# CSE 12:
# Basic data structures and object-oriented design

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Lecture Three
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# The Java Virtual Machine (JVM).

# Why study the Java VM?

- Before studying the more complicated data structures, it is important to understand the relationship between a **computer program** and the **memory** on which it operates.
- In the case of Java, this entails a discussion of the Java Virtual Machine (JVM).

# “Real machines”

- To appreciate “virtual machines”, let’s first consider how a source program is converted to an executable program on a “real machine”:
  - The programmer writes some **source code**.
  - He/she then **compiles** the source code into **machine instructions** that are specific to the particular hardware platform.

# “Real machines”

- If the programmer wants her program to run on 5 different hardware platforms, she needs to:
  - Write the source code only once (thank goodness!).
  - Compile the source code 5 times.

# “Real machines”

Source code

```
class MyClass {
  void myMethod () {
  }
  ...
```

Intel compiler

Intel machine language

Intel executable file


ARM compiler

ARM machine language

ARM executable file


Snapdragon compiler

Snapdragon machine language

Snapdragon executable file

# Java

- In the 1990s, Sun Microsystems developed a new programming language called “Java”.
  - Motto: “Write once, run everywhere.”
- This might be more aptly described as, “Compile once, run everywhere.”
  - Once Java code is compiled, it can run on any platform, irrespective of CPU type.
    - How is this possible?

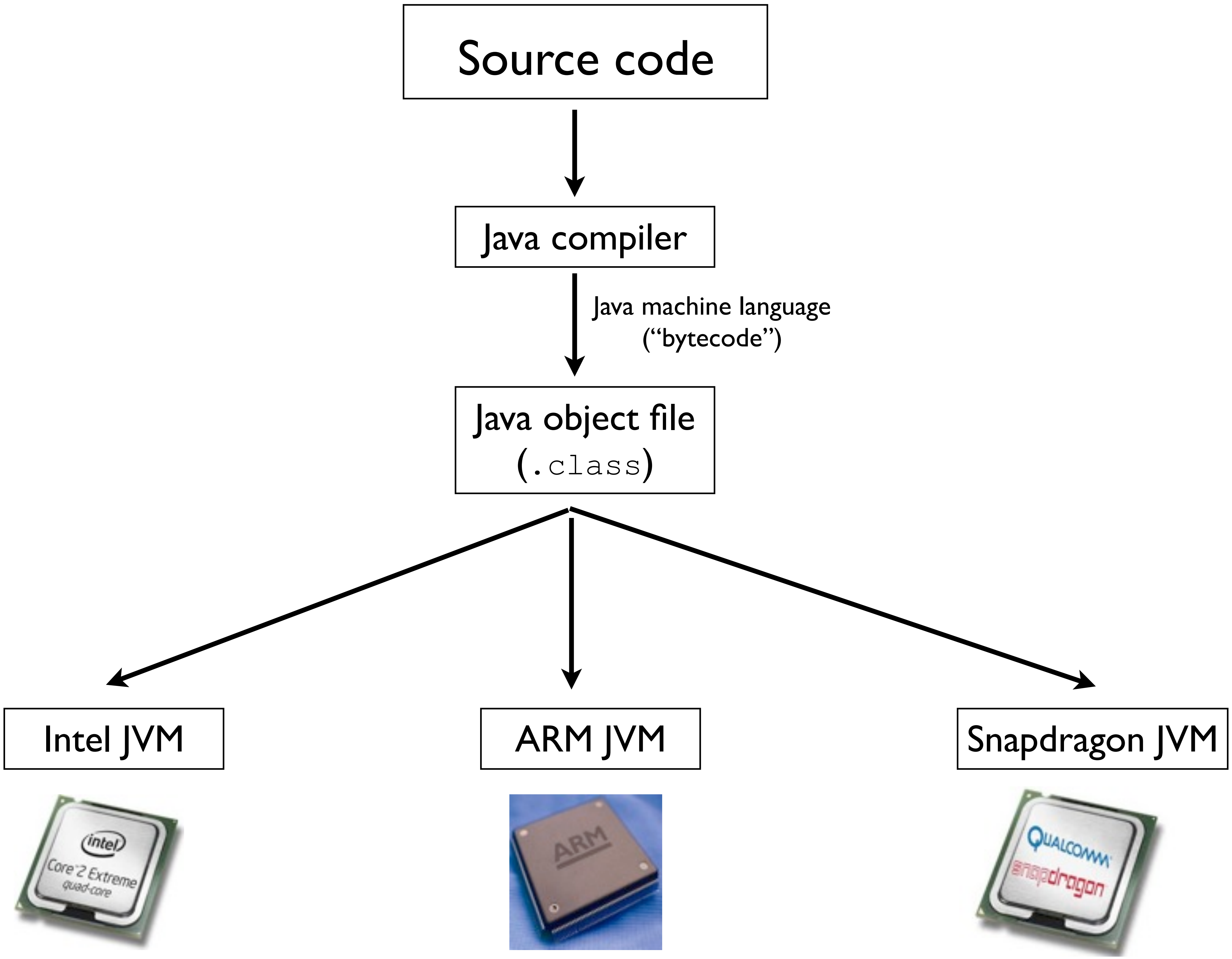
# Java Virtual Machine

- The designers of Java inserted a layer of *abstraction* between the Java compiler and the hardware CPUs.
- This abstraction is called the Java Virtual Machine (JVM).
- The JVM provides a convenient "abstract machine language" that can run on *any CPU*.
- This means that a Java program need only be compiled *once*, and it can run on *any* hardware platform.

# Java Virtual Machine

- The JVM was also designed from the ground-up to provide *security*, e.g.:
  - Bounds checking: it won't let you access the 9th element of an 8-element array.
  - Type safety: it won't let you treat an **`Integer`** as a **`String`**.

# Java Virtual Machine



# Java Virtual Machine

- *Every* compiled Java `.class` file will run on *every* Java Virtual Machine for *every* hardware platform in the *same* way.
- This *convenience through abstraction* comes at a price:
  - A new JVM must be created for every hardware platform.
  - The burden of **portable** code has shifted from software programmer to operating system designer + hardware manufacturer.

# Java Virtual Machine

- The Java Virtual Machines are, themselves, software programs.
- The JVMs simulate a "Java CPU":
    - They read the "bytecode" from the .class files, and then convert the *abstract* "Java instructions" to *real* CPU instructions.

# Java Virtual Machine

`x += 10;` — Java source code

↓

Java compiler

↓

`iinc 1, 10` — Java machine language (bytecode)

↓

JVM must convert from bytecode to native machine language in real time.

Intel JVM

↓

`addl $10, -4(%rbp)` — Intel machine language

↓

# Java Virtual Machine

- Every instruction of bytecode must be converted into a *real* instruction on the *actual* hardware CPU.
  - This incurs a cost -- Java is typically slower than C.
- The JVM plays an analogous role to the memory controller from last lecture -- it *implements an abstraction*.

# Memory management in the JVM

# Your data inside the JVM

- Compiled Java programs execute within the Java Virtual Machine.
- All Java programs need to store some **data**.
- Data are manipulated in Java using **variables**.
- It is helpful, when learning Java in general and data structures in particular, to understand *how the Java Virtual Machine manages these variables and data in memory*.

# Variables in Java

- In Java, all variables are either of *primitive* or *reference* type.
- Primitive types:

  **`boolean`**, **`byte`**, **`char`**, **`short`**, **`int`**, **`long`**, **`float`**, and **`double`**.

  E.g., **`float myHeight = 178.0;`** // cm

- Reference types:

  References to **`Object`**, subclasses of **`Object`**, all *interfaces*, and all *arrays*, e.g.:

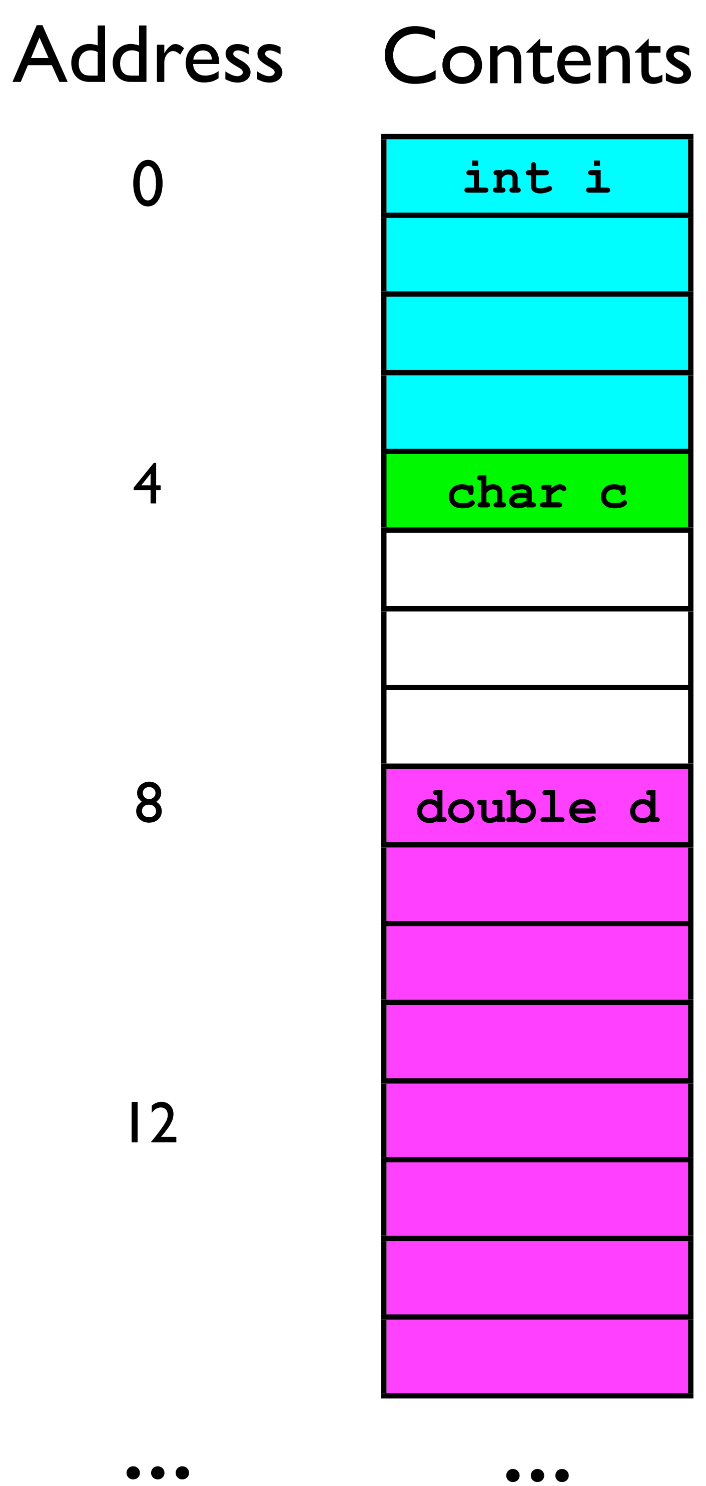
```
String s = "test";
int[] arrayOfInts = new int[16];
```

# Variables in Java

| Address | Contents |
| --- | --- |
| 0 | 11110110 |
| | 11001001 |
| | 01010001 |
| | 01011000 |
| 4 | 11101000 |
| | 11100000 |
| | 01000100 |
| | 11001110 |
| 8 | 01100101 |
| | 00101001 |
| | 01101111 |
| | 00010111 |
| ... | ... |

- The JVM's "system memory" can be viewed as a column of bytes, each with its own address.
- All data (**`int`**, **`float`**, **`Object`**, etc.) are stored somewhere in this memory column.
  - The location of each variable/object is called its *address*.

