Chapter 8 - Memory Management

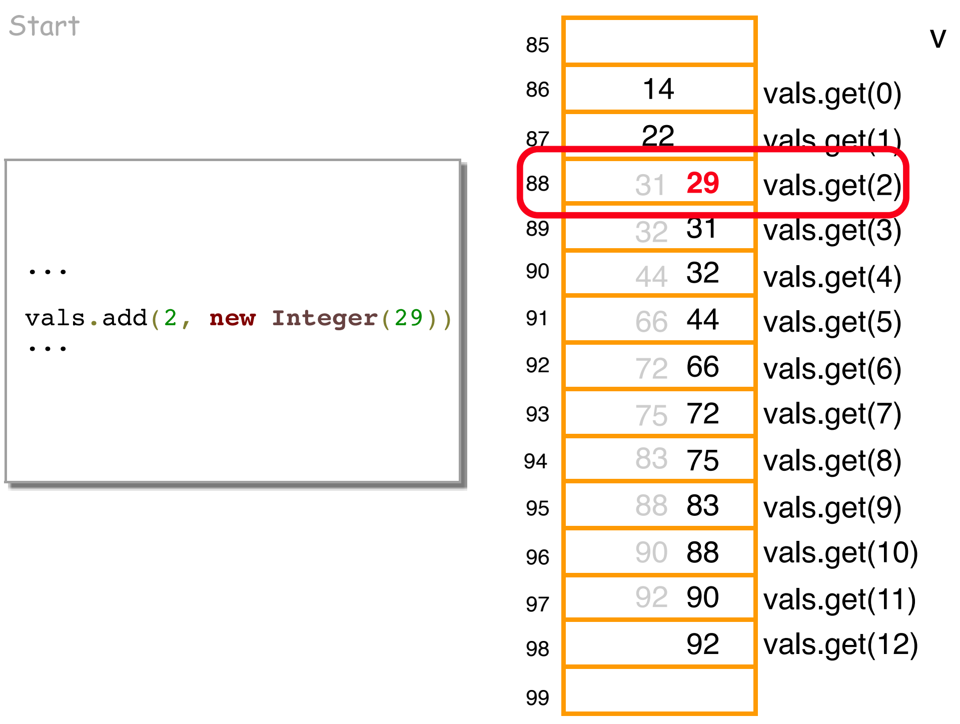
Section 8.1 - Introduction to memory management

An ArrayList stores a list of items in contiguous memory locations, which enables immediate access to any element at index i of ArrayList v by using the get() and set() methods -- the program just adds i to the starting address of the first element in v to arrive at the element. The methods `add(objRef)` and `add(i, objRef)` append and insert items into an ArrayList, respectively. Now recall that inserting an item at locations other than the end of the ArrayList requires making room by shifting higher-indexed items. Similarly, removing (via the `remove(i)` method) an item requires shifting higher-indexed items to fill the gap. Each shift of an item from one element to another element requires a few processor instructions. This issue exposes the ***ArrayList add/remove performance problem***.

For ArrayLists with thousands of elements, a single call to add() or remove() can require thousands of instructions, so if a program does many insert or remove operations on large ArrayLists, the program may run very slowly. The following animation illustrates shifting during an insertion operation.

P Participation Activity

8.1.1: ArrayList add() performance problem.



The shifting of elements done by add() and remove() requires several processor instructions per element. Doing many insertions/removes on large ArrayLists can take a significantly long time.

The following program can be used to demonstrate the issue. The user inputs an ArrayList size, and a number of elements to insert. The program then carries out several tasks. The program creates an ArrayList of size numElem, writes an arbitrary value to all elements, performs numOps appends, numOps inserts, and numOps removes. The video shows the program running for different sizes and numOps values; notice that for large values of numElem and numOps, the creation, writes, and appends all run quickly, but the inserts and removes take a noticeably long time. The video uses C++, but the main points apply equally to Java.

