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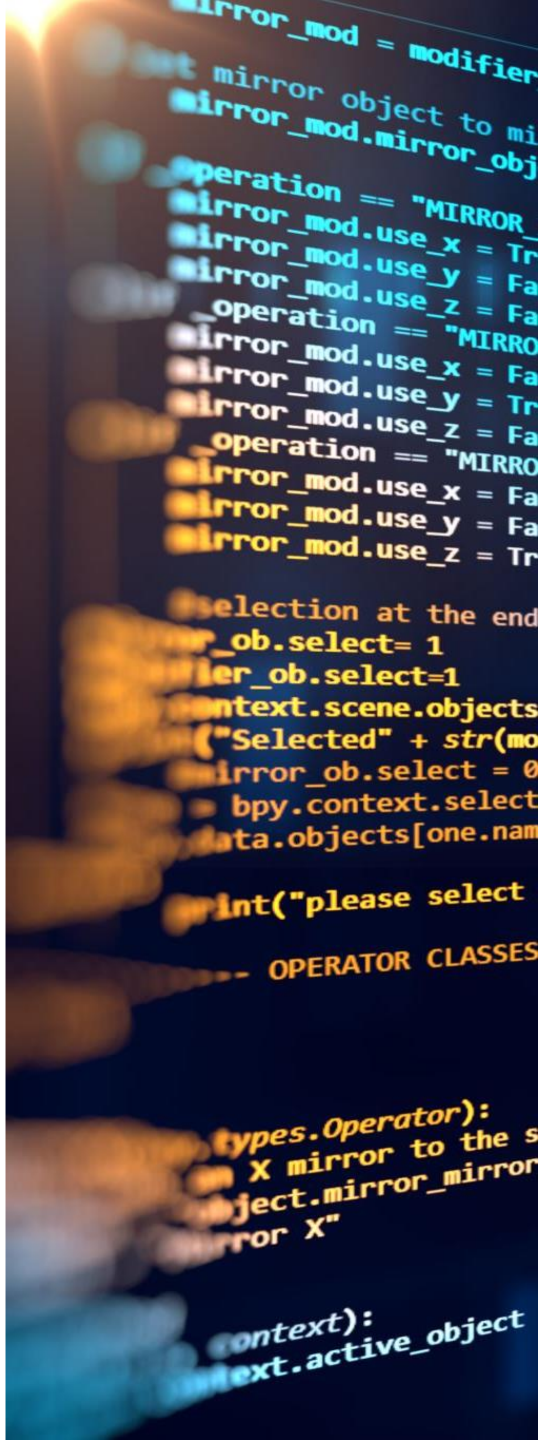
CS 1027
Fundamentals of Computer Science II

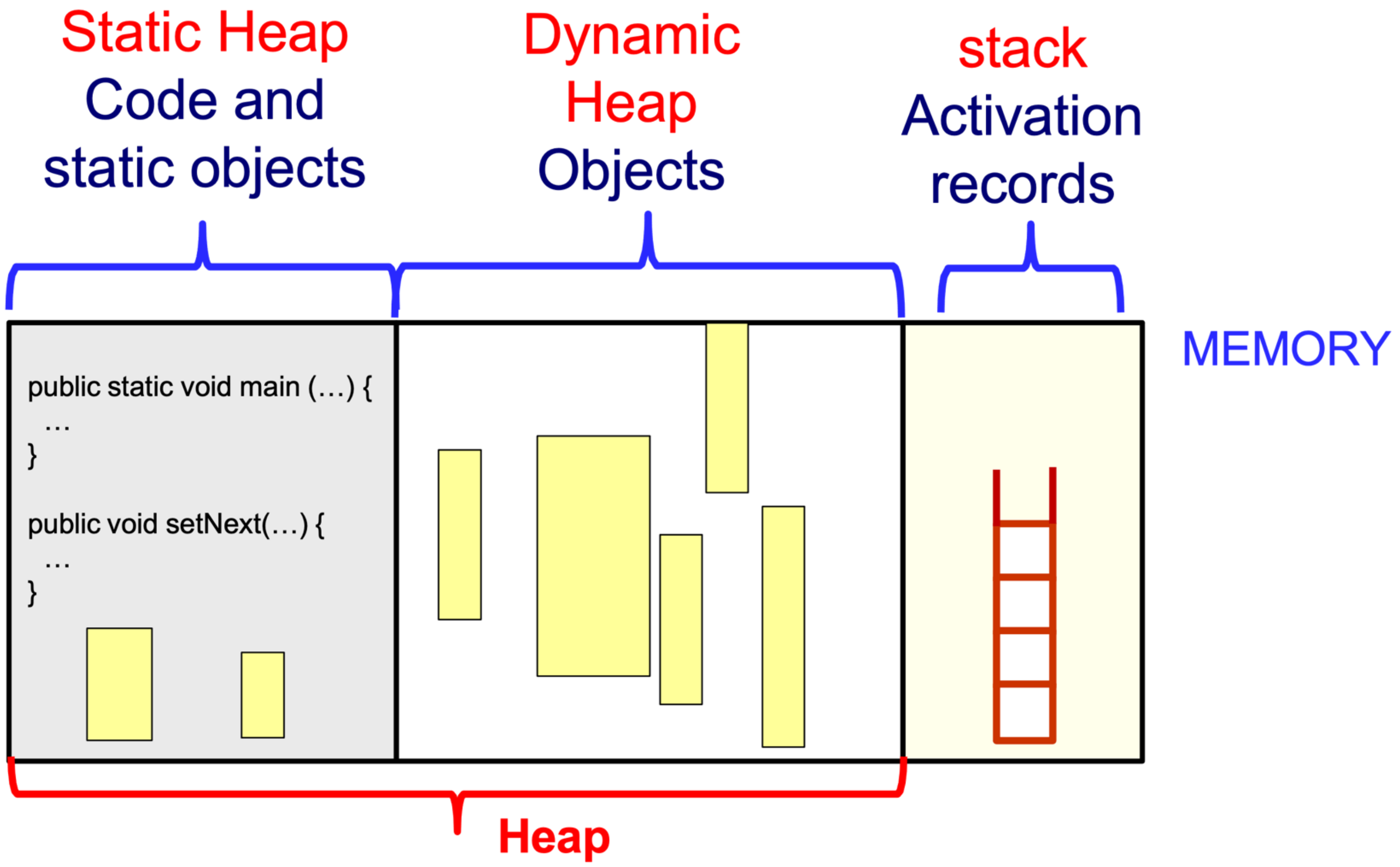
Memory Allocation in Java (cont.)