# Variables in JVM Memory

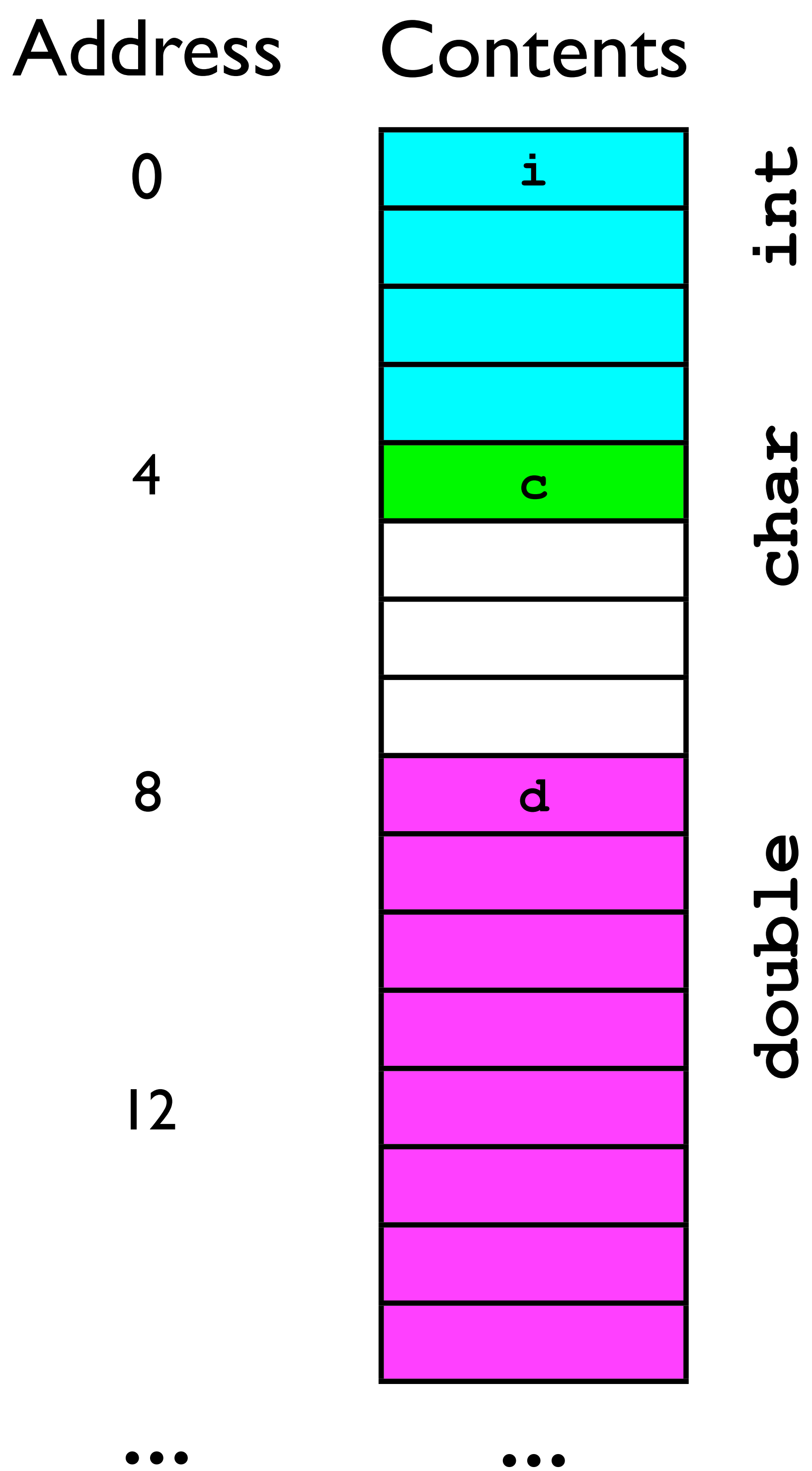



- Consider a method that declares three variables of primitive type:

```
void myMethod () {
  int i;
  char c;
  double d;
}
```

- These might be stored in memory as shown to the left.

# Variables in JVM Memory




- Different variables require different numbers of bytes for storage:

**`byte`**, **`char`**: 1

**`short`**: 2

**`int`**, **`float`**: 4

**`long`**, **`double`**: 8

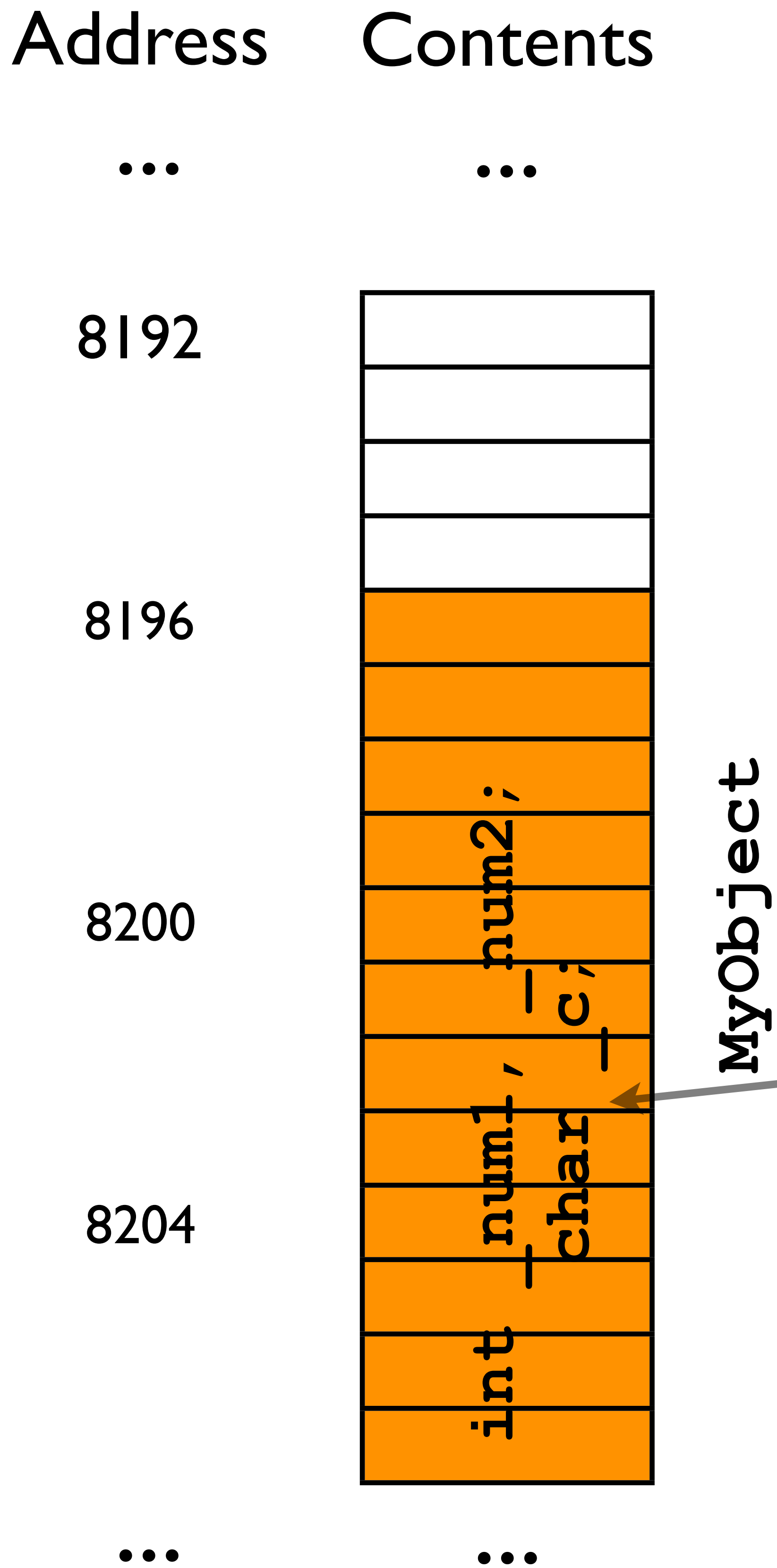
# Objects in JVM Memory

- Objects also (of course) take up memory.
  - How much memory they need depends on the **instance variables** stored in them.

```
class MyObject {
  int _num1, _num2;
  char _c;
}
```

    - 2 `ints` + 1 `char` = 9 bytes (The JVM probably rounds up to nearest multiple of 4.)
  - There is also some amount of overhead (even if your class defines no instance variables).

# Variables in JVM Memory




- An object of type **`MyObject`** may require about 12 bytes.
    - The exact amount depends on the particular JVM.
- Somewhere within those bytes are **`_num1`**, **`_num2`**, and **`_c`**.
    - The exact location depends on the particular JVM.

# References

- Consider the following code:
  `MyObject obj = new MyObject();`
- This code actually refers to **two** "things" in memory:
  - The newly created *object* of type `MyObject` (about 12 bytes).
  - The *reference* `obj` to that new object (just 4 bytes -- enough to store a memory address on a 32-bit machine).
- **A *reference* in Java stores the location (address) in memory of an object or array.**

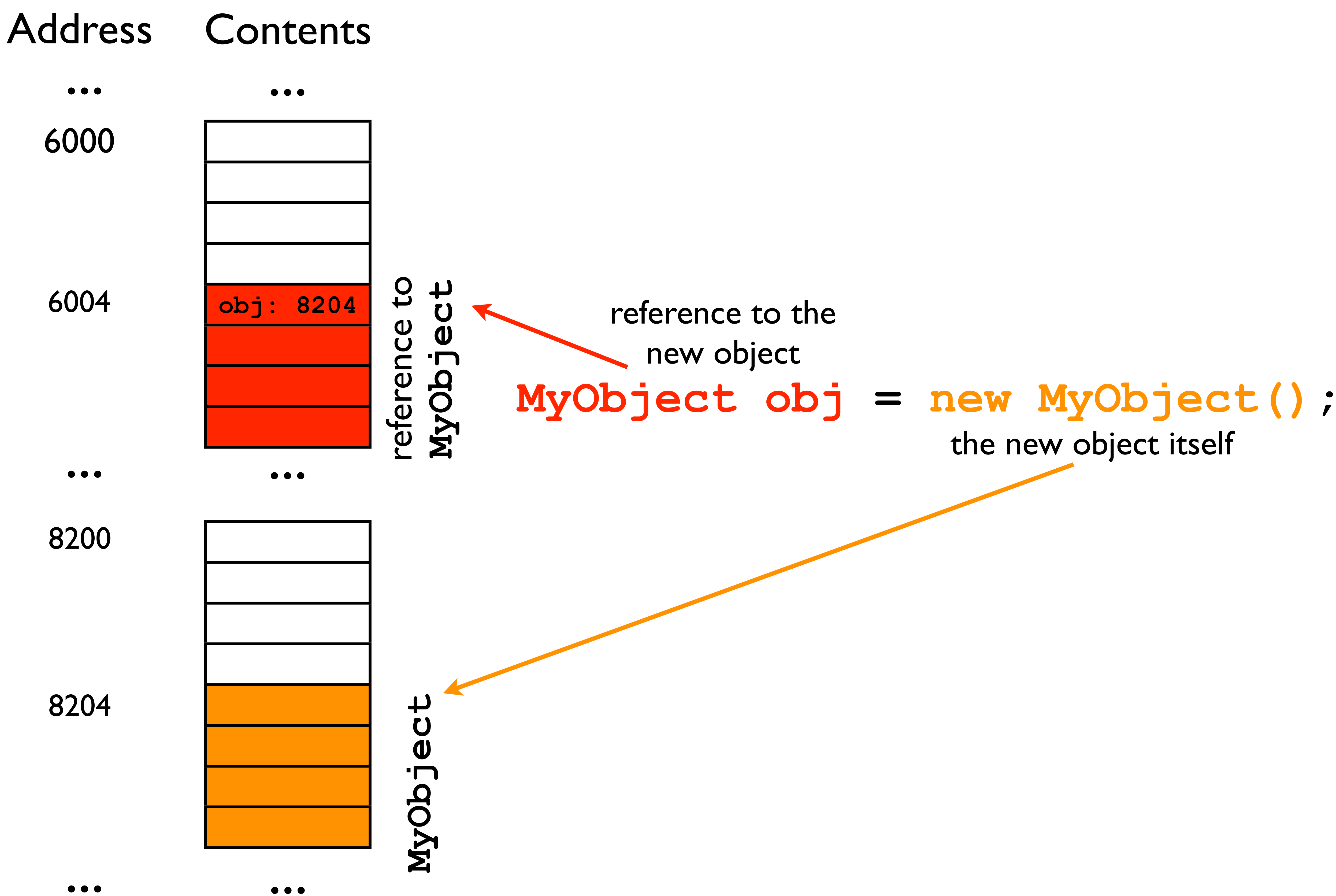
# References

- The call to **`new MyObject()`** causes the Java Virtual Machine to instantiate a new object of type **`MyObject`**.
  - Memory is *allocated* ("set aside") for the new object.
- The result of the "**`new`**" call is the *address* of the newly created object.
- In **`MyObject obj = new MyObject()`**, this address is then stored in the **`MyObject`**-reference **`obj`**.