Figure 8.1.1: Program illustrating how slow ArrayList add() and remove() operations can be.

```
import java.util.ArrayList;
import java.util.Scanner;
import java.util.Scanner;

public class ArrayListAddRemove {
   public static void main(String[] args) {
      Scanner scnr = new Scanner(System.in);
      ArrayList<Integer> myInts = new ArrayList<Integer>(); // Dummy array list to d
      int numElem = 0;                                      // User defined array si
      int numOps = 0;                                       // User defined number c
      int i = 0;                                            // Loop index

      System.out.print("\nEnter initial ArrayList size: ");
      numElem = scnr.nextInt();

      System.out.print("Enter number of ArrayList adds: ");
      numOps = scnr.nextInt();

      System.out.print("  Adding elements to ArrayList...");

      myInts.clear();
      for (i = 0; i < numElem; ++i) {
         myInts.add(new Integer(0));
      }

      System.out.println("done.");
      System.out.print("  Writing to each element...");

      for (i = 0; i < numElem; ++i) {
         myInts.set(i, new Integer(777)); // Any value
      }

      System.out.println("done.");
      System.out.print("  Doing " + numOps + " additions at the end...");

      for (i = 0; i < numOps; ++i) {
         myInts.add(new Integer(888)); // Any value
      }

      System.out.println("done.");
      System.out.print("  Doing " + numOps + " additions at index 0...");

      for (i = 0; i < numOps; ++i) {
         myInts.add(0, new Integer(444));
      }
      System.out.println("done.");
      System.out.print("  Doing " + numOps + " removes...");

      for (i = 0; i < numOps; ++i) {
         myInts.remove(0);
      }

      System.out.println("done.");
   }
}
```

```
Enter initial ArrayList size: 100000
Enter number of ArrayList adds: 40000
  Adding elements to ArrayList...done.        (fast)
  Writing to each element...done.             (fast)
  Doing 40000 additions at the end...done.    (fast)
  Doing 40000 additions at index 0...done.    (SLOW)
  Doing 40000 removes...done.                 (SLOW)
```

Video 8.1.1: ArrayList inserts.

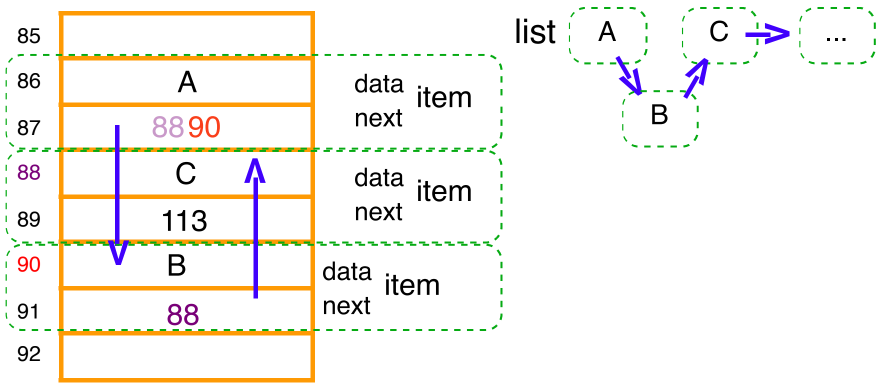
The appends are fast because they do not involve any shifting of elements, whereas each insert requires 500,000 elements to be shifted -- one at a time. 7,500 inserts thus requires 3,750,000,000 (over 3 billion) shifts.

One way to make inserts or removes faster is to use a different approach for storing a list of items. The approach does not use contiguous memory locations. Instead, each item contains a "pointer" to the next item's location in memory, as well as, the data being stored. Thus, inserting a new item B between existing items A and C just requires changing A to refer to B's memory location, and B to refer to C's location, as shown in the following animation.

P Participation Activity

8.1.2: A list avoids the shifting problem.

Start



Add new item B at location 90.
Change item A to point to 90.
Set item B to point to 88.

New list is (A, B, C, ...) -- no shifting of items after C

The animation begins with a list having some number of items, with the first two items being A and C. The first item has data A and a next reference storing the address 88, which refers to the next item's location in memory. That second item has data C, and a next reference storing address 113, which refers to the next item (not shown). The animation shows a new item being created at memory location 90, having data B. To keep the list in sorted order, item B should go between A and C in the list. So item A's next reference is changed to point to B's location of 90, and B's next reference is set to address 88.

A ***linked list*** is a list wherein each item contains not just data but also a reference -- a *link* -- to the next item in the list. Comparing ArrayLists and linked lists:

- *ArrayList*: Stores items in contiguous memory locations. Supports quick access to i'th element via the set() and get() methods, but may be slow for inserts or removes on large ArrayLists due to necessary shifting of elements.
- *Linked list*: Stores each item anywhere in memory, with each item referring to the next

item in the list. Supports fast inserts or removes, but access to i'th element may be slow as the list must be traversed from the first item to the i'th item. Also uses more memory due to storing a link for each item.

P Participation Activity

8.1.3: ArrayList performance.

#	Question	Your answer
1	Appending a new item to the end of a 1000 element ArrayList requires how many elements to be shifted?	
2	Inserting a new item at the beginning of a 1000 element ArrayList requires how many elements to be shifted?	

Section 8.2 - A first linked list

A common use of objects and references is to create a list of items such that an item can be efficiently inserted somewhere in the middle of the list, without the shifting of later items as required for an ArrayList. The following program illustrates how such a list can be created. A class is defined to represent each list item, known as a ***list node***. A node is comprised of the data to be stored in each list item, in this case just one int, and a reference to the next node in the list. A special node named head is created to represent the front of the list, after which regular items can be inserted.