Ahmed Ibrahim



Memory Allocation in Java

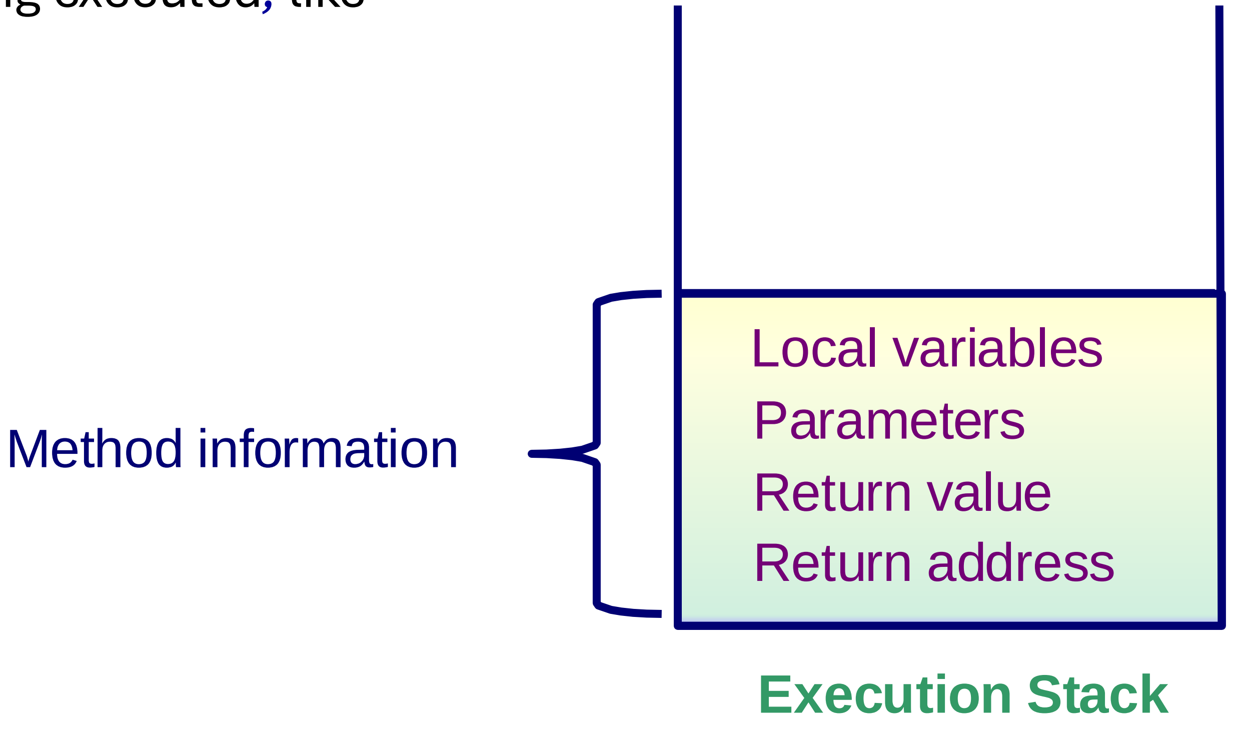
- When a program is being executed, separate areas of memory are allocated:



```
public static void main (…) {
  …
}

public void setNext(…) {
  …
}
```

Recall: Execution Stack

- The execution stack (also called runtime stack or call stack) is used to store information needed while a method is being executed, like
  - Local variables
  - Formal parameters
  - Return value
  - Return address



Recall: Execution of the Program

- When the **main** method is invoked:
  - An activation record for the main is created and pushed onto the execution stack
- When the **main** calls the method **m2**:
  - An activation record for m2 is created and pushed onto the execution stack
- When **m2** calls **m3**:
  - An activation record for m3 is created and pushed onto the execution stack
- When **m3** terminates, its activation record is popped off and control returns to **m2**

Execution of the Program

- When **m2** next calls **m4**:
  - What happens next?
  - What happens when **m4** terminates?
- What happens when **m2** terminates?
- What happens when the **main** function terminates?
  - Its activation record is popped off, and control returns to the operating system

Activation Records

- Example of what is in the activation record for a method with primitive type variables, and non-primitive variables.

```
public static int m2 (int param2)
{int local2 = 1;
 Integer i = new Integer(3);
 m3(4);
 return local2 + param2 + m4(3);}
public static void m3 (int param3)
{int[] arr = new int[param3];}
public static int m4 (int param4) {return param4 * 2;}
public static void main (String[] args) {int local1 = m2(5);}
```

To execute this program, it is first compiled and translated to Java bytecode and stored in the static heap.

```
01001100011101001011010111
01001010110101010001111011
1010100101010100011100101
11101011101011101001110000
11010101010000100011100011
10111010011000111011000001
11010100100010101000101011
```

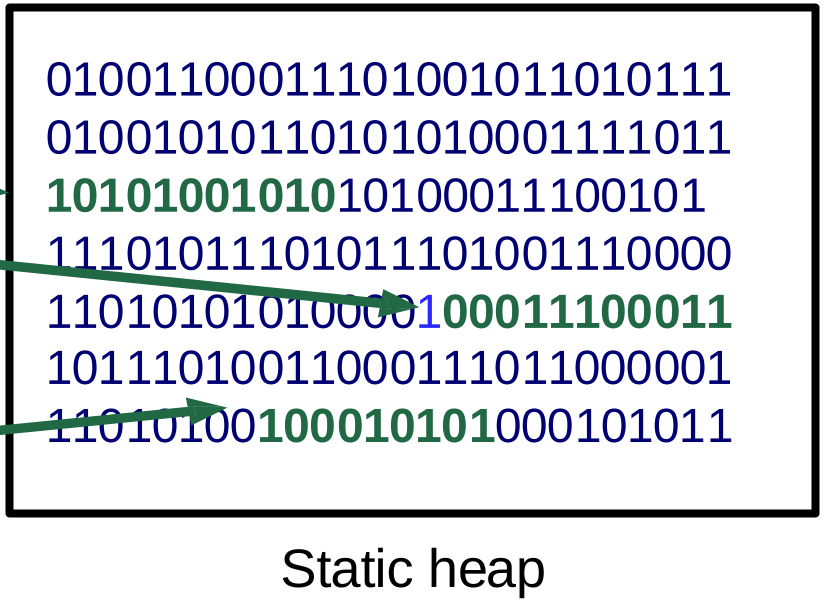
Static heap

Activation Records

- Example of what is in the activation record for a method with primitive type variables, and non-primitive variables.