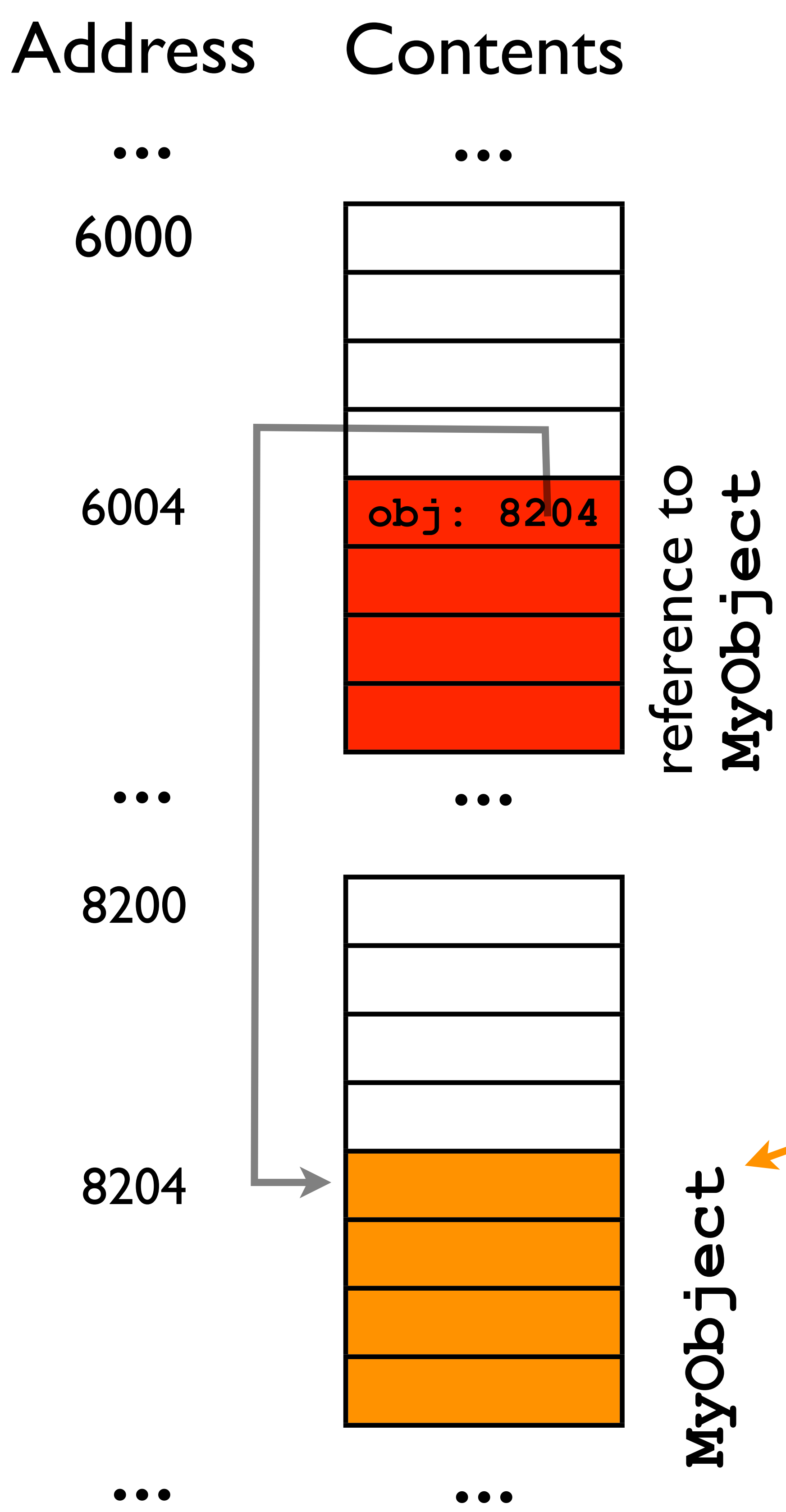
# References

- If you “forget” to store the address returned by **`new MyObject()`**, then the newly created object will be essentially “forgotten” -- there’s no way to know where in memory it is stored.
  - Example:
```
new Object();  // Creates a new object, then
               // promptly forgets where it is.
```
  - (Eventually, the garbage collector will remove it.)

# Objects, and references to objects



# Objects, and references to objects




- In effect, the reference "points to" the newly created object by storing its address.
- This is why references are sometimes called **pointers.**

reference to the new object

```
MyObject obj = new MyObject();
```

the new object itself

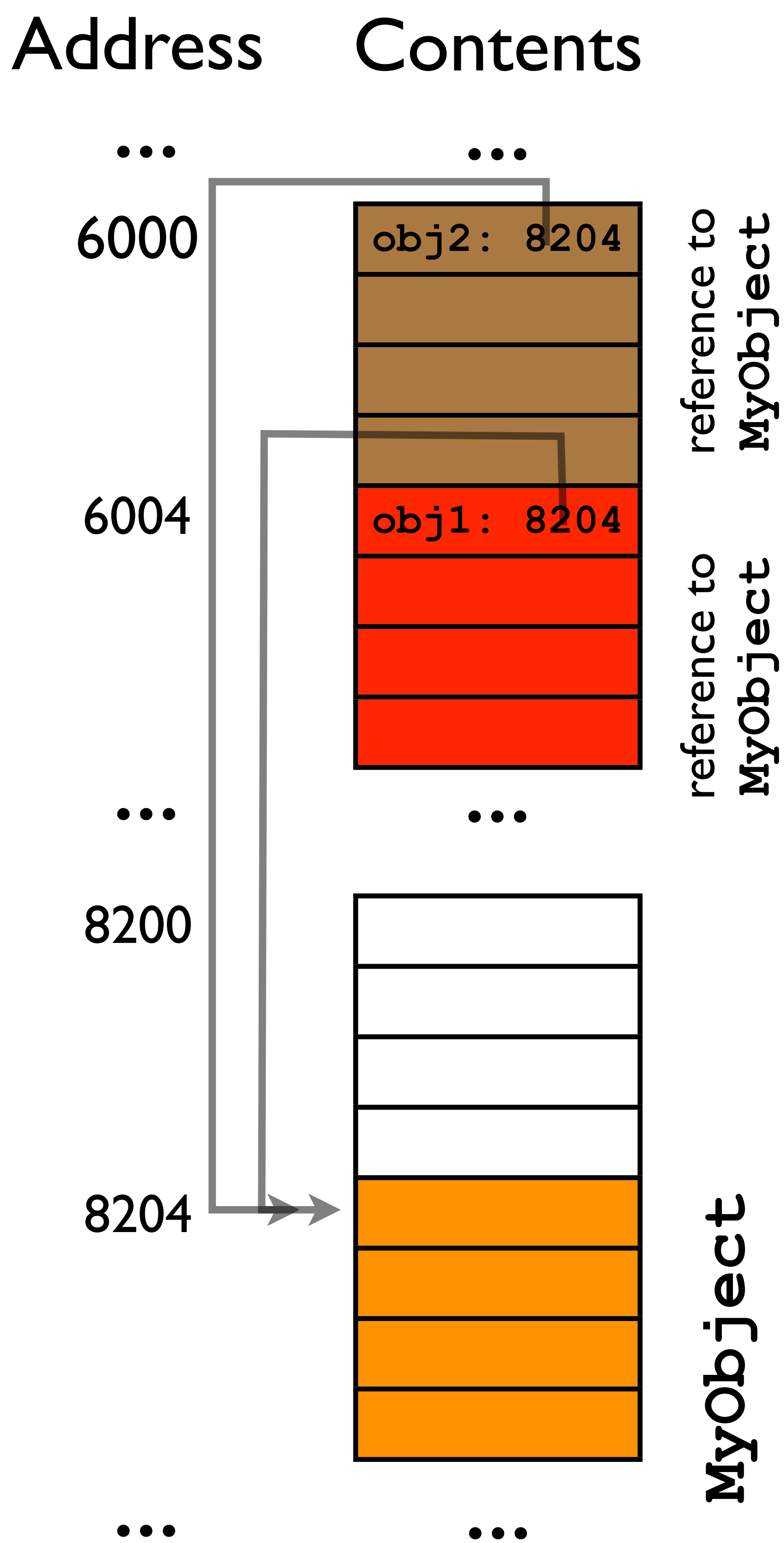
# Multiple references to same object

- Consider:

```
MyObject obj1 = new MyObject();
MyObject obj2 = obj1;
```

- Object-references `obj1` and `obj2` now point to the *same*, newly created object.
  - If you modify `obj1._num1`, this will also affect `obj2._num1`

# Multiple references to same object




```
MyObject obj1 = new MyObject();
MyObject obj2 = obj1;
```

- All you're doing in line 2 is setting the *address* stored in variable **`obj2`** to the same *address* stored in variable **`obj1`**.
- This causes **`obj2`** to "point to" the same object that **`obj1`** points to.

# Multiple references to same object

- Example:

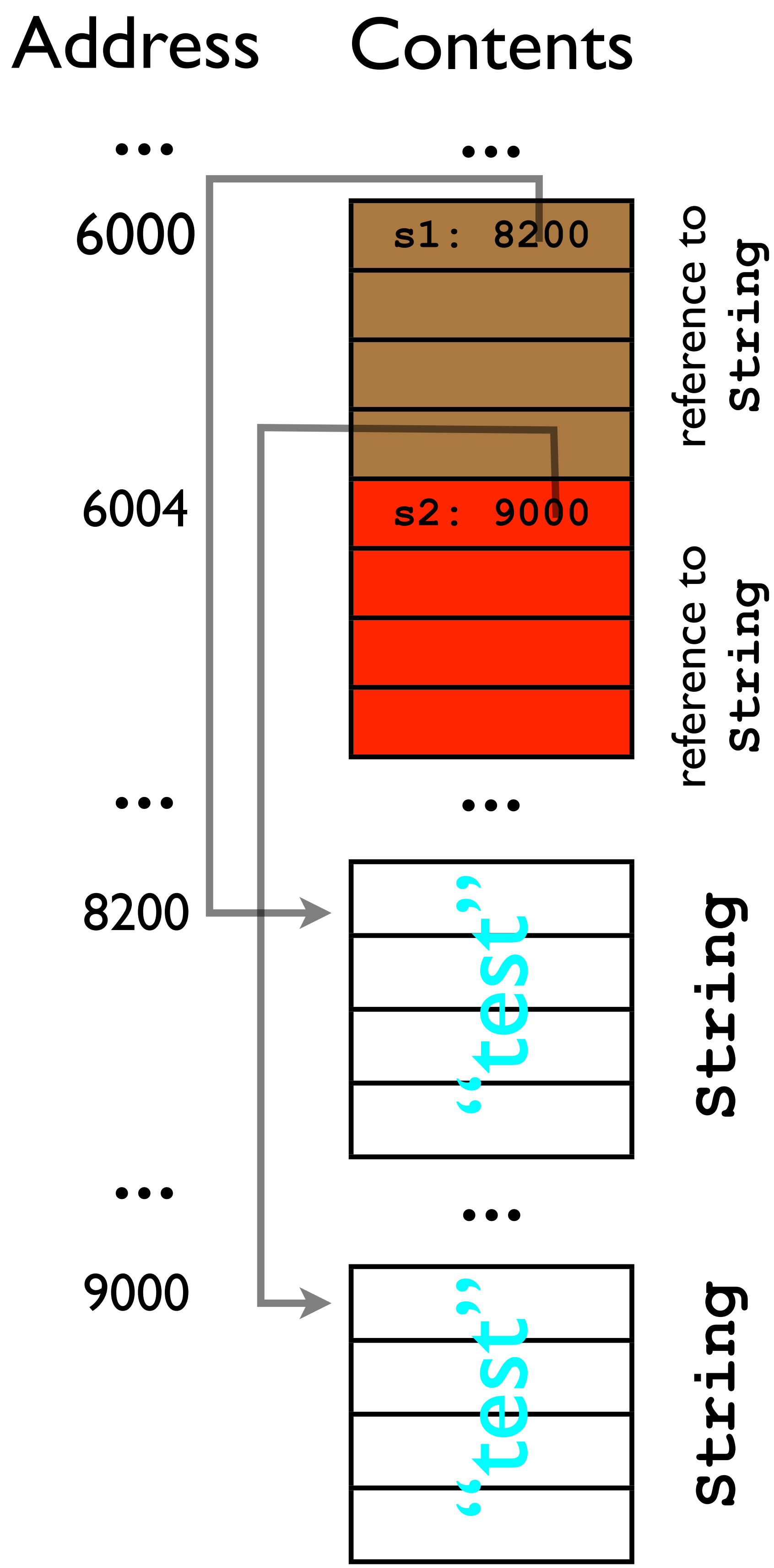
```
MyObject obj1 = new MyObject();
MyObject obj2 = obj1;
obj1._num1 = 5;
obj2._num1 = 6;
System.out.println(obj1._num1);
// Prints out 6 !
```

# == versus equals()

- The discussion of references brings up the issue of "equality" between objects.
  - ```
    String s1 = new String("test");
    String s2 = new String("test");

    s1.equals(s2)
    s1 == s2
    ```
    ```

# == versus equals()

- The discussion of references brings up the issue of "equality" between objects.
  - ```
    String s1 = new String("test");
    String s2 = new String("test");

    s1.equals(s2)  // true
    s1 == s2       // false! -- why?
    ```
- **`s1.equals(s2)`** compares the *contents* of the objects pointed to by **`s1`** and **`s2`**.
- **`s1 == s2`** compares the *addresses* stored in reference-variables **`s1`** and **`s2`**!
    ```

# == versus equals()




- `s1` and `s2` point to two different `String` objects.
- The *contents* of the two `Strings` happens to be the same.

# Dereferencing operator

- You're already well-familiar with the dereferencing operator `.` (dot).