Figure 8.2.1: A basic example to introduce linked lists.

IntNode.java

```
public class IntNode {
   private int dataVal;         // Node data
   private IntNode nextNodePtr; // Reference to the next node

   public IntNode() {
      dataVal = 0;
      nextNodePtr = null;
   }
   // Constructor
   public IntNode(int dataInit) {
      this.dataVal = dataInit;
      this.nextNodePtr = null;
   }

   // Constructor
   public IntNode(int dataInit, IntNode nextLoc) {
      this.dataVal = dataInit;
      this.nextNodePtr = nextLoc;
   }

   /* Insert node after this node.
    Before: this -- next
    After:  this -- node -- next
    */
   public void insertAfter(IntNode nodeLoc) {
      IntNode tmpNext;

      tmpNext = this.nextNodePtr;
      this.nextNodePtr = nodeLoc;
      nodeLoc.nextNodePtr = tmpNext;
      return;
   }

   // Get location pointed by nextNodePtr
   public IntNode getNext() {
      return this.nextNodePtr;
   }

   public void printNodeData() {
      System.out.println(this.dataVal);
      return;
   }
}
```

CustomLinkedList.java

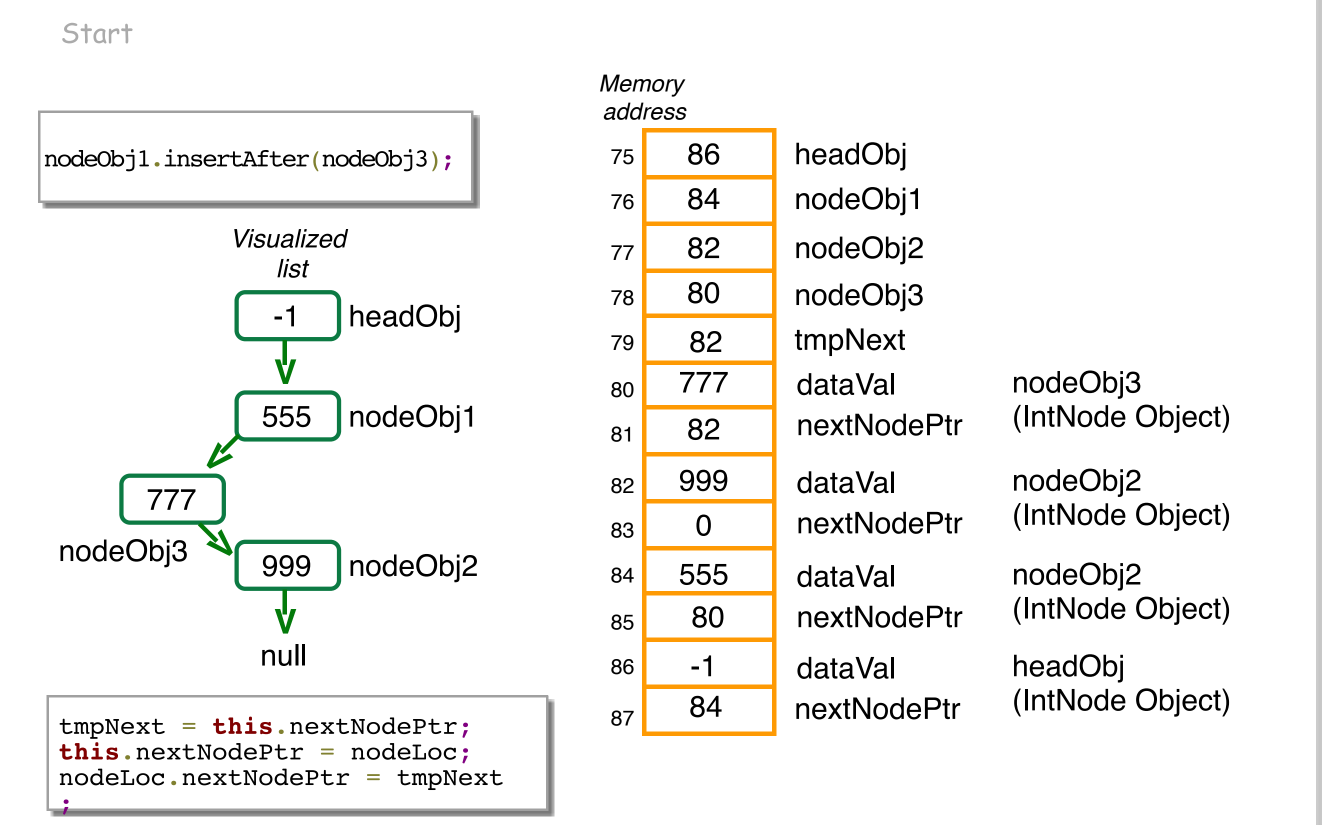
```
public class CustomLinkedList {
   public static void main (String[] args) {
      IntNode headObj;  // Create intNode objects
      IntNode nodeObj1;
      IntNode nodeObj2;
      IntNode nodeObj3;
      IntNode currObj;

      // Front of nodes list
      headObj = new IntNode(-1);

      // Insert more nodes
      nodeObj1 = new IntNode(555);
      headObj.insertAfter(nodeObj1);

      nodeObj2 = new IntNode(999);
      nodeObj1.insertAfter(nodeObj2);

      nodeObj3 = new IntNode(777);
      nodeObj1.insertAfter(nodeObj3);

      // Print linked list
```

```
-1
555
777
999
```

```
         currObj = headObj;
         while (currObj != null) {
            currObj.printNodeData();
            currObj = currObj.getNext();
         }

         return;
      }
   }
```