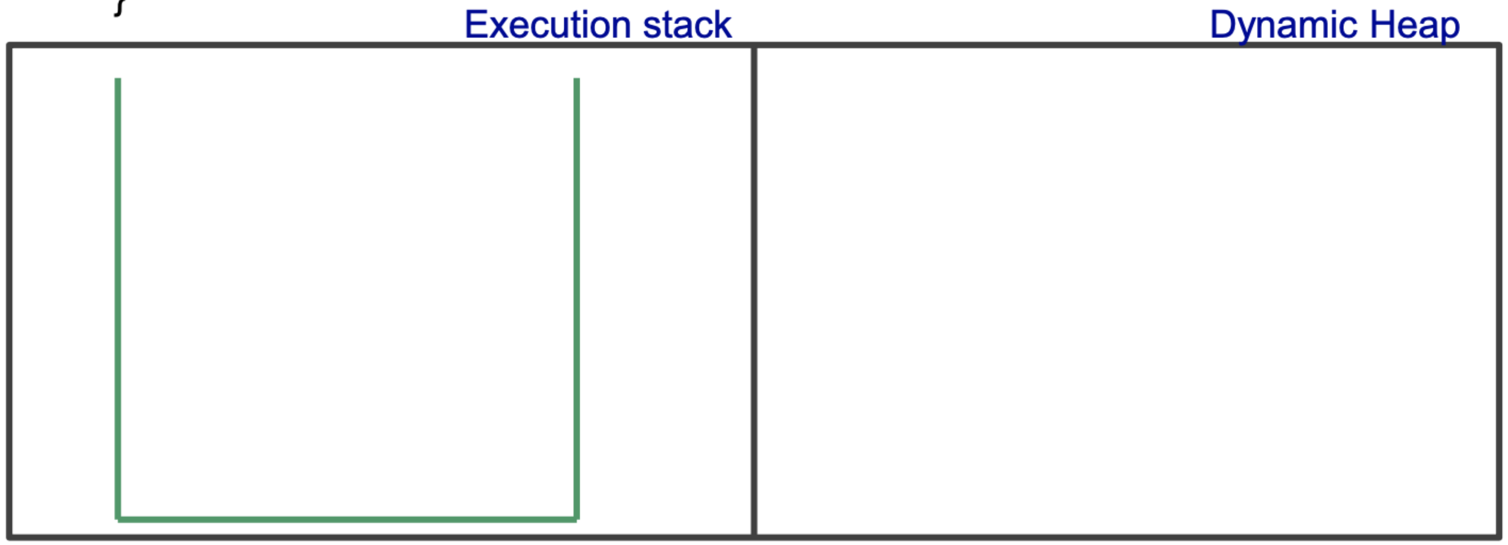
```
      public static int m2 (int param2)
      {int local2 = 1;
       Integer i = new Integer(3);
addr2  m3(4);
addr3  return local2 + param2 + m4(3);}
      public static void m3 (int param3)
      {int[] arr = new int[param3];}
      public static int m4 (int param4) {return param4 * 2;}
      public static void main (String[] args) {
addr1 int local1 = m2(5);}
```

Each instruction is assigned an address. We indicated the addresses of method invocations in the program.



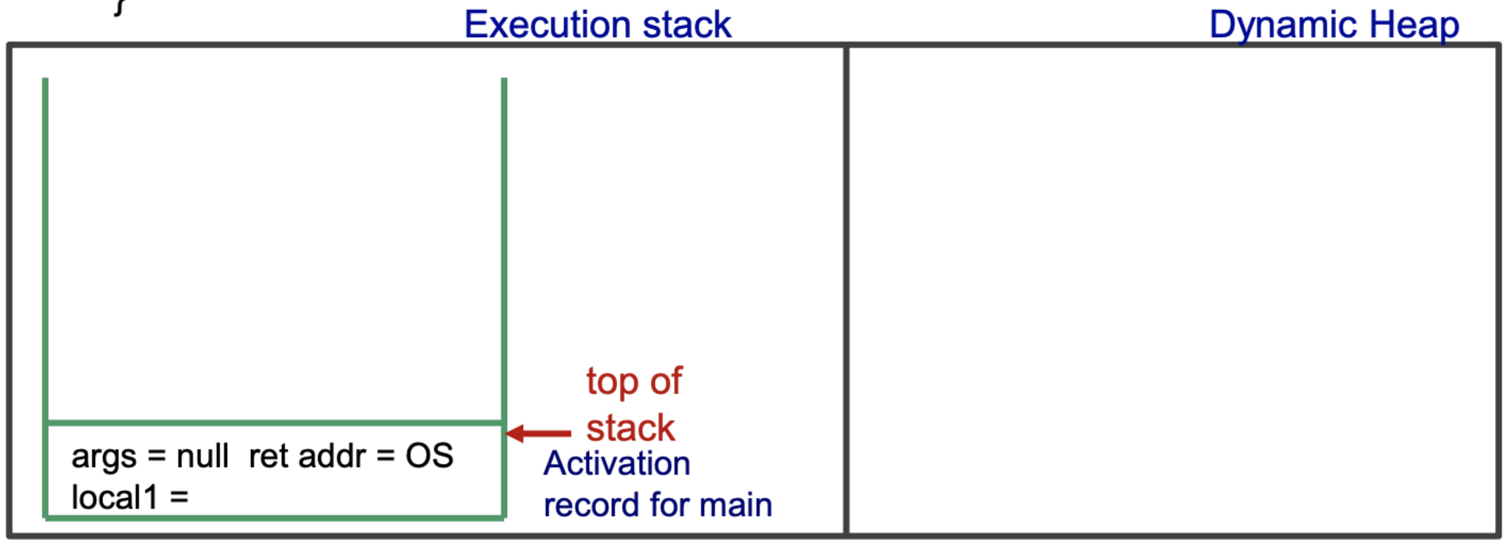
Activation Records

```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }

public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```



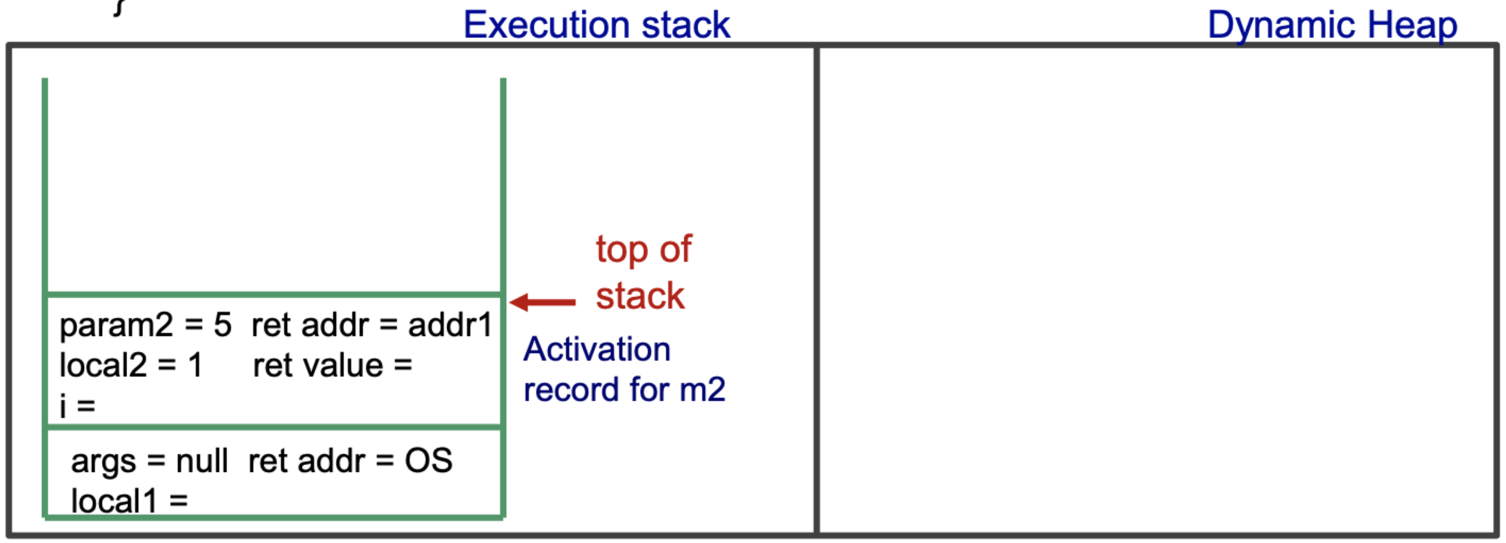
Activation Records