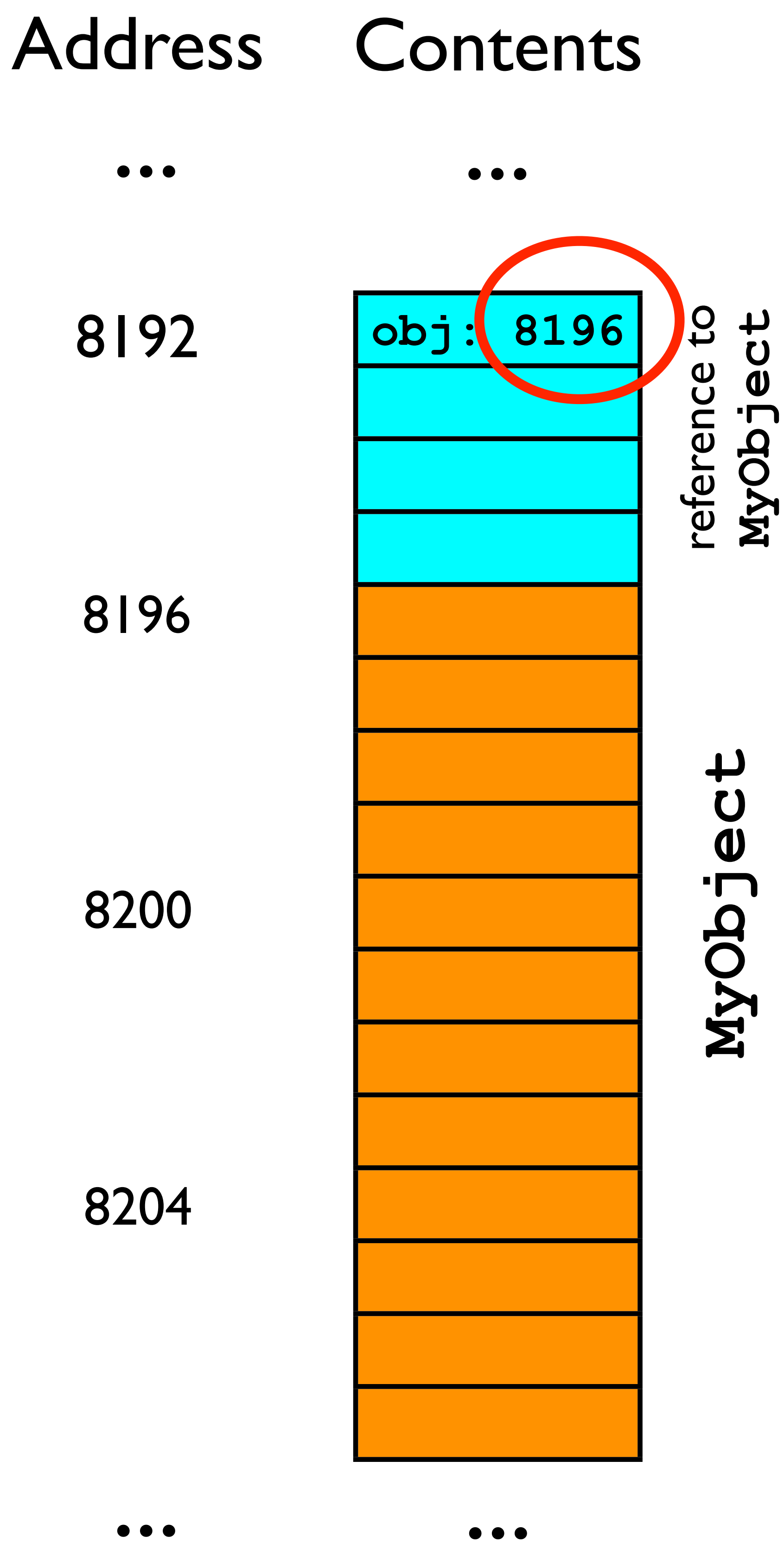
```
MyObject obj = new MyObject();
obj._num1 = 3;
```

What does this really mean in terms of memory?

Left side: valid (non-`null`) reference

Right side: name of instance/class variable.

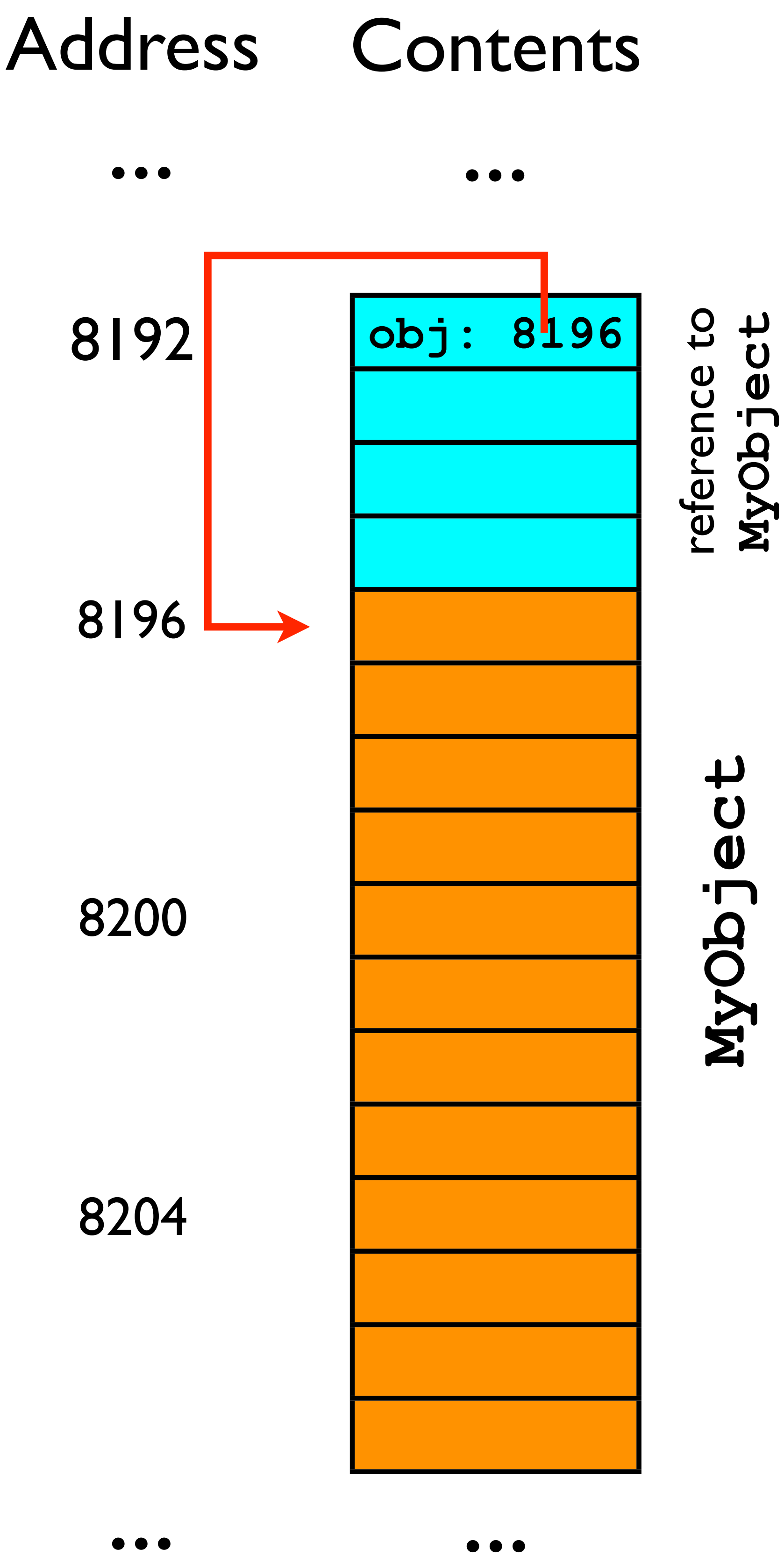
# Dereferencing operator




```
obj._num1 = 3;
```

- Step 1: read the address stored in `obj` (8196).

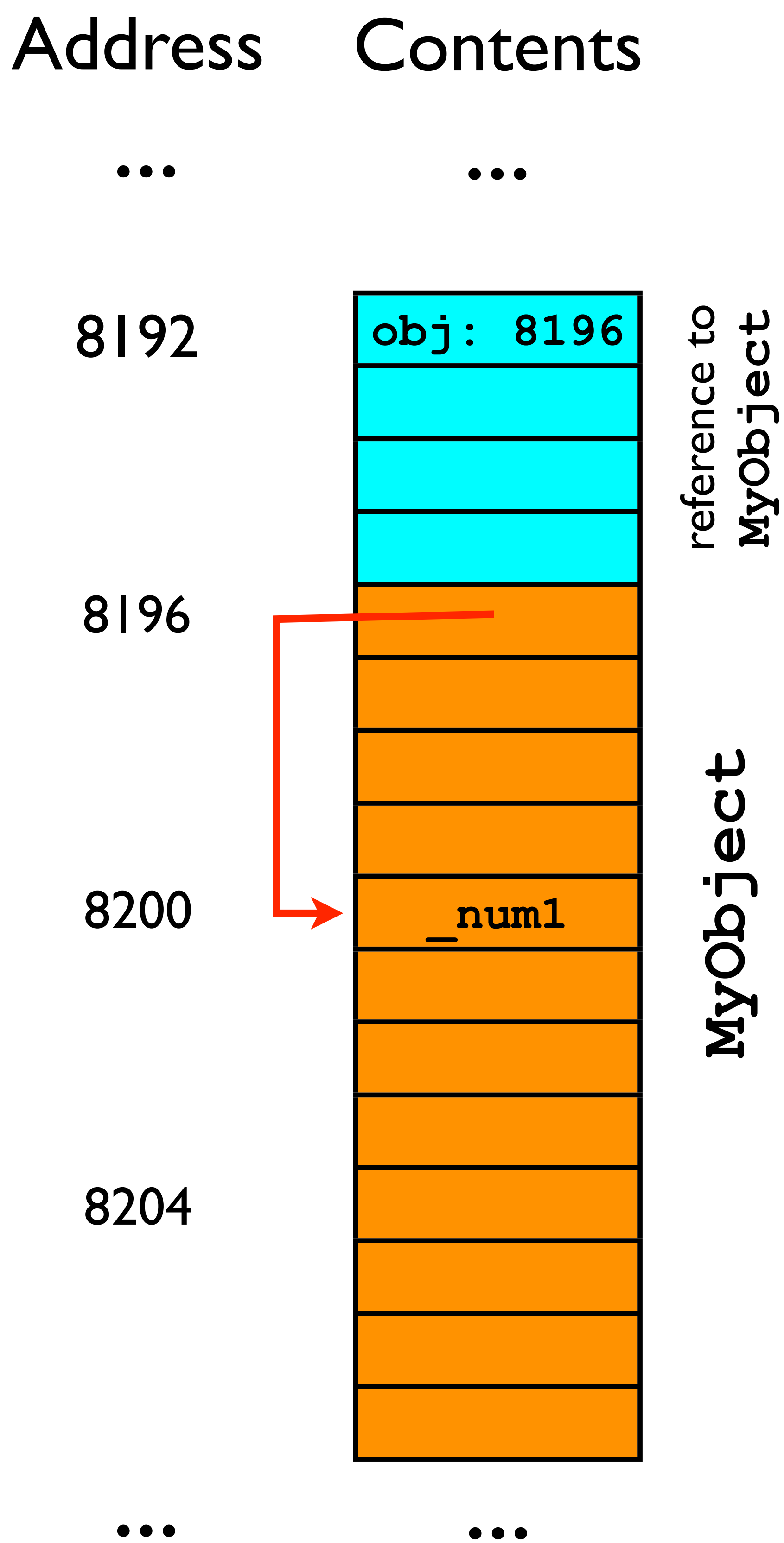
# Dereferencing operator




`obj._num1 = 3;`

- Step 1: fetch the address stored in `obj` (8196).
- Step 2: dereference ("go to") that address.

# Dereferencing operator

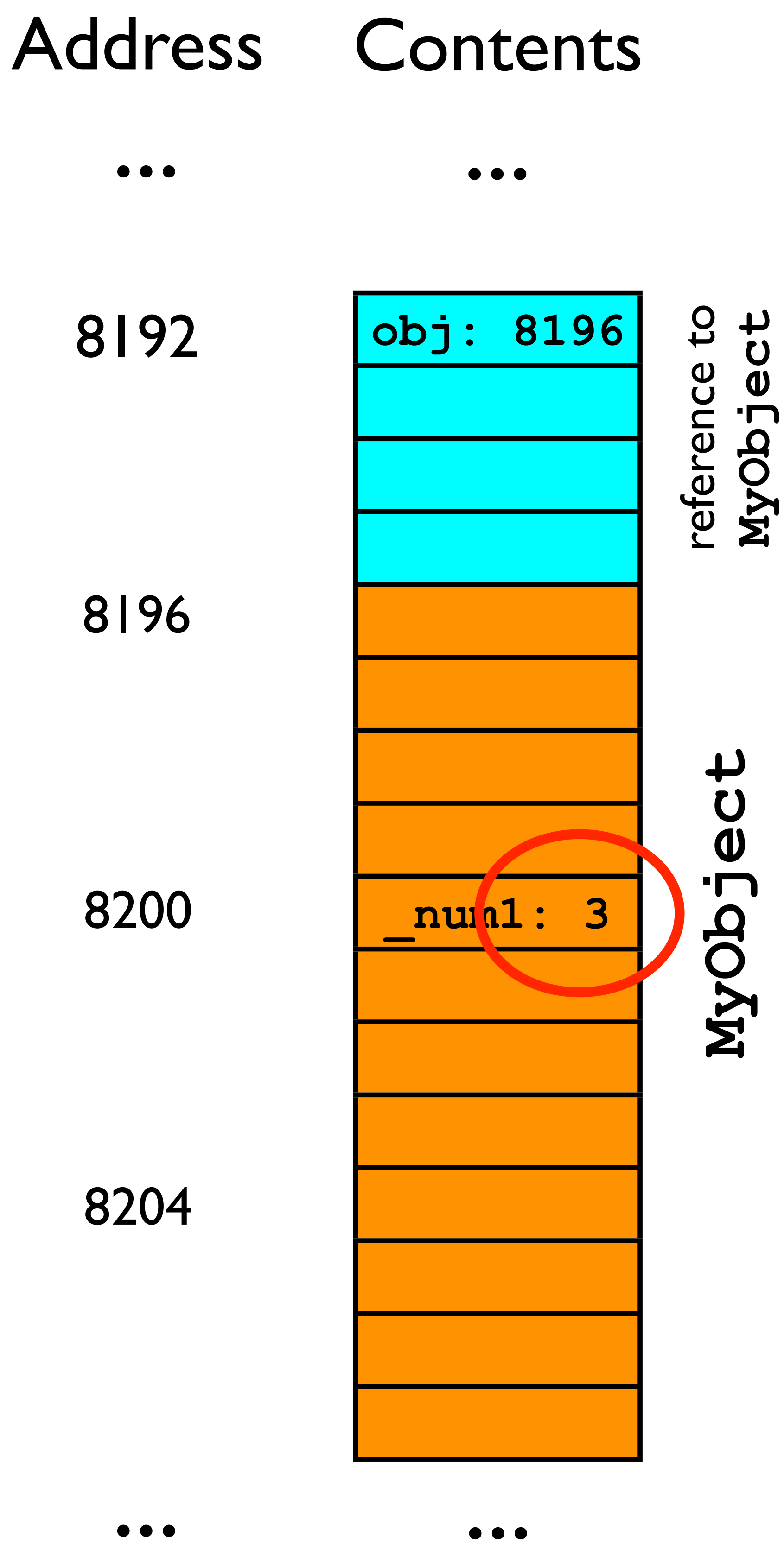



`obj._num1 = 3;`

- Step 1: fetch the address stored in `obj` (8196).
- Step 2: dereference ("go to") that address.
- Step 3: find where in that `MyObject` the instance variable `_num1` is stored.