Participation Activity

8.2.1: Inserting nodes into a basic linked list.



```
nodeObj1.insertAfter(nodeObj3);
```

```
tmpNext = this.nextNodePtr;
this.nextNodePtr = nodeLoc;
nodeLoc.nextNodePtr = tmpNext
;
```

Memory address			
75	86	headObj	
76	84	nodeObj1	
77	82	nodeObj2	
78	80	nodeObj3	
79	82	tmpNext	
80	777	dataVal	nodeObj3 (IntNode Object)
81	82	nextNodePtr	
82	999	dataVal	nodeObj2 (IntNode Object)
83	0	nextNodePtr	
84	555	dataVal	nodeObj2 (IntNode Object)
85	80	nextNodePtr	
86	-1	dataVal	headObj (IntNode Object)
87	84	nextNodePtr	

The most interesting part of the above program is the insertAfter() method, which inserts a new node after a given node already in the list. The above animation illustrates the list construction process.

The value ***null*** indicates that a reference variable does **not** refer to any object. Notice that the program in the animation above first initializes all reference variables to a value of null. This initialization allows the programmer to traverse the list and detect when the last node is reached. Because the last node in the list does not have a next node, the next field of the last node is equal to null.

Importantly, reference variables are not assigned to null by default. Instead, uninitialized reference variables have an unknown default value, which means that a programmer cannot determine if a reference variable points to a valid object or not. Explicitly initializing reference variables to null can help a programmer determine if a particular reference variable refers to a valid object before attempting to access the object's fields and methods. Attempting to access an object's fields or methods via an uninitialized or null reference is a very common error that results in either a compilation error or a runtime exception. The former occurs for errors detectable by the compiler (e.g., when a programmer uses an invalid reference within the method it was defined). The latter, also known as a ***null pointer exception***, occurs for more complex errors undetectable by the compiler.

P Participation Activity

8.2.2: A first linked list.

Some questions refer to the above linked list code and animation.

#	Question	Your answer
1	A linked list has what key advantage over a sequential storage approach like an array or ArrayList?	An item can be inserted somewhere in the middle of the list without having to shift all subsequent items.
		Uses less memory overall.
		Can store items other than int variables.
2	What is the purpose of a list's head node?	Stores the first item in the list.
		Provides a reference to the first item's node in the list, if such an item exists.
		Stores all the data of the list.
3	After the above list is done having items inserted, at what memory address is the last list item's node located?	80
		82

		84
		86
4	After the above list has items inserted as above, if a fourth item was inserted at the front of the list, what would happen to the location of node1?	Changes from 84 to 86.
		Changes from 84 to 82.
		Stays at 84.

In contrast to the above program that defines one reference variable for each item allocated by the new operator, a program commonly defines just one or a few variables to manage a large number of items allocated using the new operator. The following example replaces the above main() method, showing how just two reference variables, currObj and lastObj, can manage 20 allocated items in the list.

Figure 8.2.2: Managing many new items using just a few reference variables.