```
      public static int m2 (int param2) {
         int local2 = 1;
         Integer i = new Integer(3);
addr2    m3(4);
addr3    return local2 + param2 + m4(3);
      }

      public static void m3 (int param3) {
         int[] arr = new int[param3];
      }

public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```



Activation Records

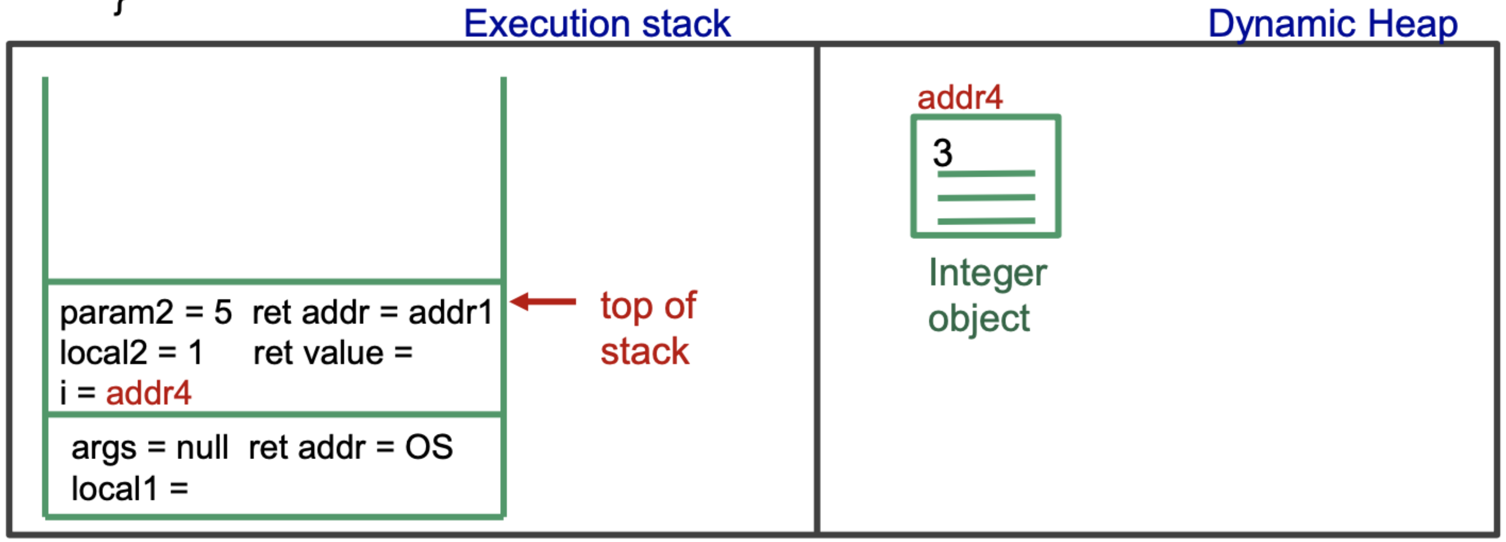
```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }

public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```



Activation Records

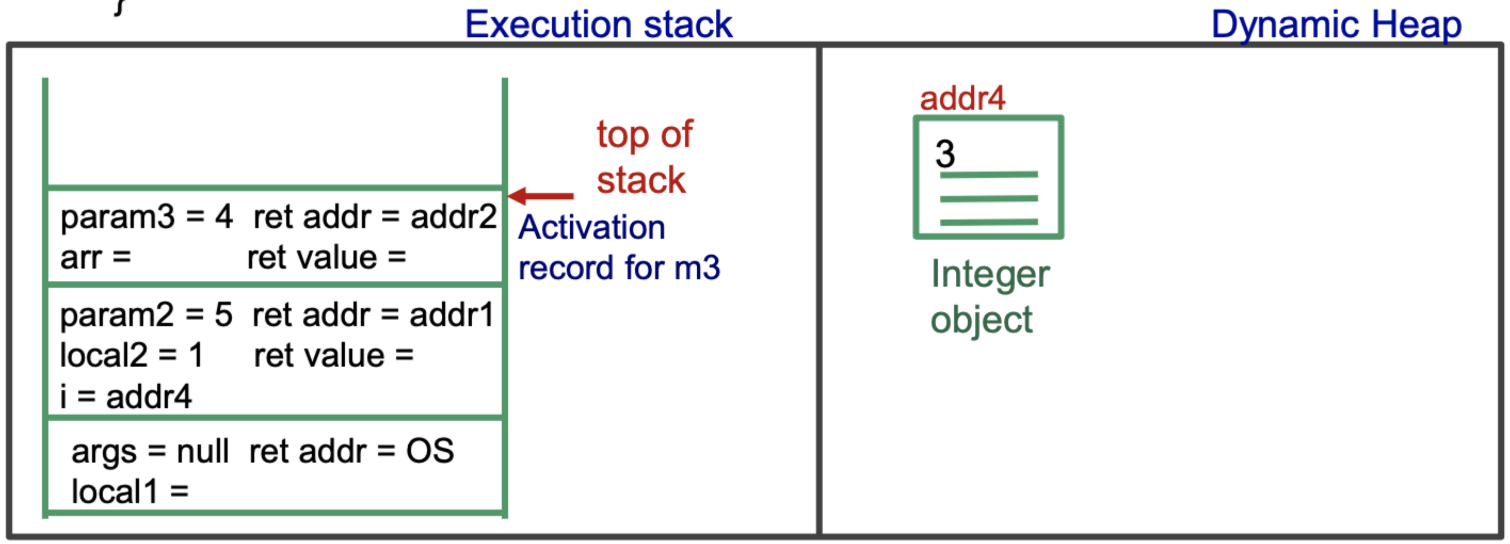
```
public static int m2 (int param2) {
    int local2 = 1;
    Integer i = new Integer(3);
addr2 m3(4);
addr3 return local2 + param2 + m4(3);
}