(This is hidden from the programmer, but the JVM knows where it is.)

# Dereferencing operator




`obj._num1 = 3;`

- Step 1: fetch the address stored in **`obj`** (8196).
- Step 2: dereference ("go to") that address.
- Step 3: find where in that **`MyObject`** the instance variable **`_num1`** is stored.
- Step 4: set its value to 3.

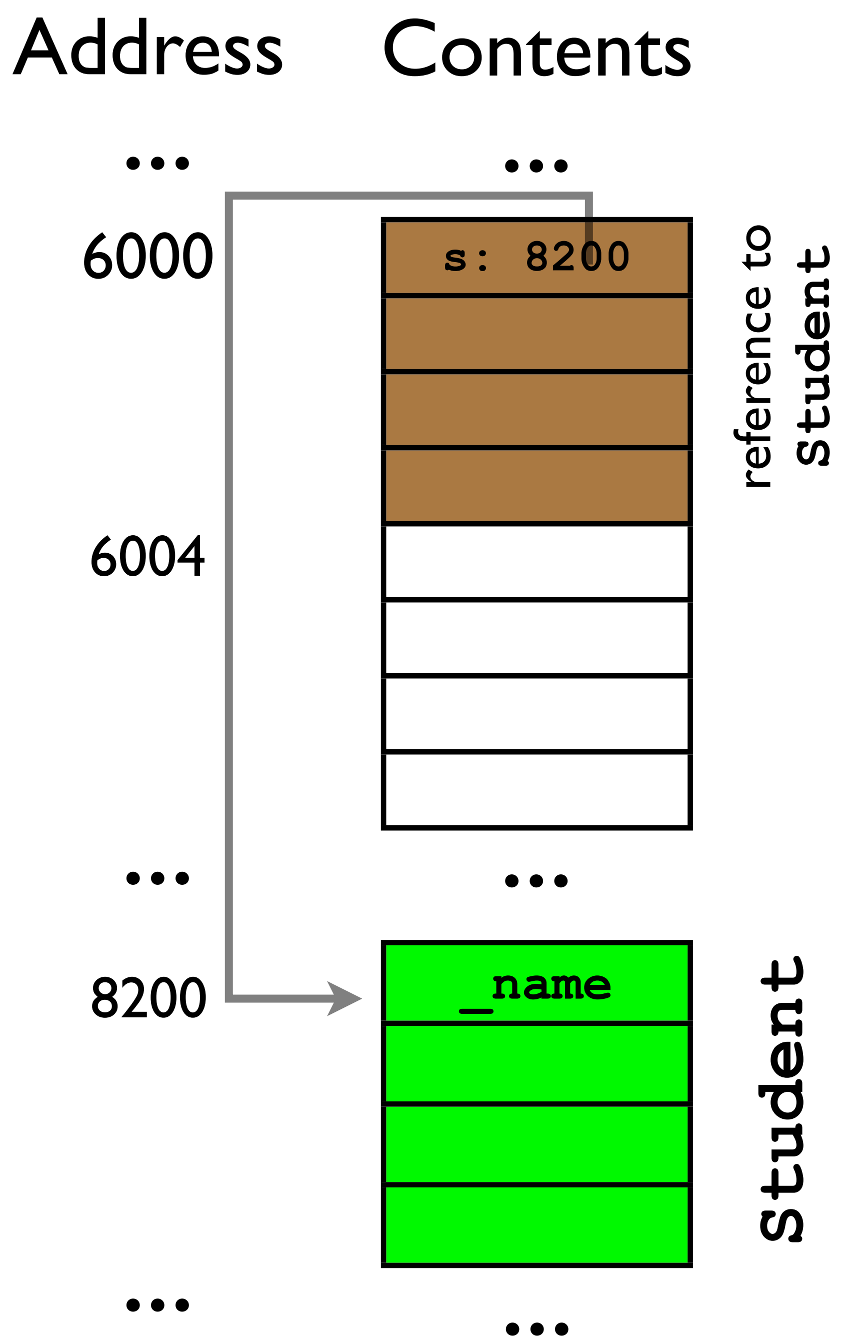
# References inside objects

- It is commonplace for objects to contain instance variables that are references to other objects.

```
class Student {
  String _name;
  int _age;
}
```

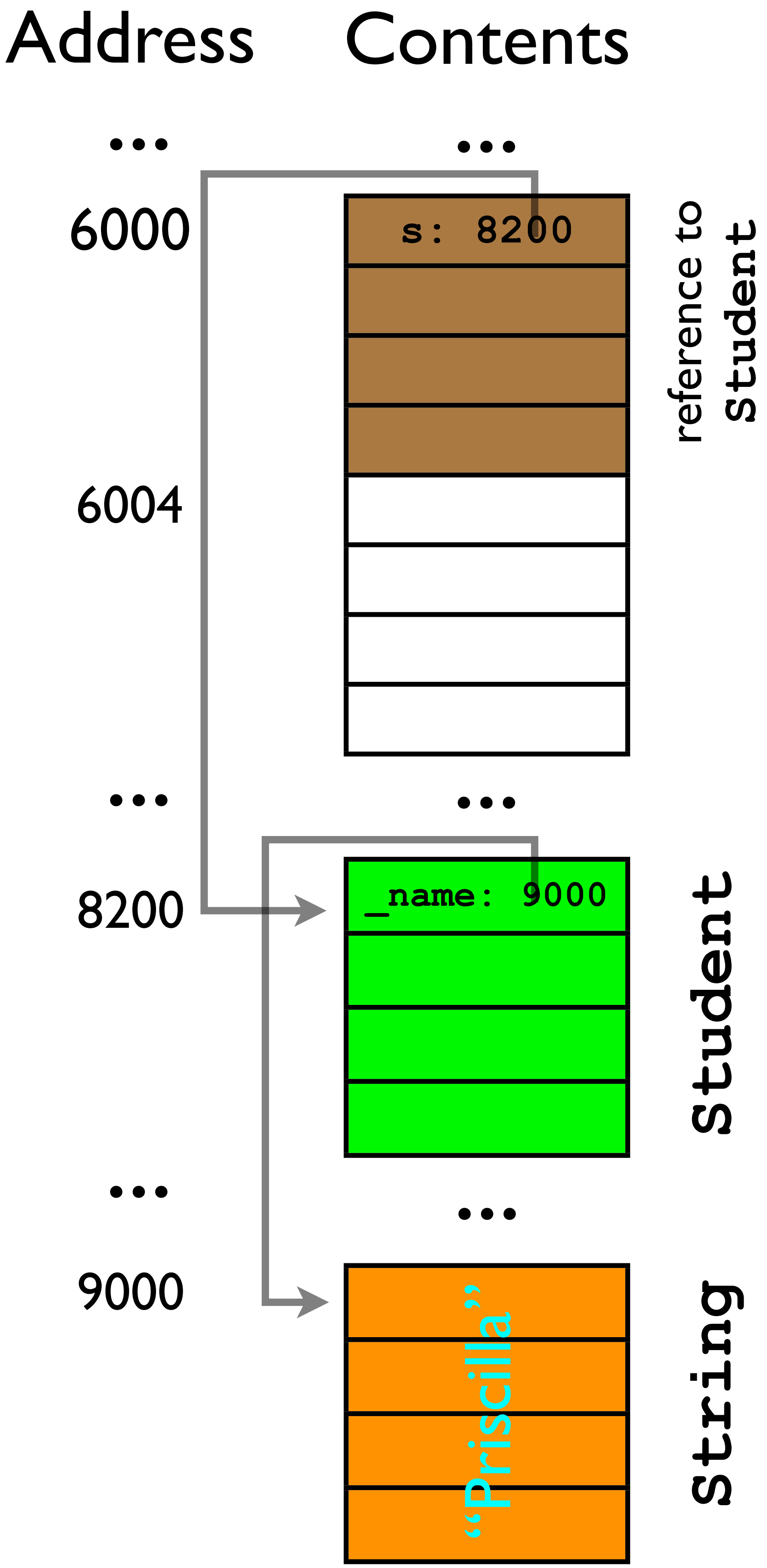
The `_name` instance variable of a `Student` object is a reference to a `String` object.

# References inside objects




```
Student s = new Student();
```

# References inside objects

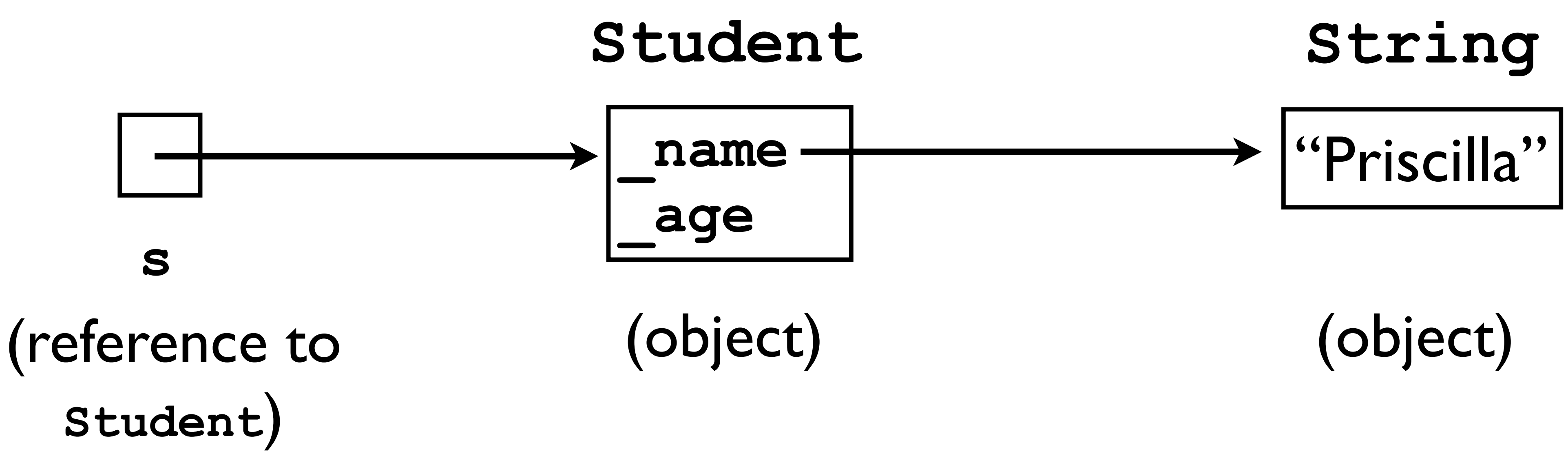



```
Student s = new Student();
s._name = "Priscilla";
```

# Simplified memory diagrams

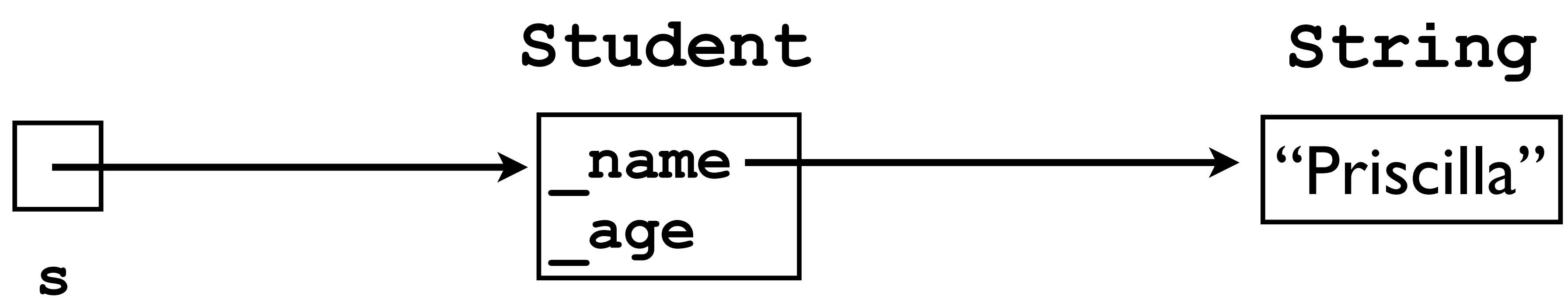
- We've seen these columnar memory diagrams a lot now.
- Let's take a more "abstract" perspective on memory and not worry about the particular memory addresses as much.
- Let's also move the objects out of the memory column to illustrate their relationships better.
  - In reality, of course, the objects are all stored somewhere on some memory DIMM (chip) as a sequence of 1's and 0's...
    - Yada yada yada...