IntNode.java

```
public class IntNode {
   private int dataVal;         // Node data
   private IntNode nextNodePtr; // Reference to the next node

   public IntNode() {
      dataVal = 0;
      nextNodePtr = null;
   }

   // Constructor
   public IntNode(int dataInit) {
      this.dataVal = dataInit;
      this.nextNodePtr = null;
   }

   // Constructor
   public IntNode(int dataInit, IntNode nextLoc) {
      this.dataVal = dataInit;
      this.nextNodePtr = nextLoc;
   }

   /* Insert node after this node.
    Before: this -- next
    After:  this -- node -- next
```

```
     */
   public void insertAfter(IntNode nodeLoc) {
      IntNode tmpNext;

      tmpNext = this.nextNodePtr;
      this.nextNodePtr = nodeLoc;
      nodeLoc.nextNodePtr = tmpNext;
      return;
   }

   // Get location pointed by nextNodePtr
   public IntNode getNext() {
      return this.nextNodePtr;
   }

   public void printNodeData() {
      System.out.println(this.dataVal);
      return;
   }
}
```

CustomLinkedList.java

```
public class CustomLinkedList {
   public static void main (String[] args) {
      IntNode headObj; // Create IntNode objects
      IntNode currObj;
      IntNode lastObj;
      int i = 0;       // Loop index

      headObj = new IntNode(-1); // Front of nodes list
      lastObj = headObj;

      for (i = 0; i < 20; ++i) { // Append 20 rand nums
         int rand = (int)(Math.random() * 100000); // random int (0-100000)
         currObj = new IntNode(rand);

         lastObj.insertAfter(currObj); // Append curr
         lastObj = currObj;
      }

      currObj = headObj; // Print the list
      while (currObj != null) {
         currObj.printNodeData();
         currObj = currObj.getNext();
      }

      return;
   }
}
```

```
-1
40271
6951
29273
86846
64952
65650
98162
51229
30690
```

```
61008
17489
87486
24318
44035
32368
10906
75441
88659
65688
18443
```

P Participation Activity

8.2.3: Managing a linked list.

Finish the program so that it finds and prints the smallest value in the linked list.

IntNode.java CustomLinkedList.java

```

public class IntNode {
   private int dataVal;          // Node data
   private IntNode nextNodePtr; // Reference to the next

   public IntNode() {
      dataVal = 0;
      nextNodePtr = null;
   }

   // Constructor
   public IntNode(int dataInit) {
      this.dataVal = dataInit;
      this.nextNodePtr = null;
   }

   // Constructor
   public IntNode(int dataInit, IntNode nextLoc) {
      this.dataVal = dataInit;
```

Run

Normally, a linked list would be maintained by member methods of another class, such as IntList. Private fields of that class might include the list head (a list node allocated by the list class constructor), the list size, and the list tail (the last node in the list). Public member methods might include insertAfter (insert a new node after the given node), pushBack (insert a new node after the last node), pushFront (insert a new node at the front of the list, just after the head), deleteNode (deletes the node from the list), etc.

Exploring further:

- More on linked lists from Oracle's Java tutorials

C Challenge Activity

8.2.1: Linked list negative values counting.

Assign negativeCntr with the number of negative values in the linked list.

```
      while (currObj != null) {
         System.out.print(currObj.getDataVal() + ", ");
         currObj = currObj.getNext();
      }
      System.out.println("");

      currObj = headObj; // Count number of negative numbers
      while (currObj != null) {

         /* Your solution goes here  */

         currObj = currObj.getNext();
      }
      System.out.println("Number of negatives: " + negativeCntr);

      return;
   }
}
// ===== end =====
```

Run

Section 8.3 - Memory regions: Heap/Stack

A program's memory usage typically includes four different regions:

- ***Code*** -- The region where the program instructions are stored.

- ***Static memory*** -- The region where static fields and local variables (variables defined inside methods starting with the keyword "static") are allocated. The name "static" comes from these variables not changing (static means not changing); they are allocated once and last for the duration of a program's execution, their addresses staying the same.
- ***The stack*** -- The region where a method's local variables are allocated during a method call. A method call adds local variables to the stack, and a return removes them, like adding and removing dishes from a pile; hence the term "stack." Because this memory is automatically allocated and deallocated, it is also called ***automatic memory***.
- ***The heap*** -- The region where the "new" operator allocates memory for objects. The region is also called ***free store***.

In Java, the code and static memory regions are actually integrated into a region of memory called the ***method area*** , which also stores information for every class type used in the program.

The following animation illustrates:

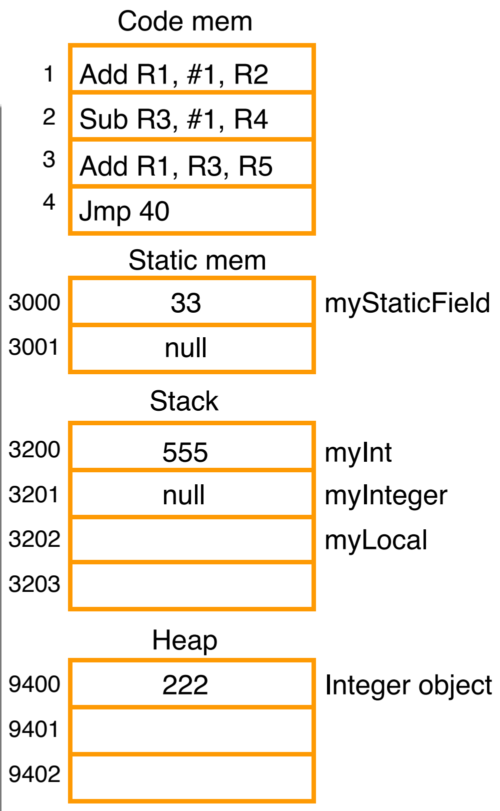
P Participation Activity

8.3.1: Use of the four regions of memory.