public static void m3 (int param3) {
    int[] arr = new int[param3];
}

public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

An object is created



Activation Records

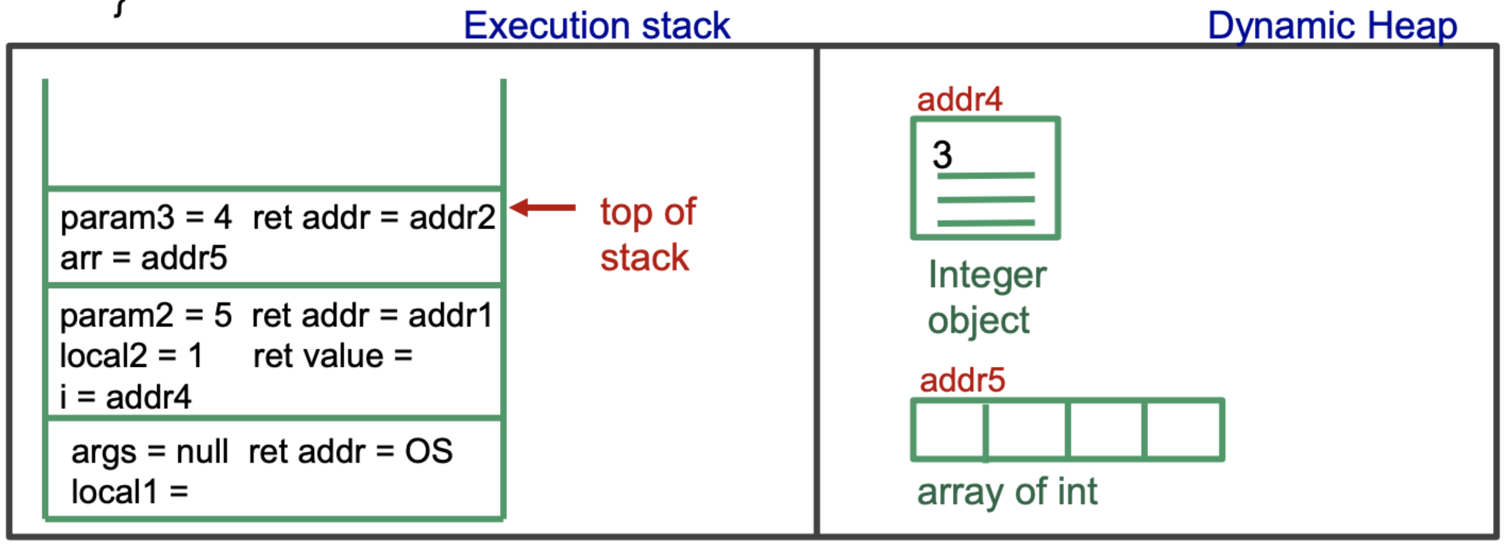
```
    public static int m2 (int param2) {
       int local2 = 1;
       Integer i = new Integer(3);
addr2  m3(4);
addr3  return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
       int[] arr = new int[param3];
    }

public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```



Activation Records

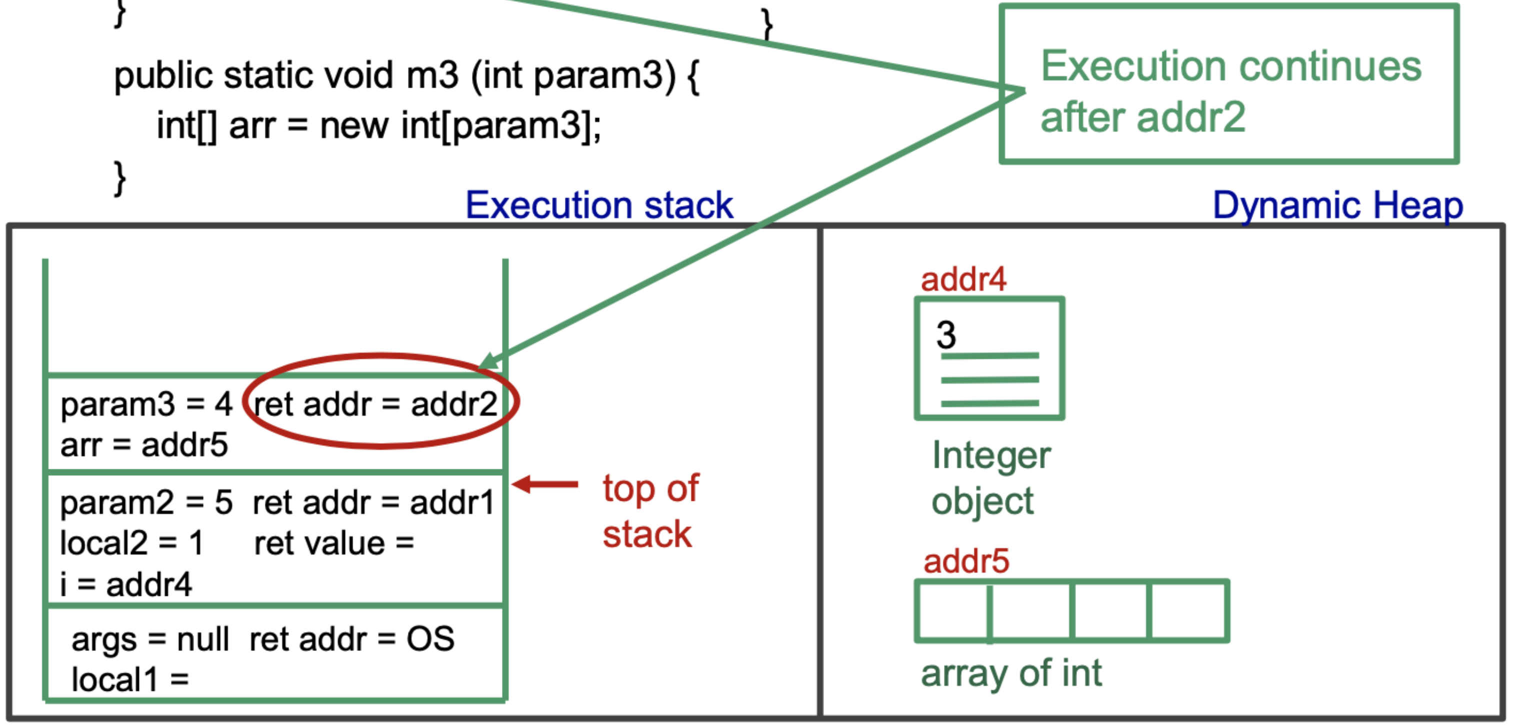
```
      public static int m2 (int param2) {
         int local2 = 1;
         Integer i = new Integer(3);
addr2    m3(4);
addr3    return local2 + param2 + m4(3);
      }

