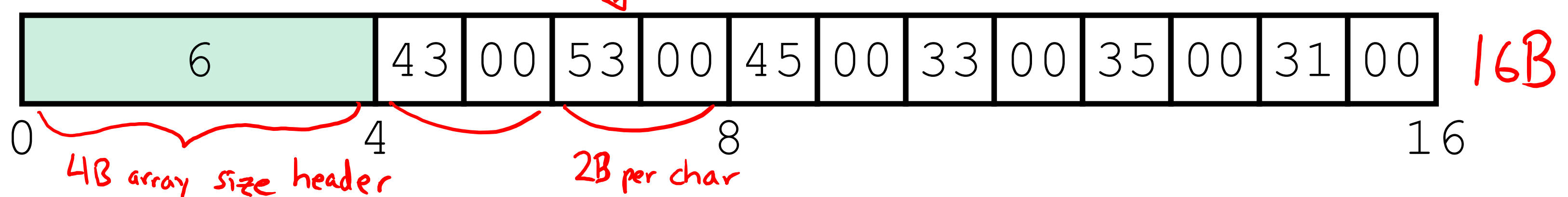
- Two-byte Unicode instead of ASCII
  - Represents most of the world's alphabets
- String not bounded by a '\0' (null character)
  - Bounded by hidden length field at beginning of string
- All String objects read-only (vs. StringBuffer)

Example: the string "CSE351"

C:
(ASCII)



Java:
(Unicode)



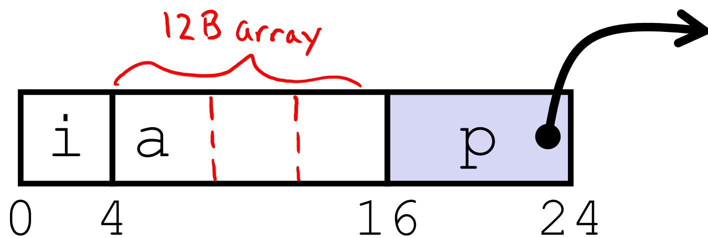
Data in Java: Objects

- 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;
};
```

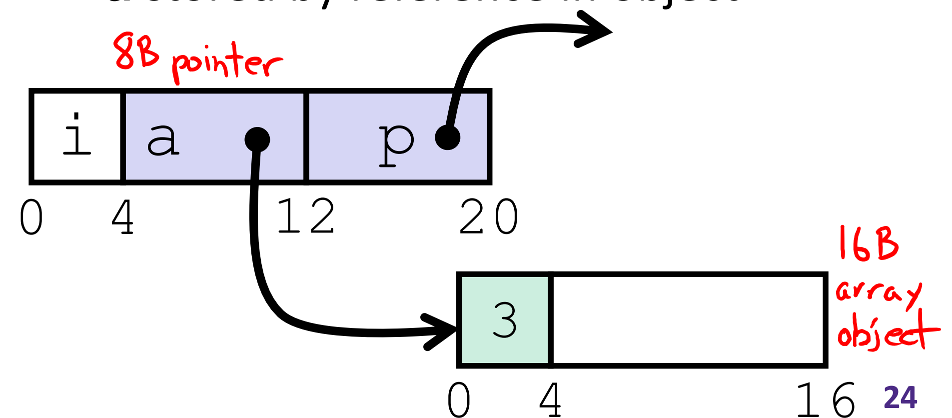
- `a[]` stored "inline" as part of struct



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;
```