Start

"new" allocates memory in the heap

```
// Program is stored in code memory
public class MemoryRegionEx {
   public static int myStaticField = 33;

   public static void myFct() {
      int myLocal = 999; // On stack
      System.out.print(" " + myLocal);
      return;
   }

   public static void main (String[] args) {
      int myInt = 555;            // On stack
      Integer myInteger = null; // On stack

      myInteger = new Integer(222); // In heap
      System.out.print(myInteger.intValue() +
                       " " + myInt);

      myInteger = null;

      myFct(); // Stack grows, then shrinks

      return;
   } // Object deallocated automatically
}
```



P Participation Activity

8.3.2: Stack and heap definitions.

Code | Static memory | Free store | Automatic memory | The stack | The hea

Drag and drop above item	A function's local variables are allocated in this region while a function is called.
	The memory allocation operator (new) affects this region.
	Global and static local variables are allocated in this region once for the duration of the program.
	Another name for "The heap" because the programmer has explicit control of this memory.
	Instructions are stored in this region.
	Another name for "The stack" because the programmer does not explicitly control this memory.

Reset

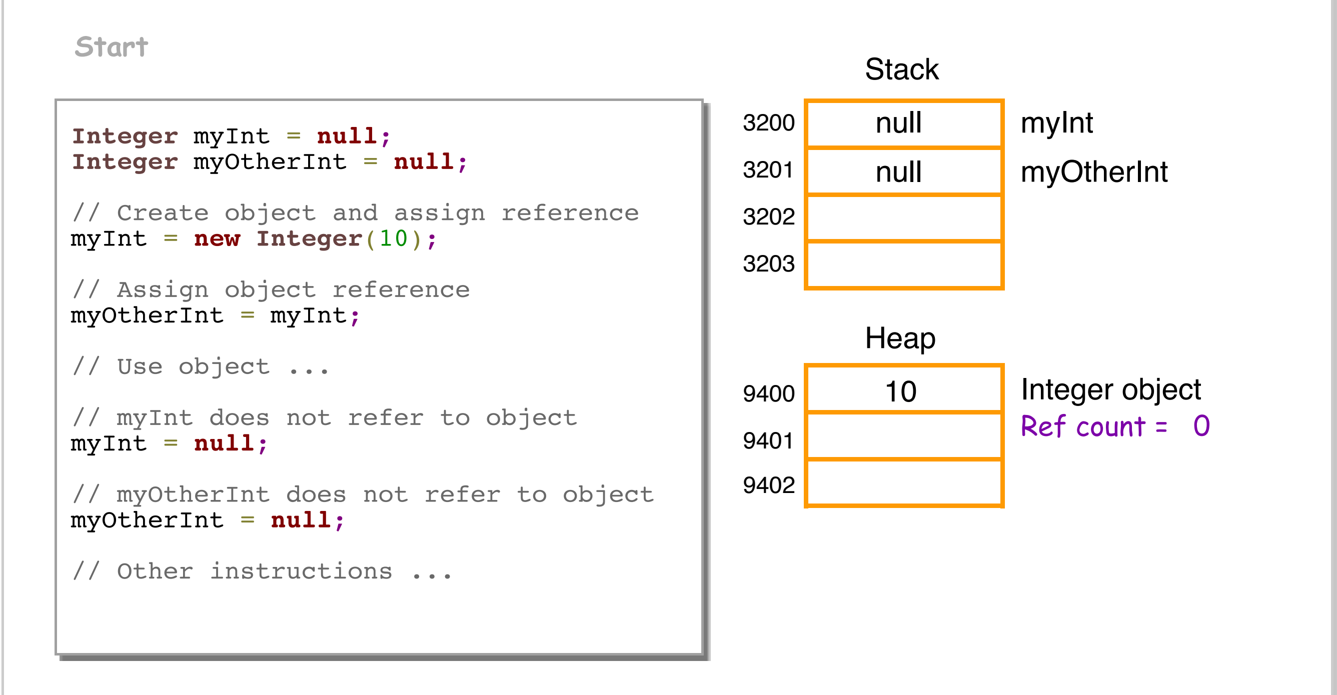
Section 8.4 - Basic garbage collection

Because the amount of memory available to a program is finite, objects allocated to the heap must eventually be deallocated when no longer needed by the program. The Java programming language uses a mechanism called ***garbage collection*** wherein a program's executable includes automatic behavior that at various intervals finds all unreachable -- i.e., unused -- allocated memory locations, and automatically frees such memory locations in order to enable memory reuse. Garbage collection can present the programmer with the illusion of a nearly unlimited memory supply at the expense of runtime overhead.