# Simplified figure for `class Student`

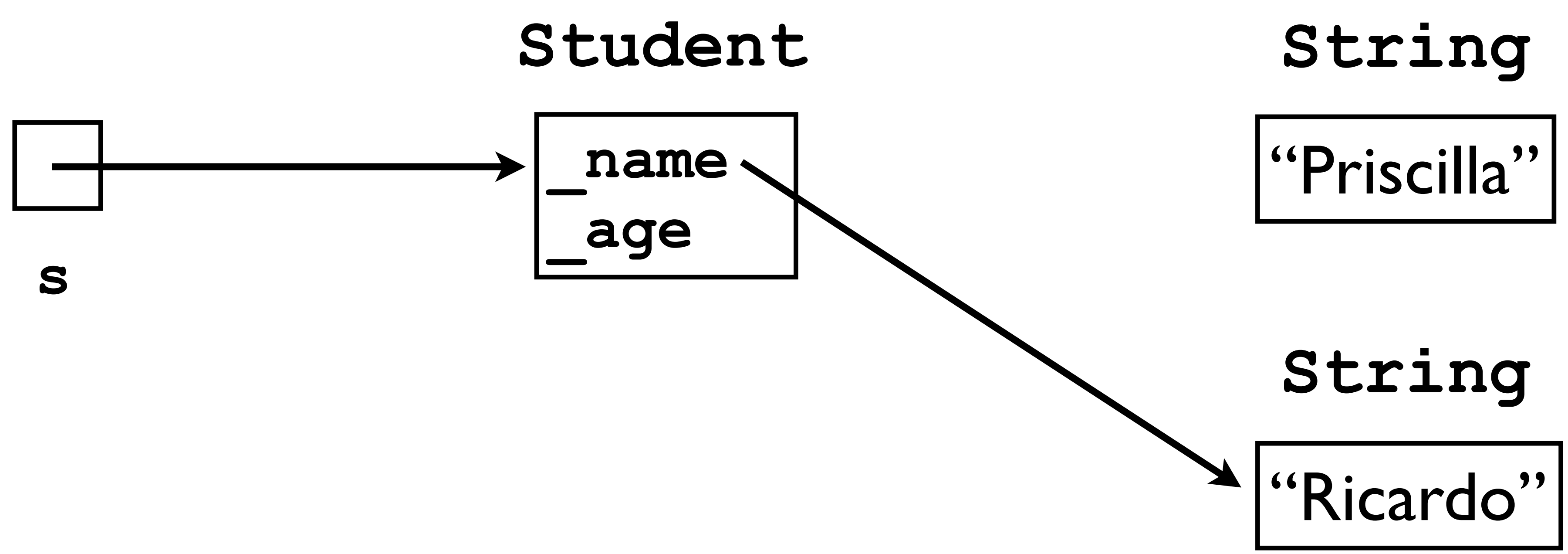



**Inside the boxes**: Sometimes I will write the *names* of instance variables and sometimes their *values*; it should be clear from the context.

# Even simpler figure for `class Student`



# Changing `s._name`




```
s._name = “Ricardo”;
```

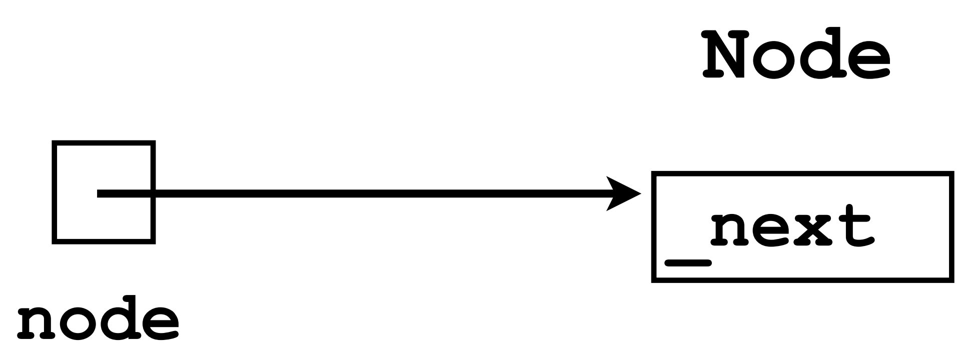
# Here's where things get fun...

- It is also (sometimes) useful for an object to contain a reference to *another* object of the *same class*.
- In this way, we can "chain" together multiple objects.
- Example:

```
class Node {
  Node _next;
}
```

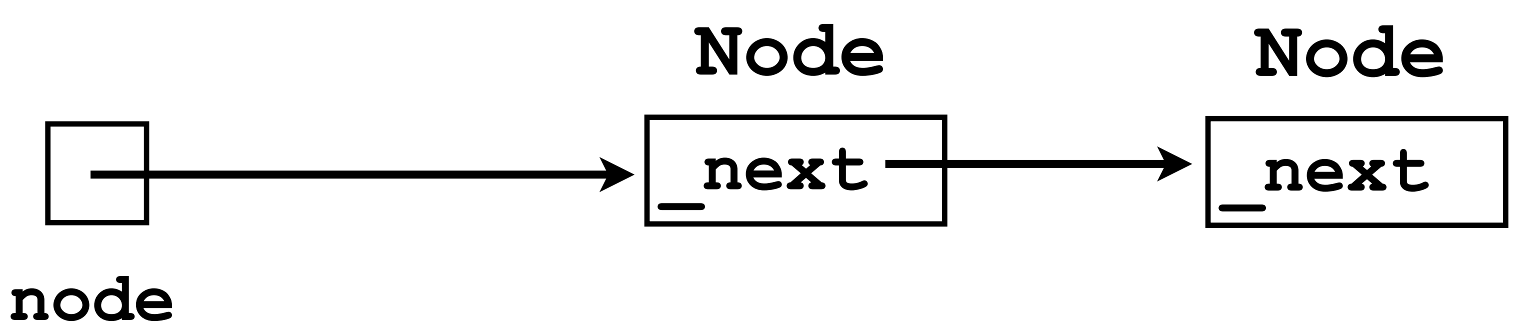
# Chain of **Nodes**

```
Node node = new Node();
```



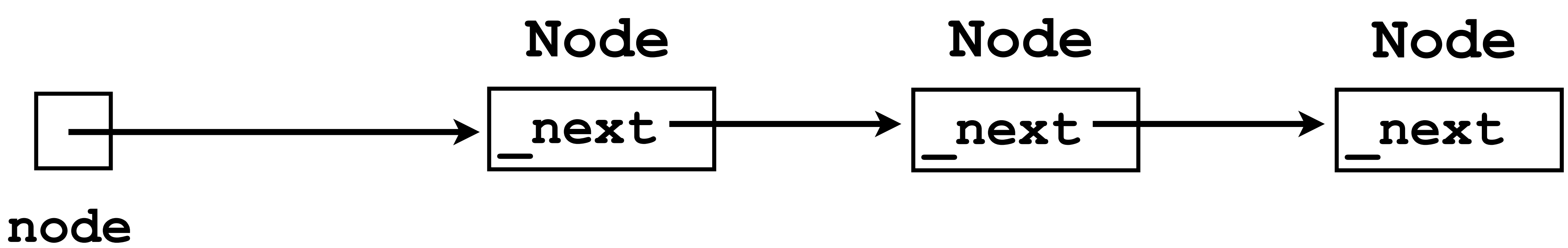
# Chain of **Nodes**

```
Node node = new Node();
node._next = new Node();
```



# Chain of **Nodes**

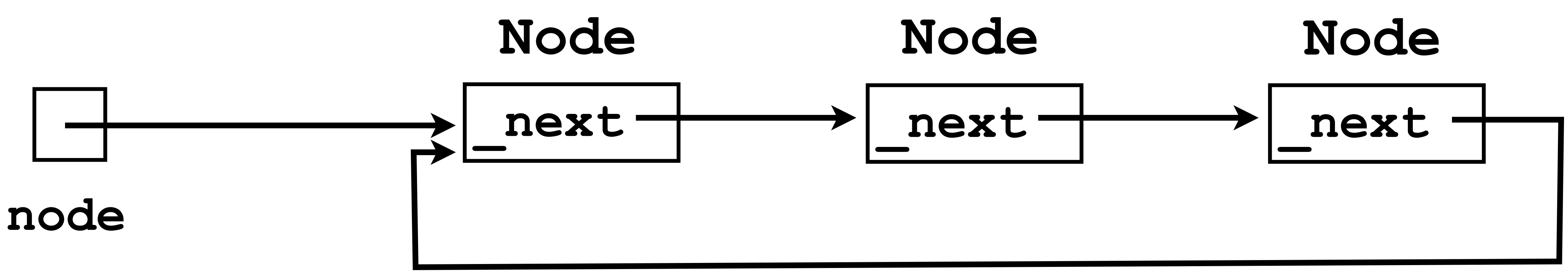
```
Node node = new Node();
node._next = new Node();
node._next._next = new Node();
```



# Loop of **Nodes**

We can even create a “loop”:

```
node._next._next._next = node;
```



# Node chains and loops

- Why would we want to build these bizarre structures?
    - They are sometimes useful in implementing ADTs.

# Linked lists.

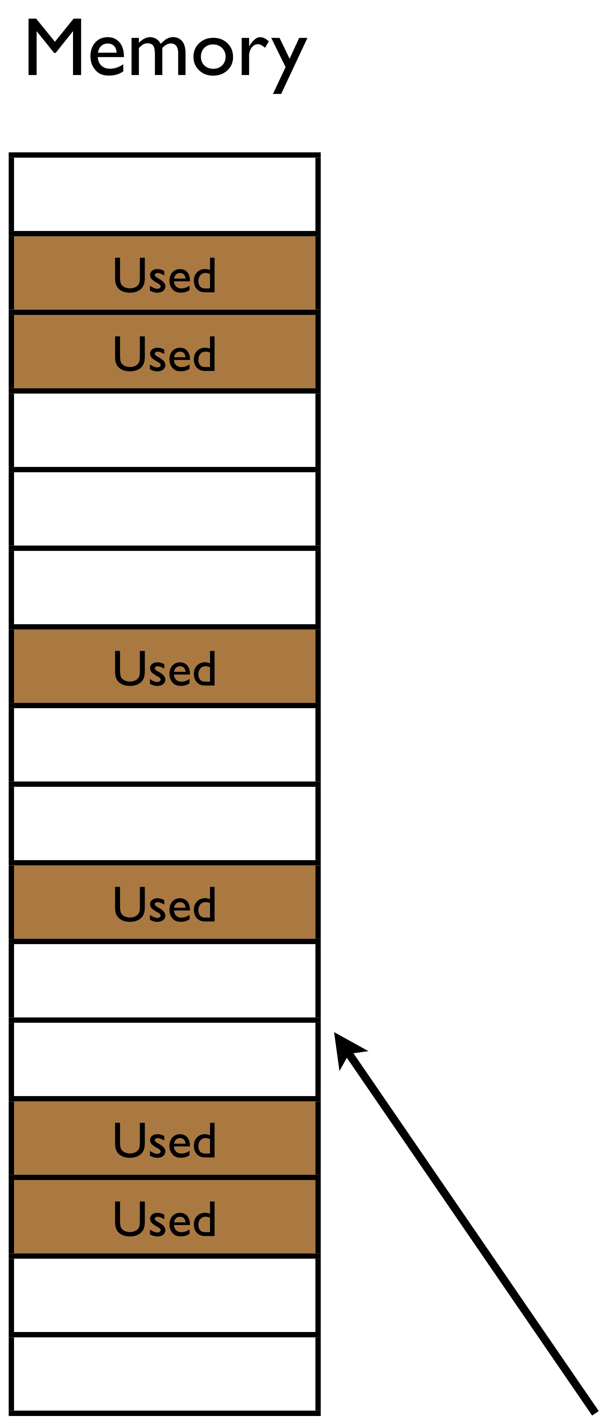
# ArrayLists

- Recall from last lecture that we discussed how to implement a reasonable `List` interface using an array.
- We called this implementation an `ArrayList`.
- The `ArrayList.add(o)` method would automatically resize its internal `_underlyingStorage` array whenever it got full.
- This is more convenient for the user than having to manage the array him/herself.

# Problems with **`ArrayLists`**

- However, the **`ArrayList`** is unsatisfying in a few ways:
  - It is still wasteful in memory -- after doubling the size of the **`_underlyingStorage`**, about half of the array elements are unused.
  - It does not solve the *contiguity problem*.