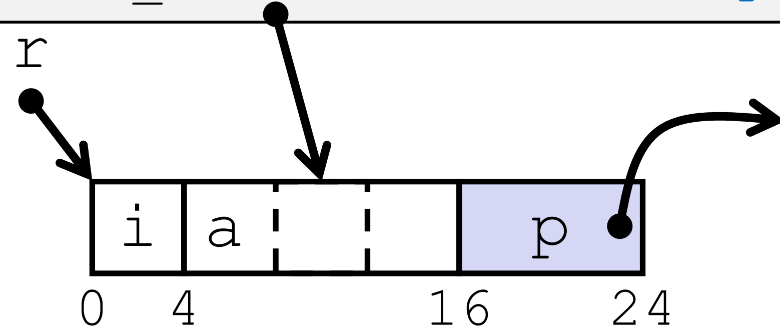
references

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

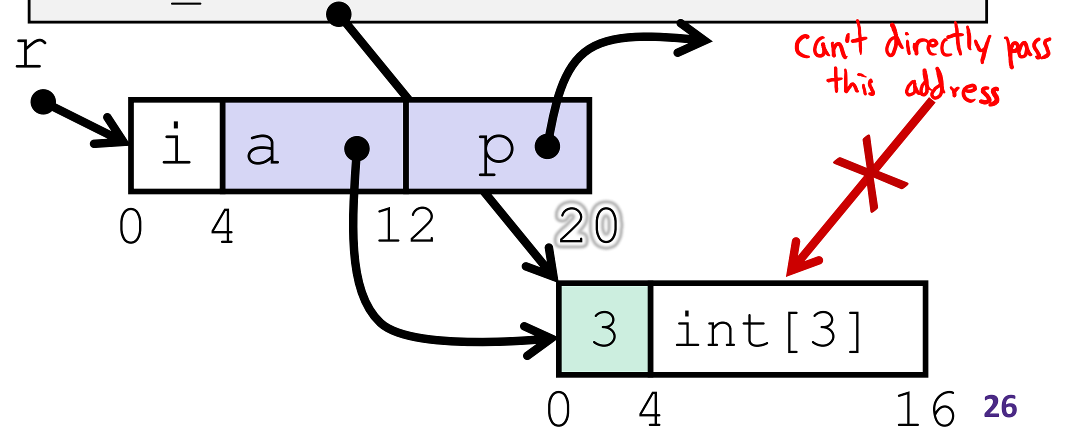
C:

```
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 arithemetic 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

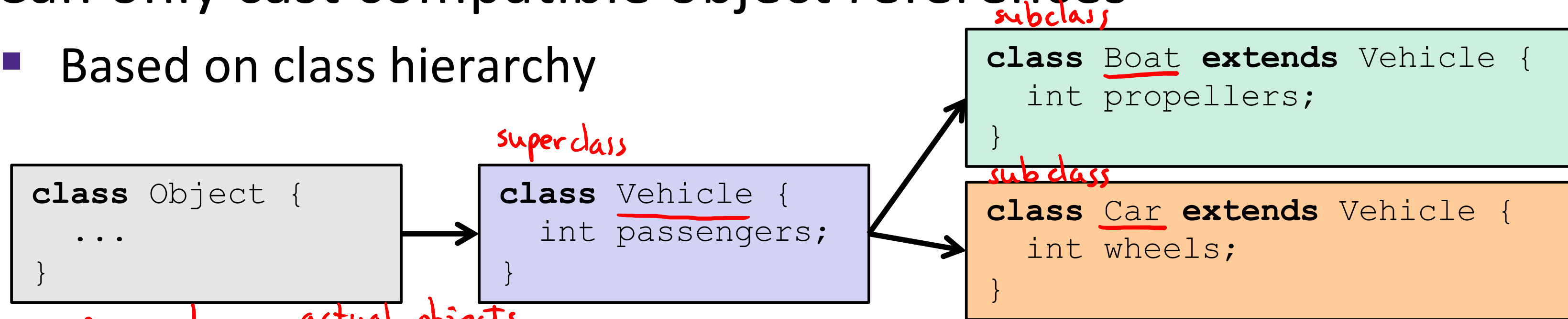
move by x bytes

s	n	p		s	n	p	

0 8 16 24 x

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();

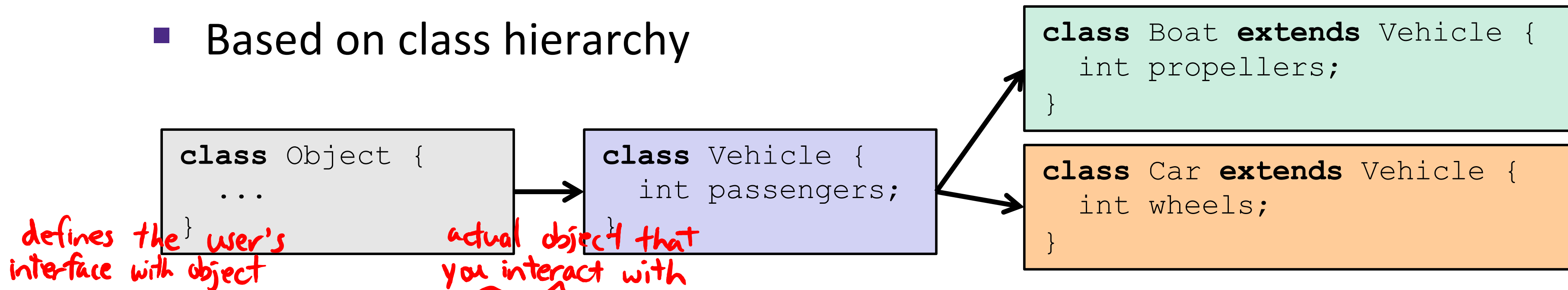
Car       c3 = new Vehicle();

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();
Vehicle v2 = v1;
Car     c2 = new Boat();

Car     c3 = new Vehicle();
what if:    v = new Boat();
Boat    b2 = (Boat) v;

Car     c4 = (Car) v2;
Car     c5 = (Car) b1;
```