In order to determine which allocated objects the program is currently using at runtime, the Java virtual machine keeps a count, known as a ***reference count***, of all reference variables that are currently referring to an object. If the reference count is zero, then the object is considered an ***unreachable object*** and is eligible for garbage collection, as no variables in the program refer to the object. The Java virtual machine marks unreachable objects, and deallocation occurs the next time the Java virtual machine invokes the garbage collector. The following animation illustrates.

P Participation Activity

8.4.1: Marking unused objects for deallocation.



Start

```
Integer myInt = null;
Integer myOtherInt = null;

// Create object and assign reference
myInt = new Integer(10);

// Assign object reference
myOtherInt = myInt;

// Use object ...

// myInt does not refer to object
myInt = null;

// myOtherInt does not refer to object
myOtherInt = null;

// Other instructions ...
```

The program initially allocates memory for an Integer object and assigns a reference to the object's memory location to variables myInt and myOtherInt. Thus, the object's reference count is displayed as two at that point in the program's execution. After the object is no longer needed, the reference variables are assigned a value of *null*, indicating that the reference variables no longer refer to an object. Consequently, the object's reference count decrements to zero, and the Java virtual machine marks that object for deallocation.

P Participation Activity

8.4.2: Garbage collection.

Garbage collection | Object reference count | Unreachable object

Drag and drop above item	Object that is not referenced by any valid reference variables in the program.
	Value updated by the Java virtual machine in order to keep track of the number of variables referencing an object.
	Automatic process of finding unused allocated memory locations and deallocating that unreachable memory.