      public static void m3 (int param3) {
         int[] arr = new int[param3];
      }

public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```

An object is created



Activation Records

```
     public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
     }

     public static void m3 (int param3) {
        int[] arr = new int[param3];
     }

public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```

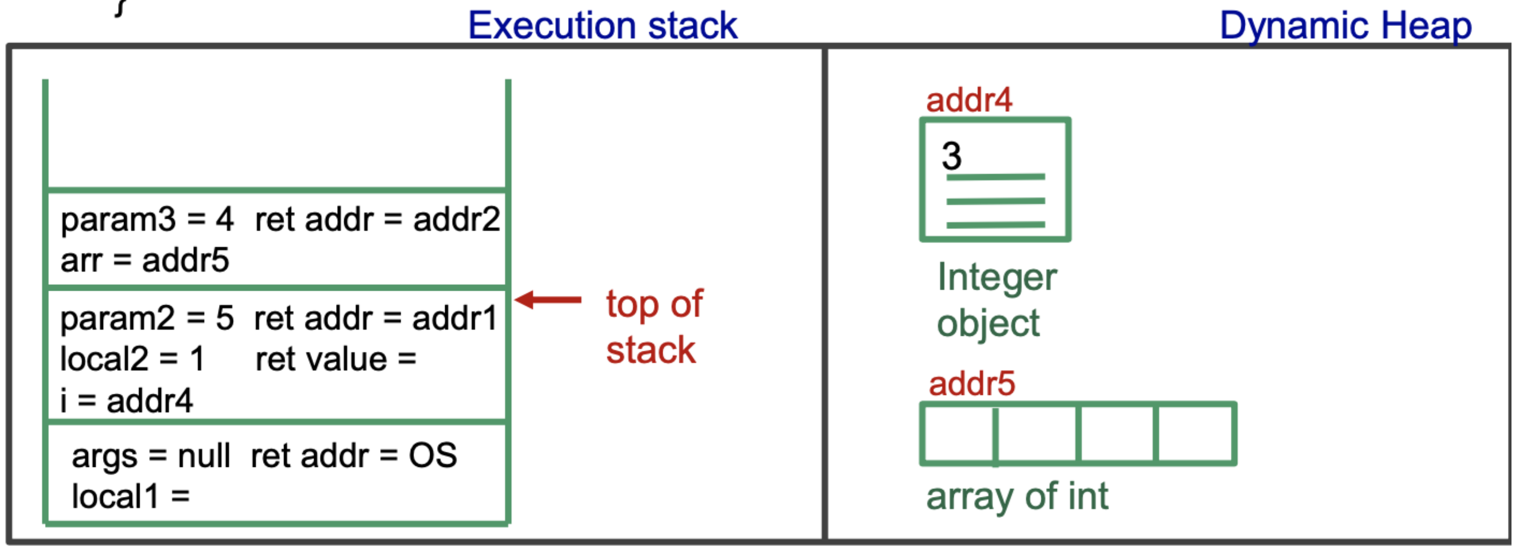


Activation Records