- `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 `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

```
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();
...
```

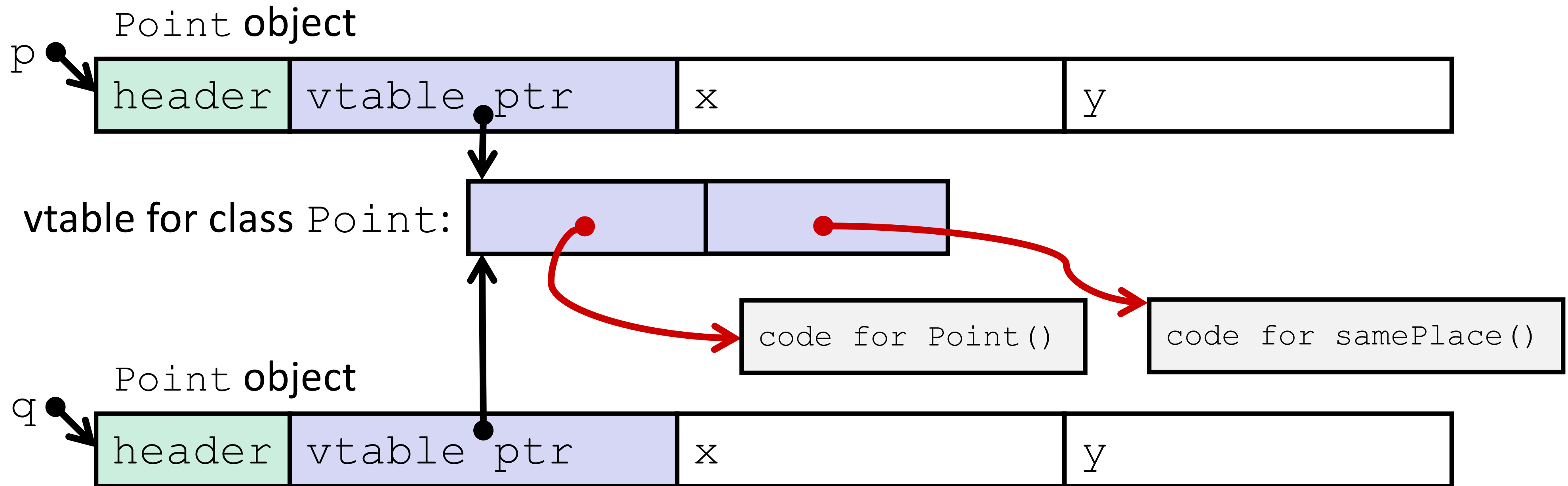
fields

constructor

method(s)