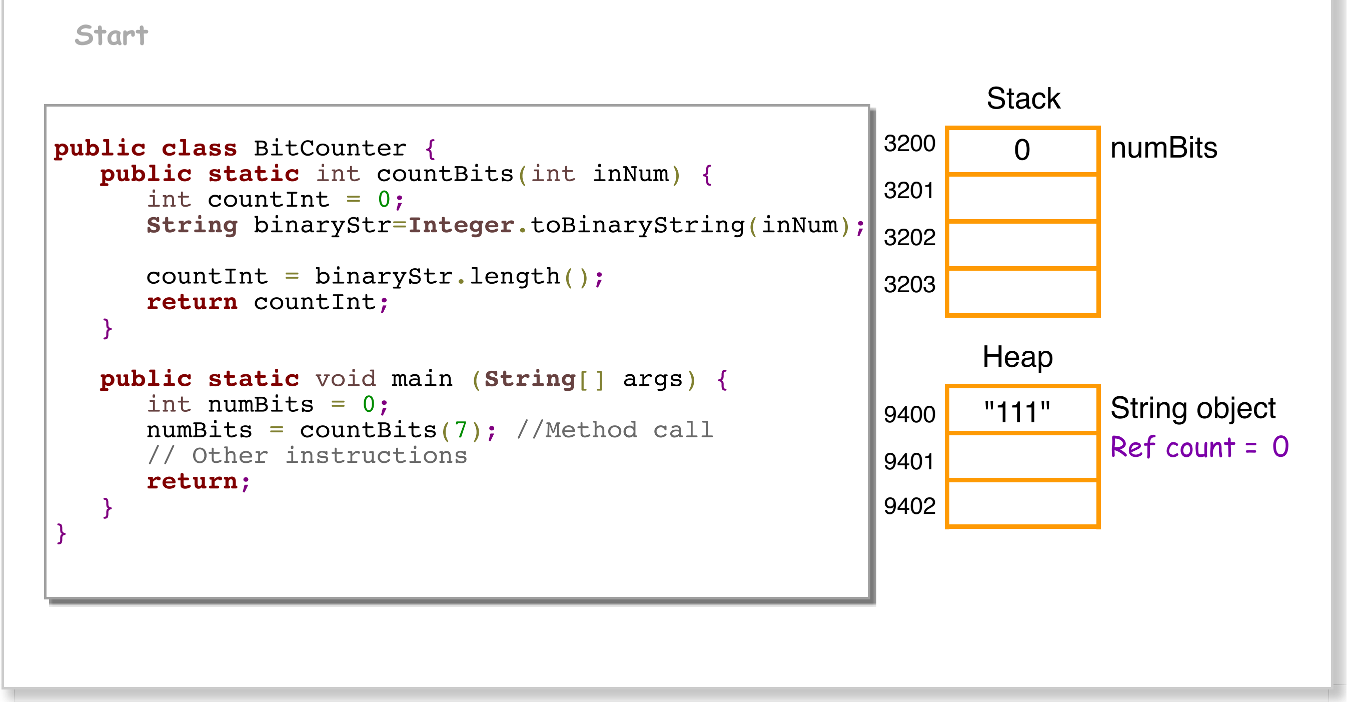
Reset

Section 8.5 - Garbage collection and variable scope

A programmer does not explicitly have to set a reference variable to null in order to indicate that the variable no longer refers to an object. The Java virtual machine can automatically infer a null reference once the variable goes out of scope -- i.e., the reference variable is no longer visible to the program. For example, local reference variables that are defined within a method go out of scope as soon as the method returns. The Java virtual machine decrements the reference counts associated with the objects referred to by any local variables within the method. The following animation illustrates.

P Participation Activity

8.5.1: Marking unused objects in methods.



```
public class BitCounter {
   public static int countBits(int inNum) {
      int countInt = 0;
      String binaryStr=Integer.toBinaryString(inNum);

      countInt = binaryStr.length();
      return countInt;
   }

   public static void main (String[] args) {
      int numBits = 0;
      numBits = countBits(7); //Method call
      // Other instructions
      return;
   }
}
```

Every time CountBits() is invoked, the method defines a local reference variable called binaryStr, which refers to a newly allocated String object used to store the binary representation of the integer num. The initialization of binaryStr increments the object's reference count. When the method returns, the reference variable binaryStr goes out of scope, and the Java virtual machine will decrement the reference count for the String object. The reference count for that String object becomes zero and the object is marked for deallocation, which occurs whenever the Java virtual machine invokes the garbage collector.

Although CountBits() happens to allocate binaryStr in the same memory location whenever CountBits() is called, note that Java makes no such guarantee. Also, recall that main() is itself a method. Thus, the Java virtual machine will decrement the reference count of any objects associated with reference variables defined in main() upon returning from main().

P Participation Activity

8.5.2: Garbage collection and variable scope.

#	Question	Your answer
1	A method's local reference variables automatically go out of scope when the method returns.	True
		False
2	A programmer must explicitly set all reference variables to null in order to indicate that the objects to which the variables referred are no longer in use.	True
		False

Section 8.6 - Java example: Employee list using ArrayLists

P Participation Activity

8.6.1: Managing an employee list using an ArrayList.

The following program allows a user to add to and list entries from an ArrayList, which maintains a list of employees.

1. Run the program, and provide input to add three employees' names and related data. Then use the list option to display the list.
2. Modify the program to implement the deleteEntry method.
3. Run the program again and add, list, delete, and list again various entries.

Reset

```
import java.util.ArrayList;
import java.util.Scanner;

public class EmployeeManager {

   static Scanner scnr = new Scanner(System.in);

   public static void main(String[] args) {
      // Declare program variables. The ArrayLists have names, departments
      // and salaries

      final int MAX_ELEMENTS = 10;
      final char EXIT_CODE = 'X';
      final String PROMPT_ACTION = "Add, Delete, List or eXit (a,d,l,x): ";

      ArrayList<String> name       = new ArrayList<String>(MAX_ELEMENTS);
      ArrayList<String> department = new ArrayList<String>(MAX_ELEMENTS);
      ArrayList<String> title      = new ArrayList<String>(MAX_ELEMENTS);
      int nElements = 0;
```

```
a
Rajeev Gupta
Sales
nager
```

Run

Below is a solution to the above problem.

P Participation Activity

8.6.2: Managing an employee list using an ArrayList (solution).

Reset

```java
import java.util.ArrayList;
import java.util.Scanner;

public class MemoryManagement {

   static Scanner scnr = new Scanner(System.in);

   public static void main(String[] args) {
      // Declare program variables. The ArrayLists have names, departments,
      // and salaries

      final int MAX_ELEMENTS = 10;
      final char EXIT_CODE = 'X';
      final String PROMPT_ACTION = "Add, Delete, List, or eXit (a,d,l,x): ";

      ArrayList<String> name       = new ArrayList<String>(MAX_ELEMENTS);
      ArrayList<String> department = new ArrayList<String>(MAX_ELEMENTS);
      ArrayList<String> title      = new ArrayList<String>(MAX_ELEMENTS);
      int nElements = 0;
```

```
a
Rajeev Gupta
Sales
nager
```

Run