```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }
```

```
public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

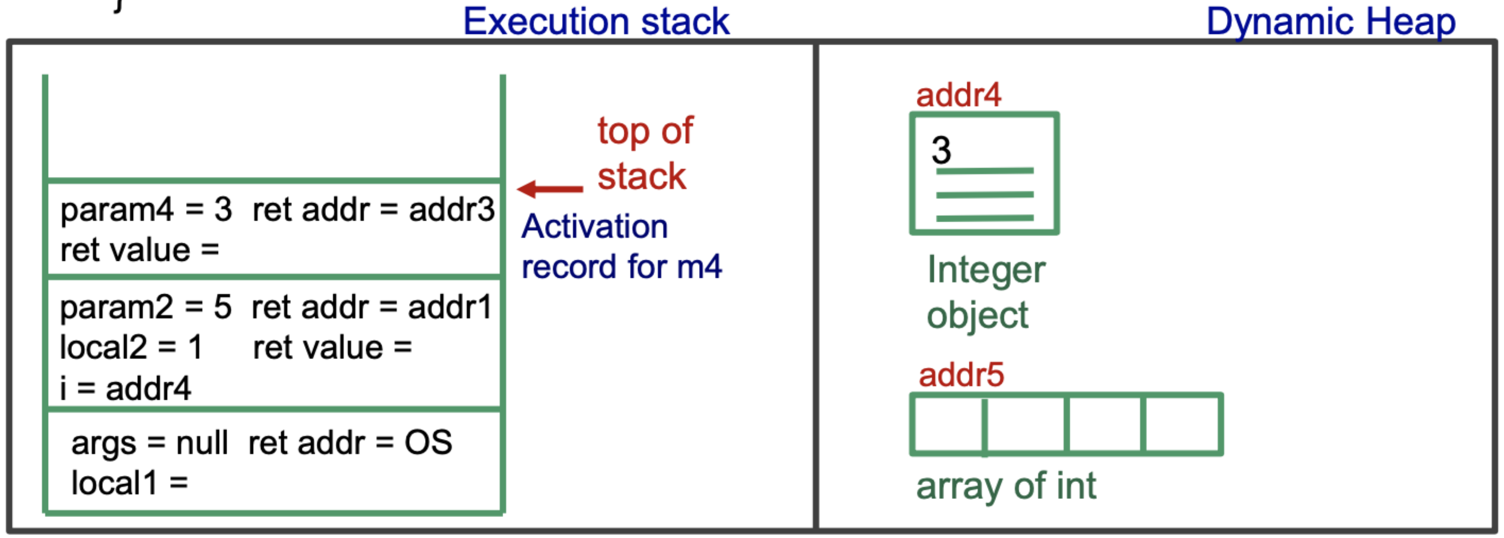
This invocation to m4 is next made



Activation Records

```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }

public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

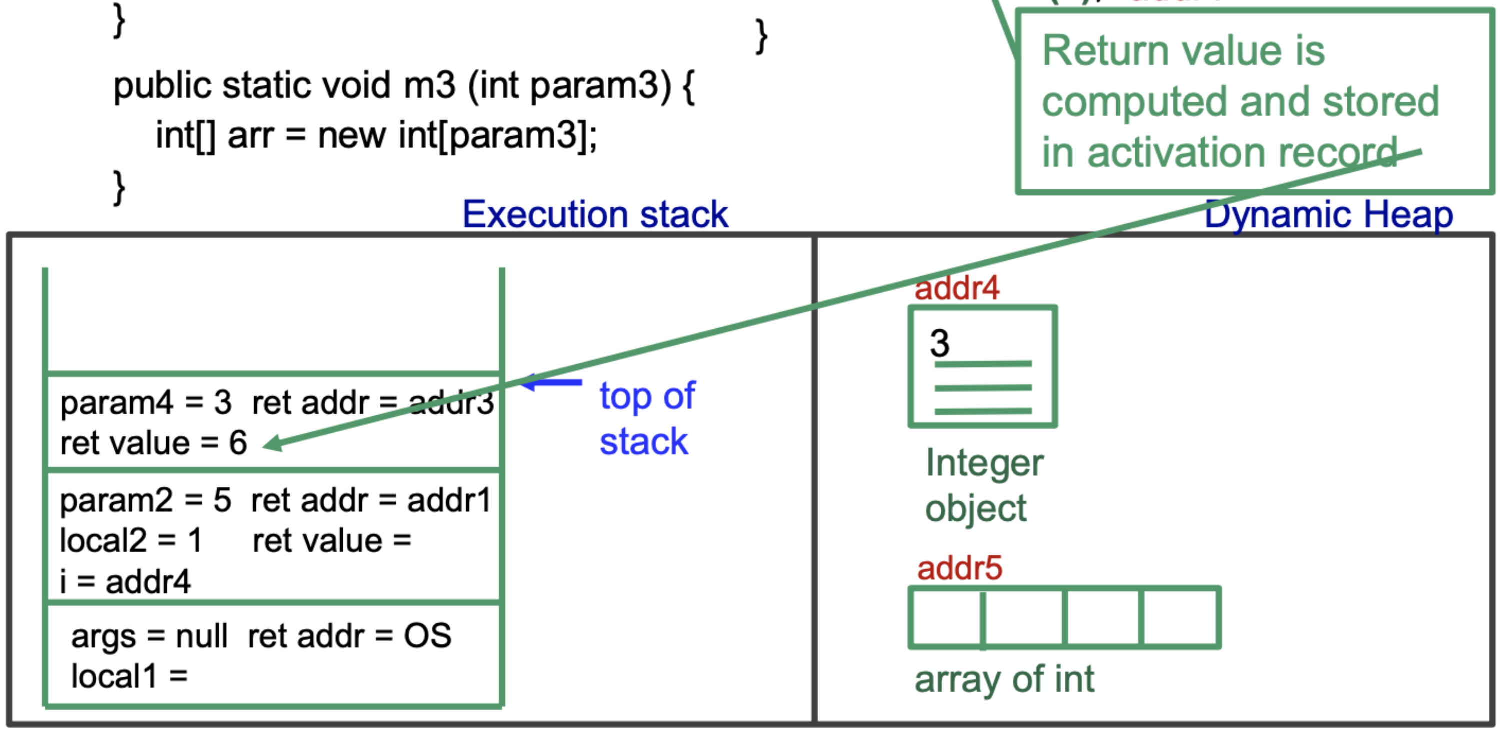
This invocation to m4 is next made



Activation Records

```
      public static int m2 (int param2) {
          int local2 = 1;
          Integer i = new Integer(3);
addr2     m3(4);
addr3     return local2 + param2 + m4(3);
      }

      public static void m3 (int param3) {
          int[] arr = new int[param3];
      }
```