creation

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

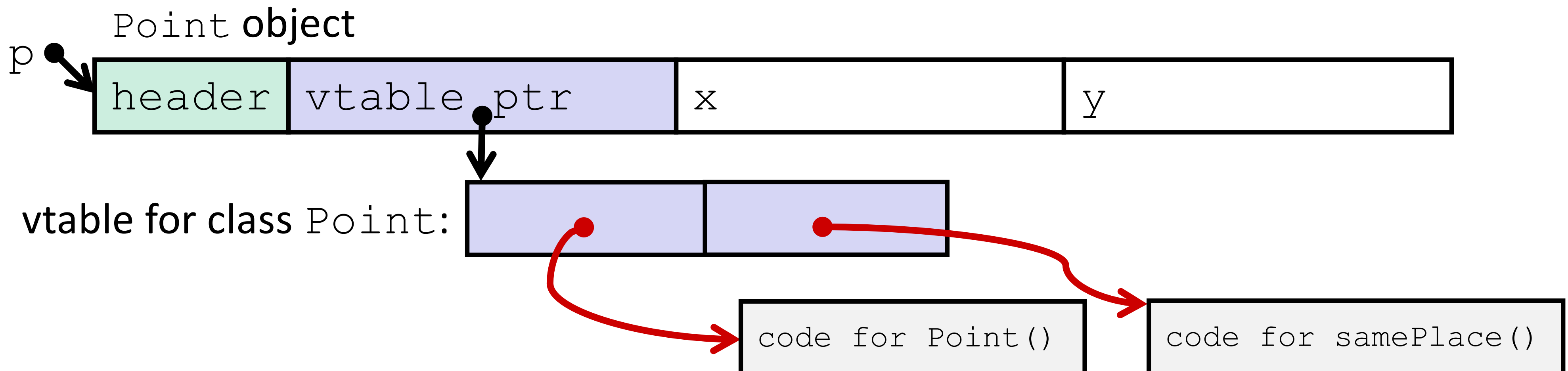
- **When we call `new`:** allocate space for object (data fields and references), initialize to zero/null, and run constructor method

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

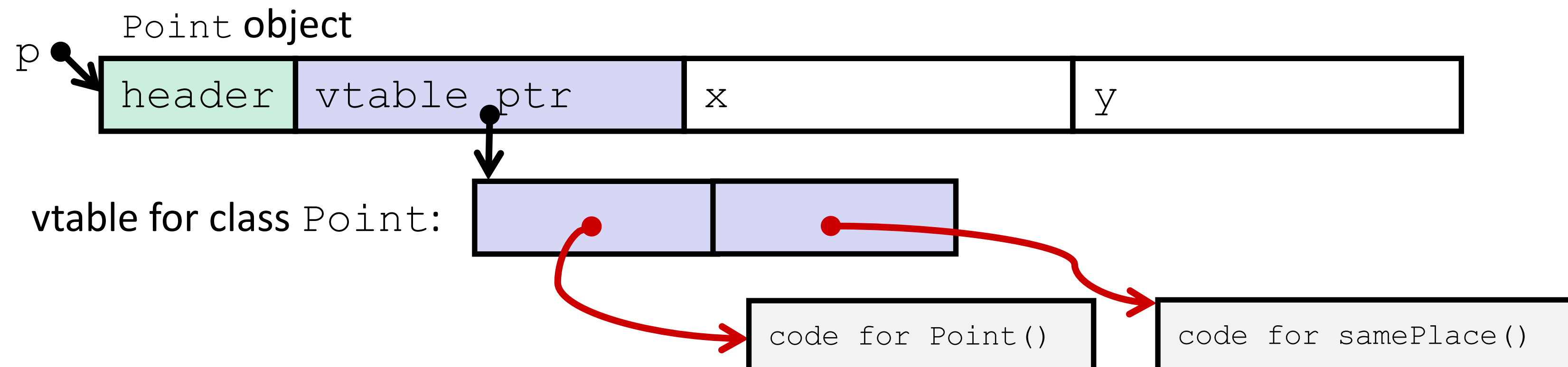
- Static methods are just like functions
- Instance methods:
  - Can refer to *this;*
  - Have an implicit first parameter for *this;* and
  - Can be overridden in subclasses
- The code to run when calling an instance method is chosen *at runtime* by lookup in the vtable