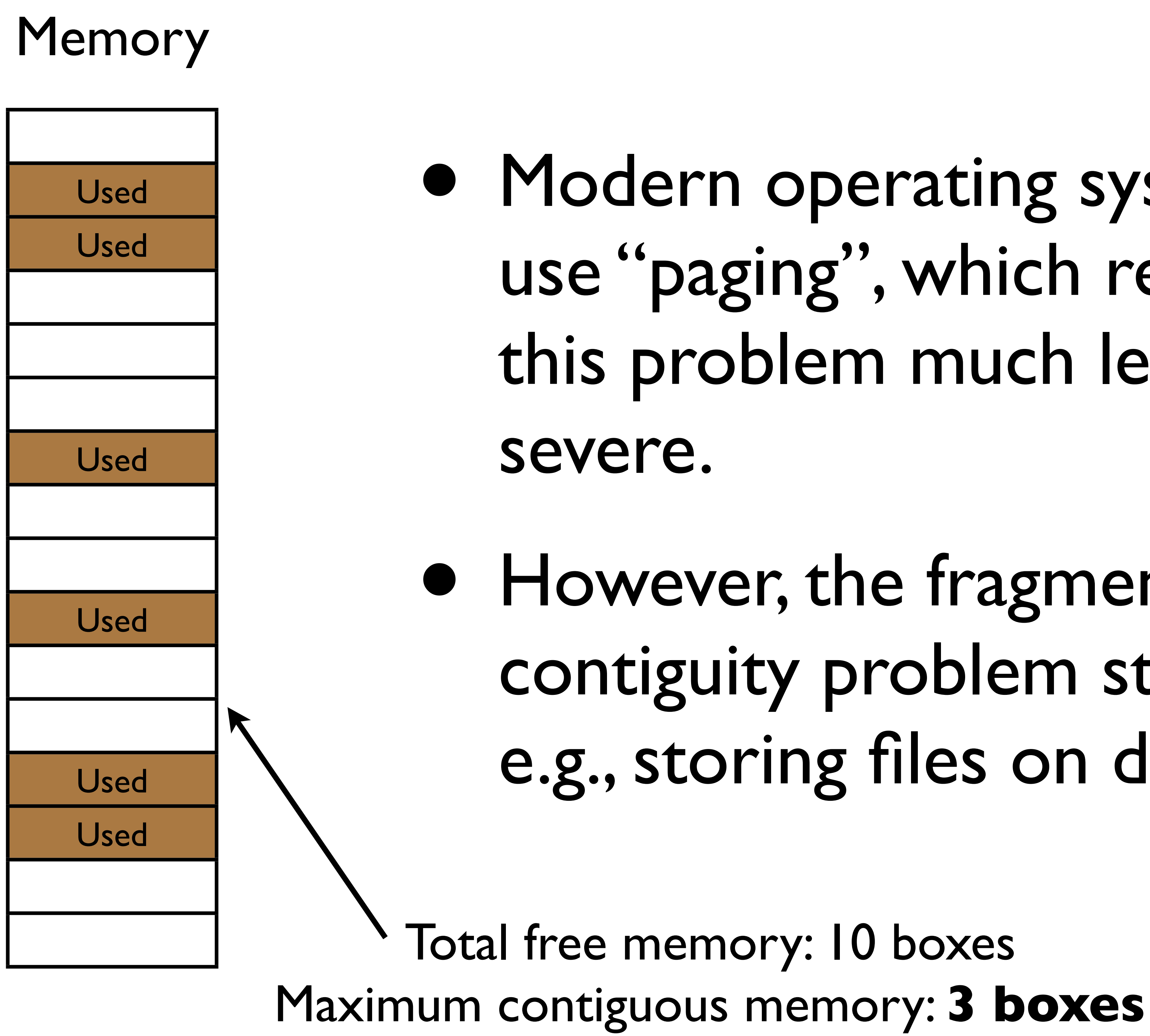
# Contiguity problem




- Sometimes the pool of free memory can become "fragmented" -- split into small chunks.
- In this case, it may not be possible to allocate one large, contiguous array.

Total free memory: 10MB
Maximum contiguous memory: 3MB

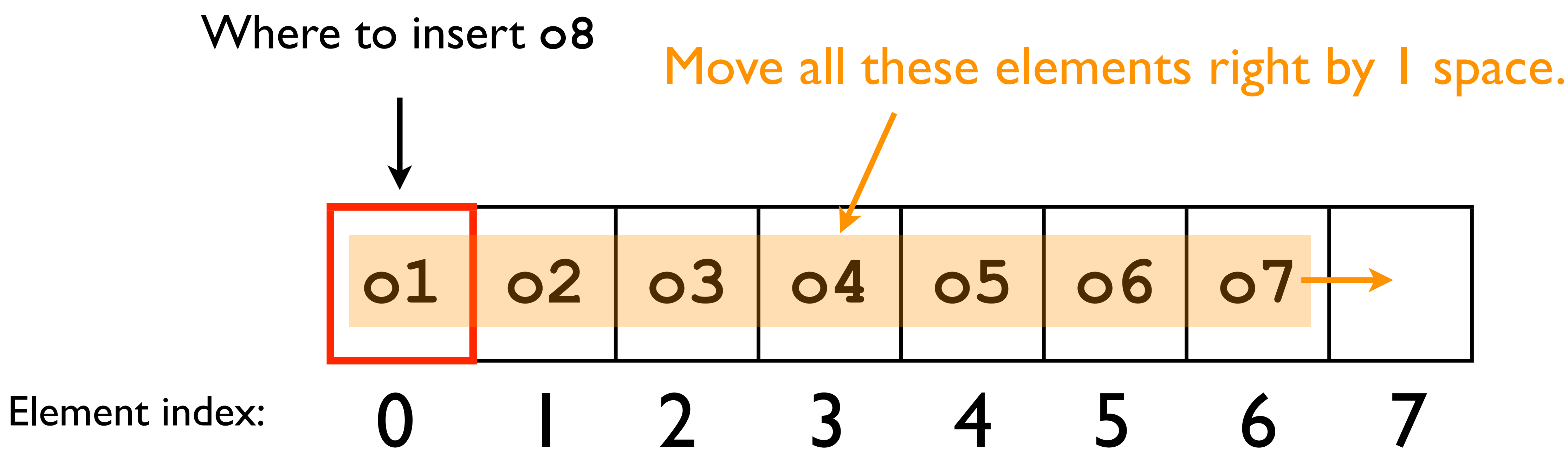
# Contiguity problem




- Modern operating systems use “paging”, which render this problem much less severe.
- However, the fragmentation/ contiguity problem still exists, e.g., storing files on disk.

# Problems with `ArrayLists`

- Another disadvantage of **`ArrayLists`** arises when you want to add an object to the *front* of the list: **`arrayList.addToFront(o8);`**




- We have to move all the other elements first!

# Problems with **`ArrayLists`**

- Another disadvantage of **`ArrayLists`** arises when you want to add an object to the *front* of the list: **`arrayList.addToFront(o8);`**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **o8** | **o1** | **o2** | **o3** | **o4** | **o5** | **o6** | **o7** |
| Element index: | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

- We have to move all the other elements first!
  - This is expensive!

# Linked lists

- Linked lists provide a convenient ADT for storing ordered data.
- Linked lists store exactly as many elements as are needed -- no "wasted space".
- They can be easily resized.
- Linked lists do not suffer from the "contiguity problem".
- They do, however, offer their own wonderful disadvantages :-) (more later).

# Linked lists

- Let's conceptualize a linked list by considering one of the fundamental operations of the `LinkedList` ADT:

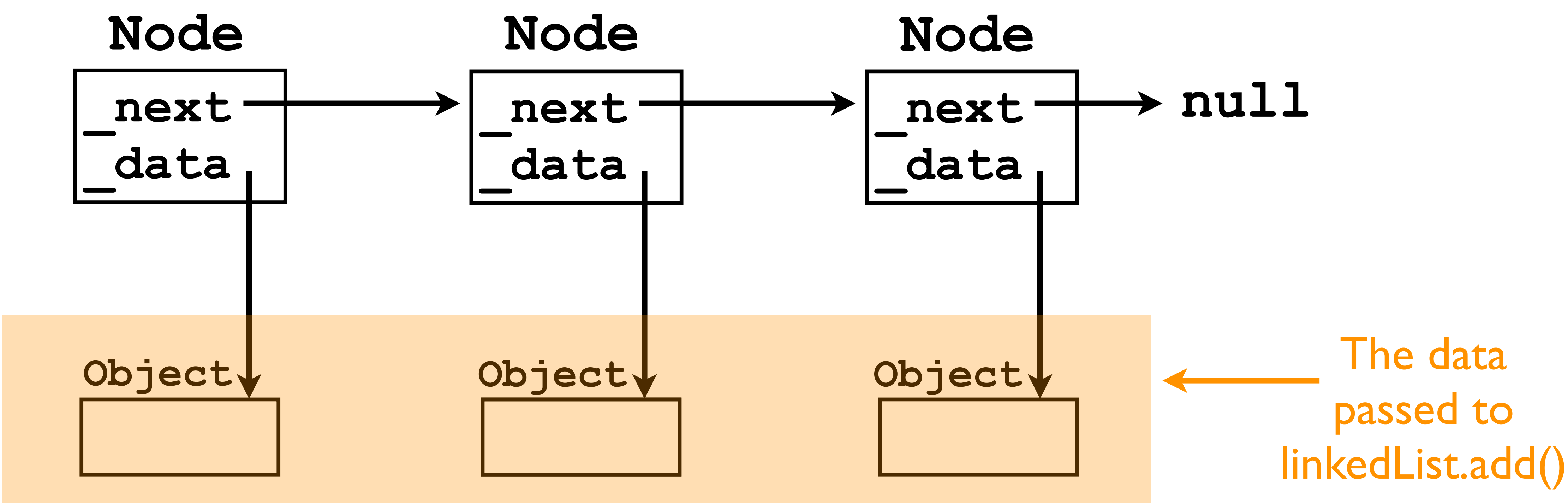
```
void add (Object o);
```

# Adding a new data element

- General strategy:

  1. Store the user's data in "nodes on a chain":

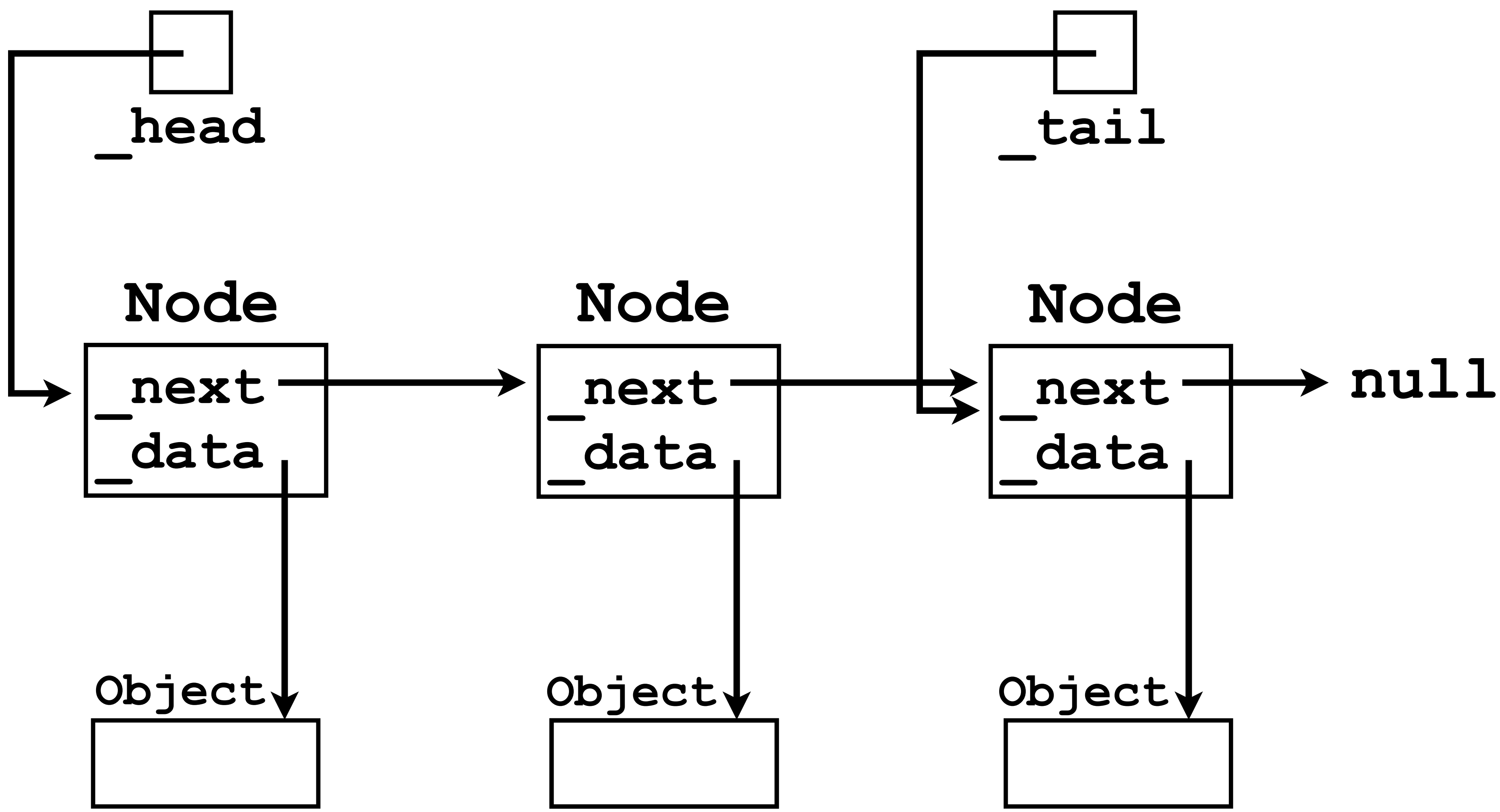
```
class Node {
  Node _next;
  Object _data;
}
```



# Adding a new data element

- General strategy:

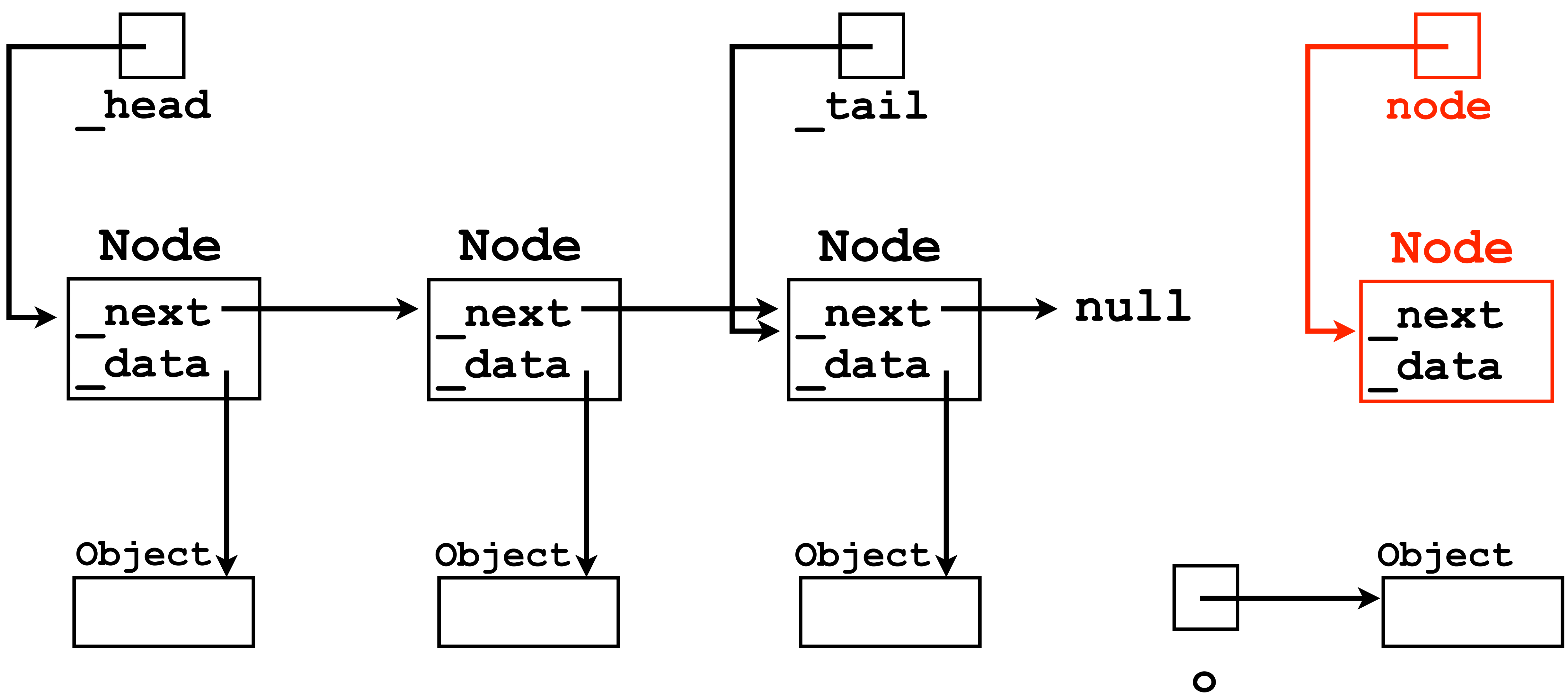
    2. We also maintain pointers to the first ("head") and last ("tail") node in the chain.



# Adding a new data element

- General strategy:

3. Each time **`add(o)`** is called, we create a new node. `Node node = new Node();`

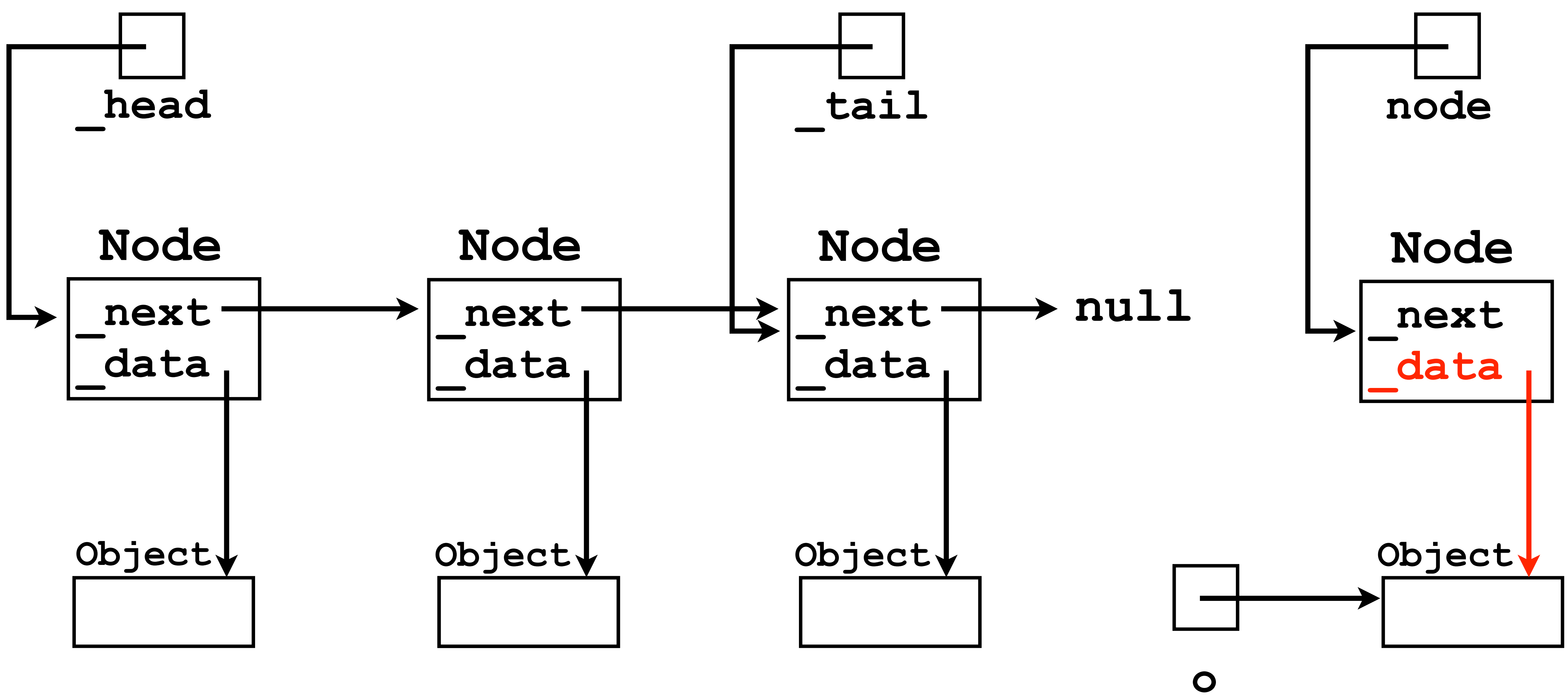


# Adding a new data element

- General strategy:

4. We store o “inside” the new **Node**.

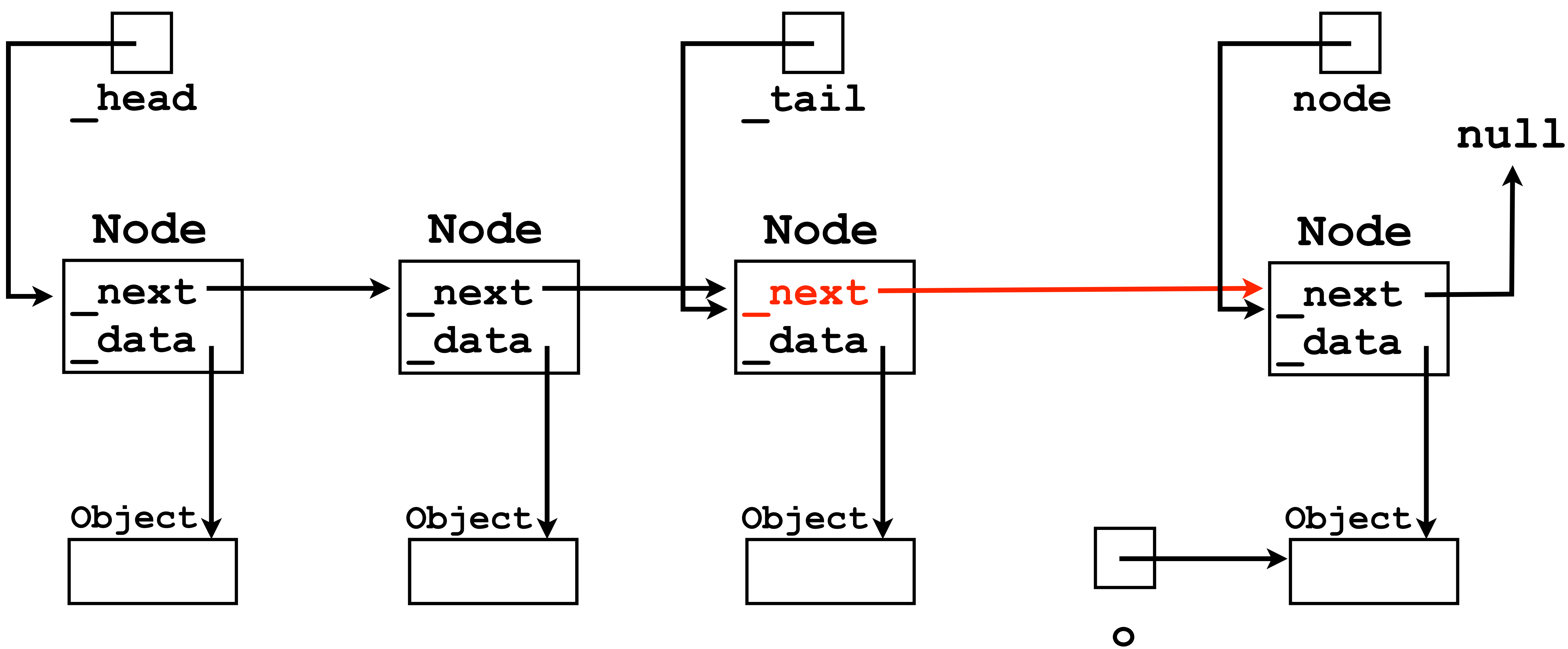
```
node._data = o;
```



# Adding a new data element

- General strategy:

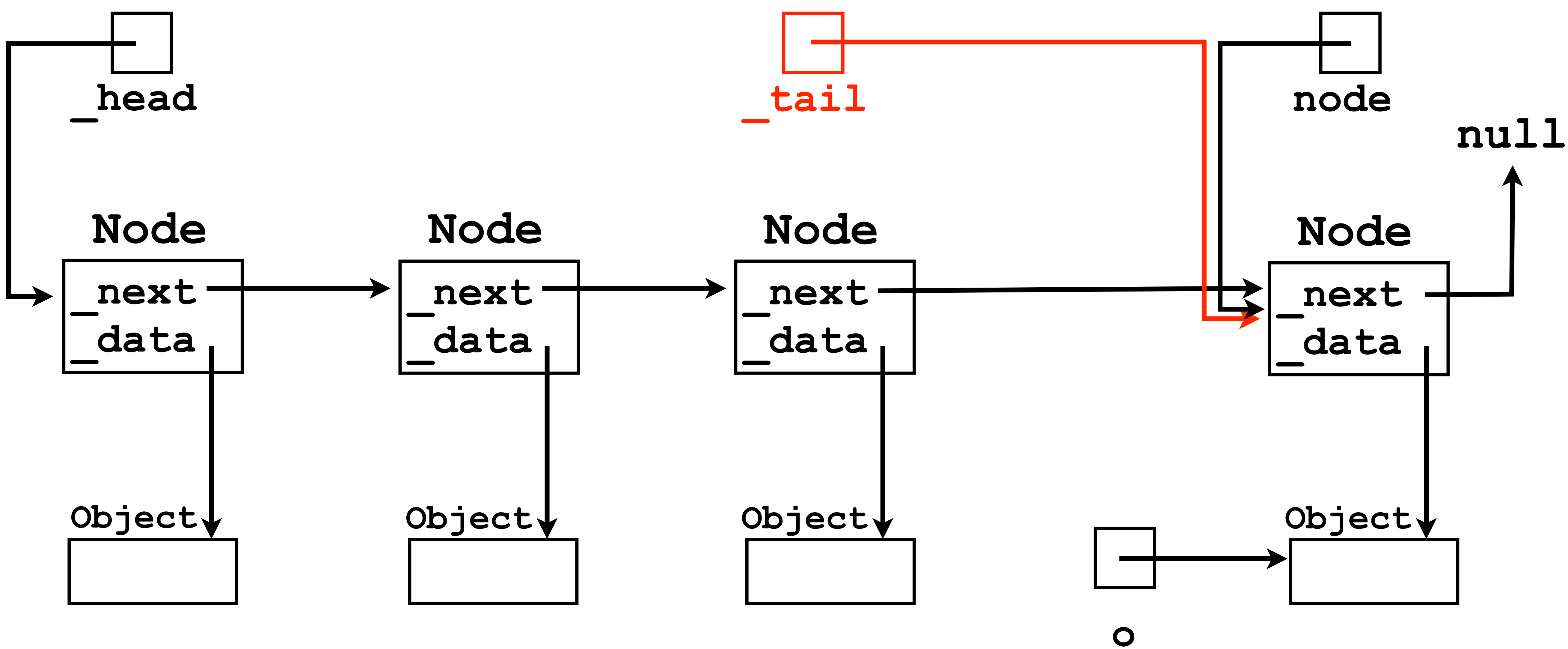
  5. We connect the new **Node** to the rest of the chain. `_tail._next = node;`



# Adding a new data element

- General strategy:

  6. We update the `_tail` pointer to point to the new node. `_tail = node;`



# Adding a new data element

- General strategy:
  - Done!