Java:

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

C pseudo-translation:

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



Subclassing

```
class 3DPoint extends Point {
    double z;
    boolean samePlace(Point p2) {
        return false;
    }
    void sayHi() {
        System.out.println("hello");
    }
}
```

new field

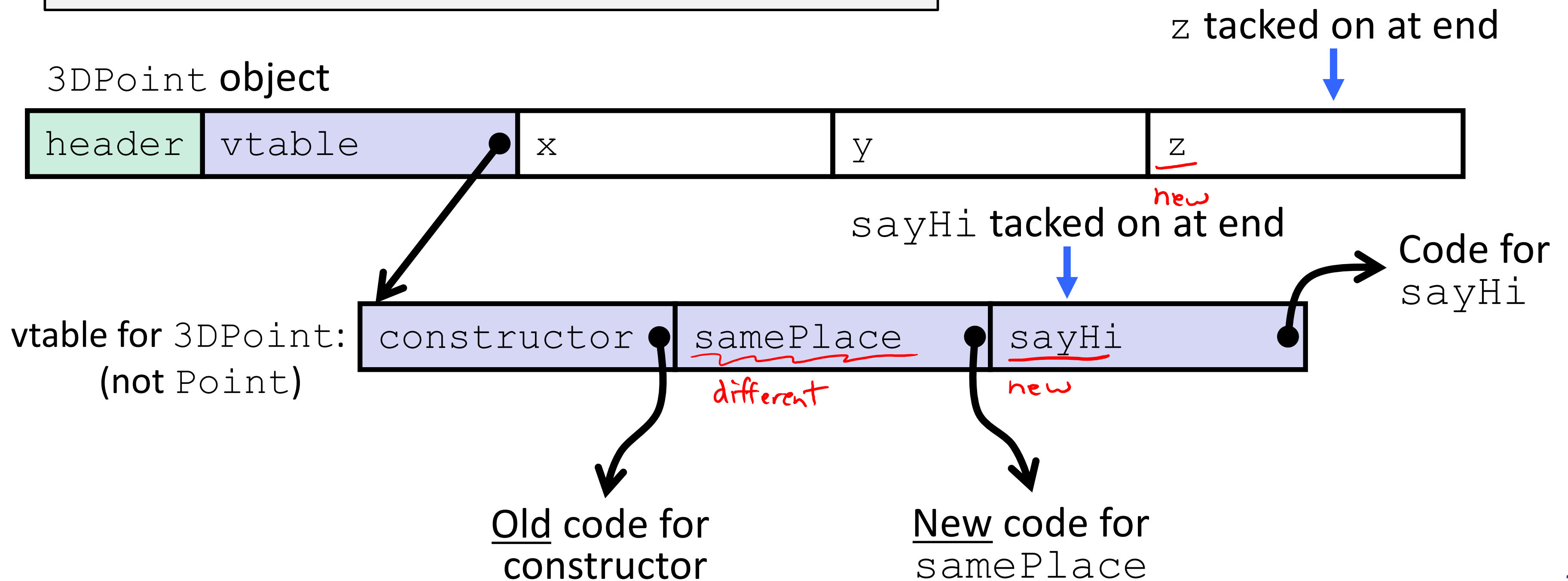
override method

new method

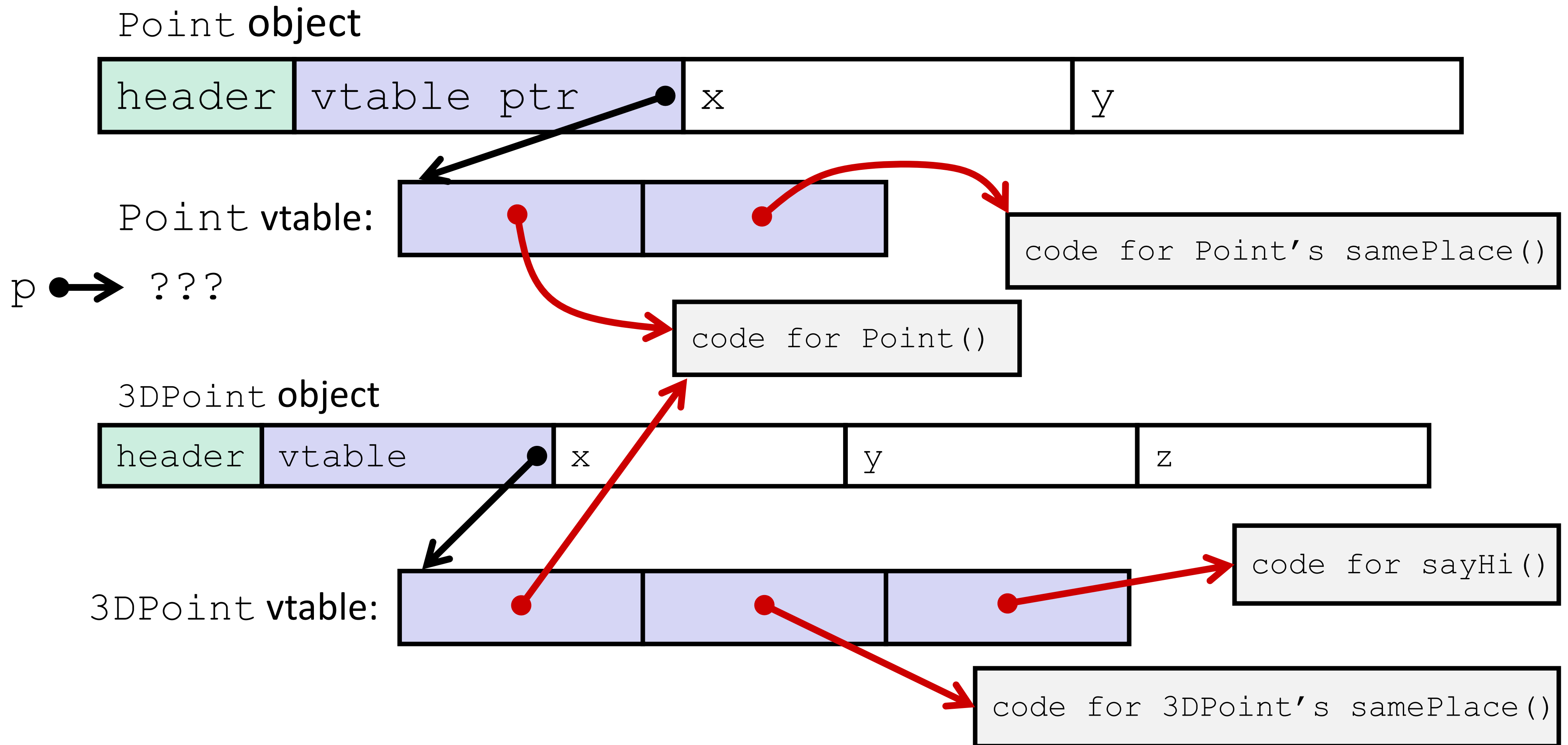
- Where does "z" go? At end of fields of `Point`
  - `Point` fields are always in the same place, so `Point` code can run on `3DPoint` objects without modification
- Where does pointer to code for two new methods go?
  - No constructor, so use default `Point` constructor
  - To override "`samePlace`", use same vtable position
  - Add new pointer at end of vtable for new method "`sayHi`"

Subclassing

```
class 3DPoint 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;
```

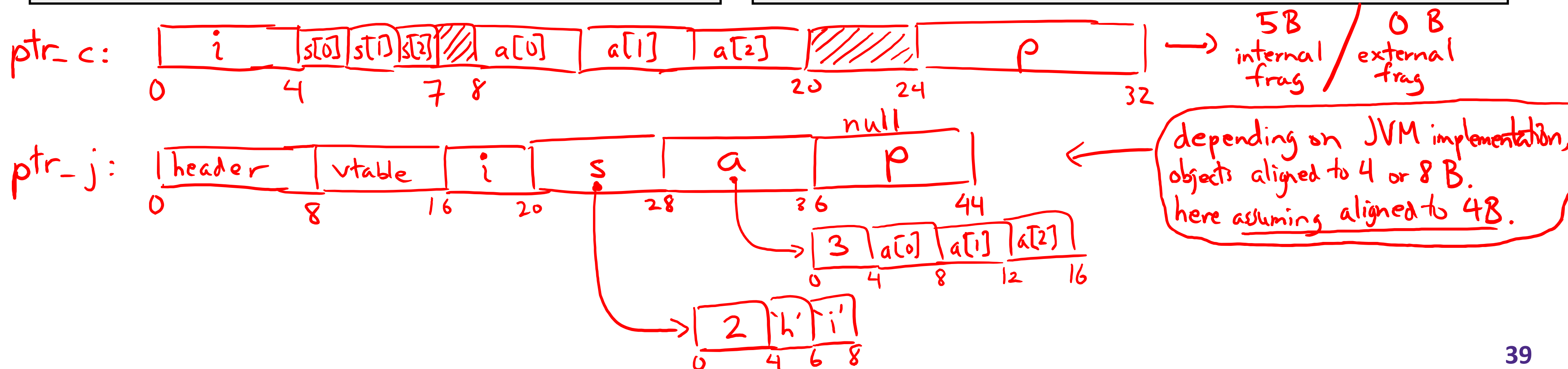
```
class jobj {
  int i;
  String s = "hi";
  int[] a = new int[3];
  jobj p;
}
jobj ptr_j = new jobj();
```

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` (32 B) and `ptr_j`? (44 B)

```
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();
```



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 =
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```

Assembly language:

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get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
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Machine code:

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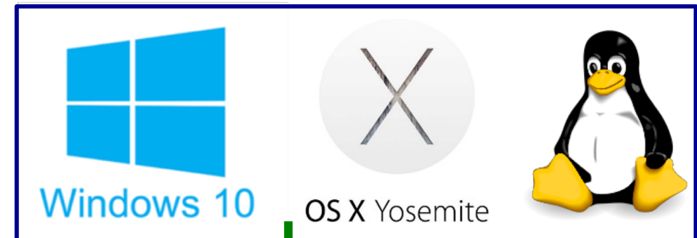
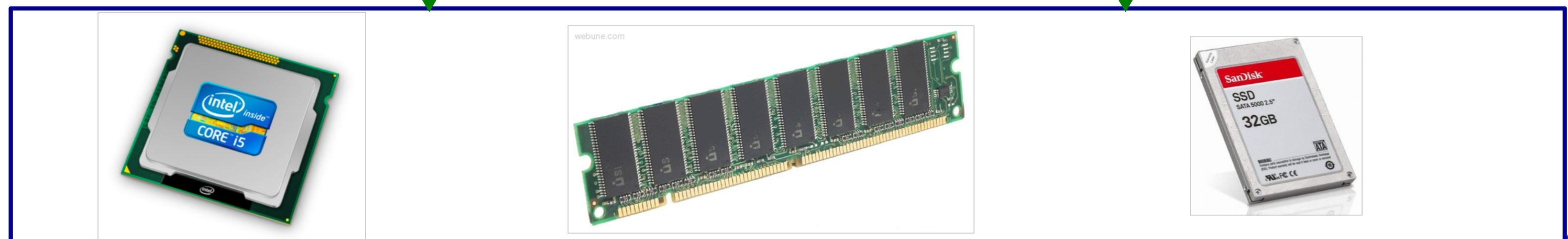
```

OS:



Computer system:



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