```
public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

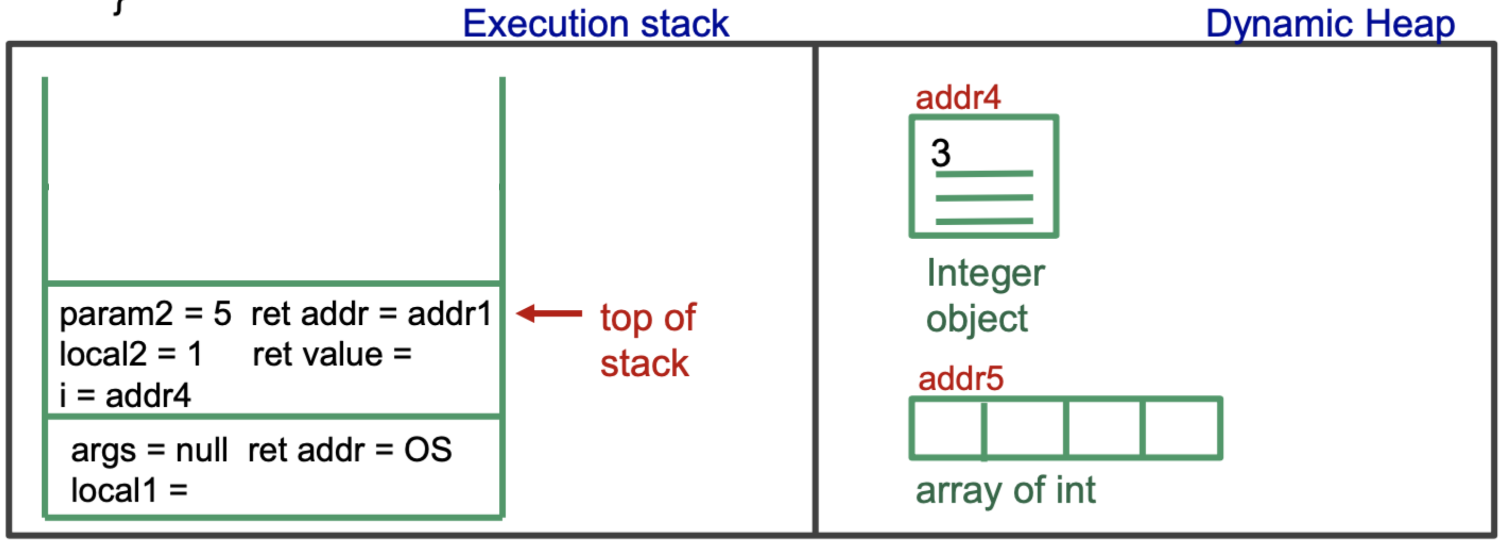


Return value is computed and stored in activation record
Execution stack
Dynamic Heap
param4 = 3 ret addr = addr3
ret value = 6
param2 = 5 ret addr = addr1
local2 = 1 ret value =
i = addr4
args = null ret addr = OS
local1 =
top of stack
addr4
3
Integer object
addr5
array of int

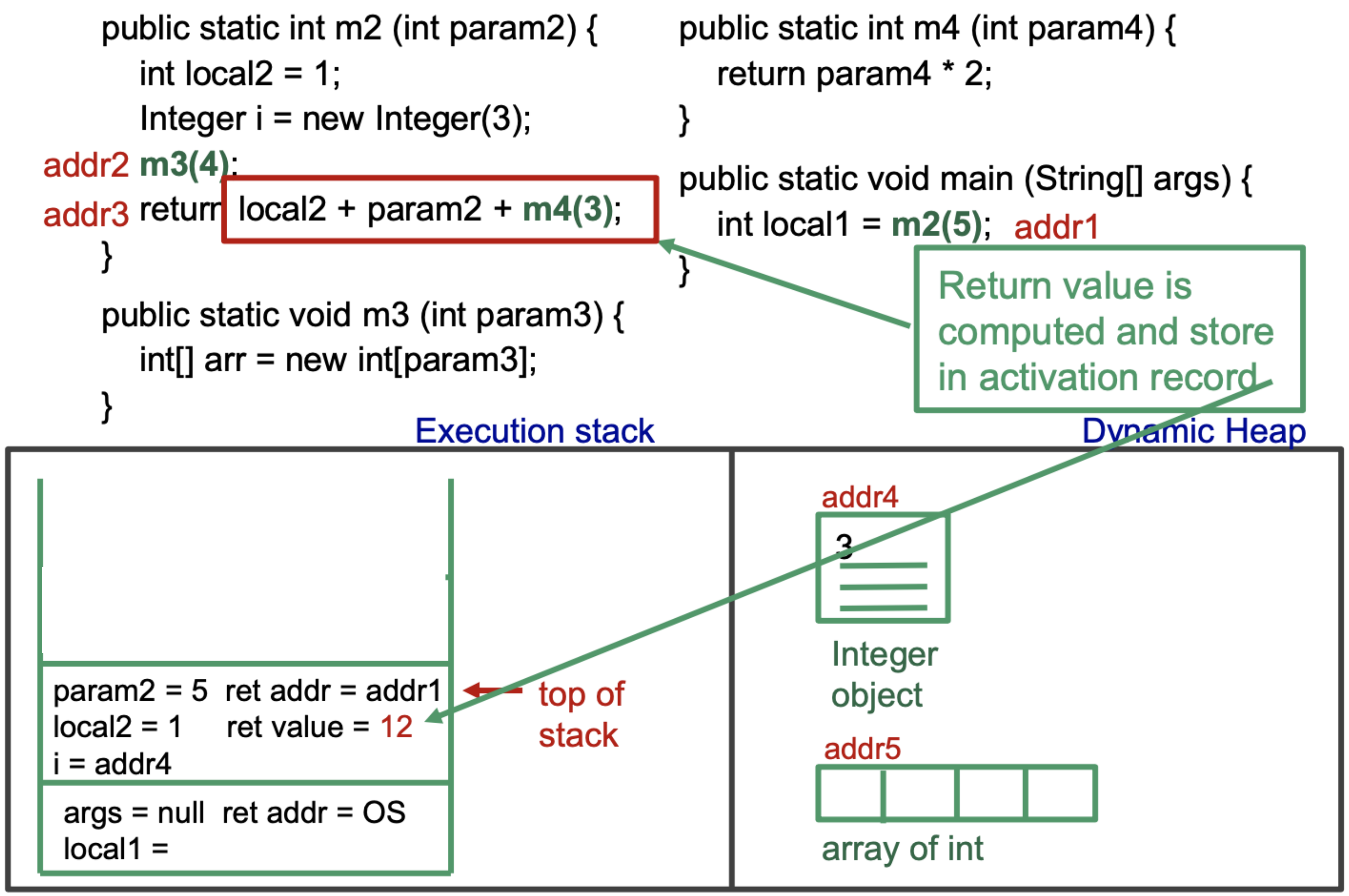
Activation Records

```
    public static int m2 (int param2) {
       int local2 = 1;
       Integer i = new Integer(3);
addr2  m3(4);
addr3  return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
       int[] arr = new int[param3];
    }

public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```

Execution continues after addr3



Activation Records



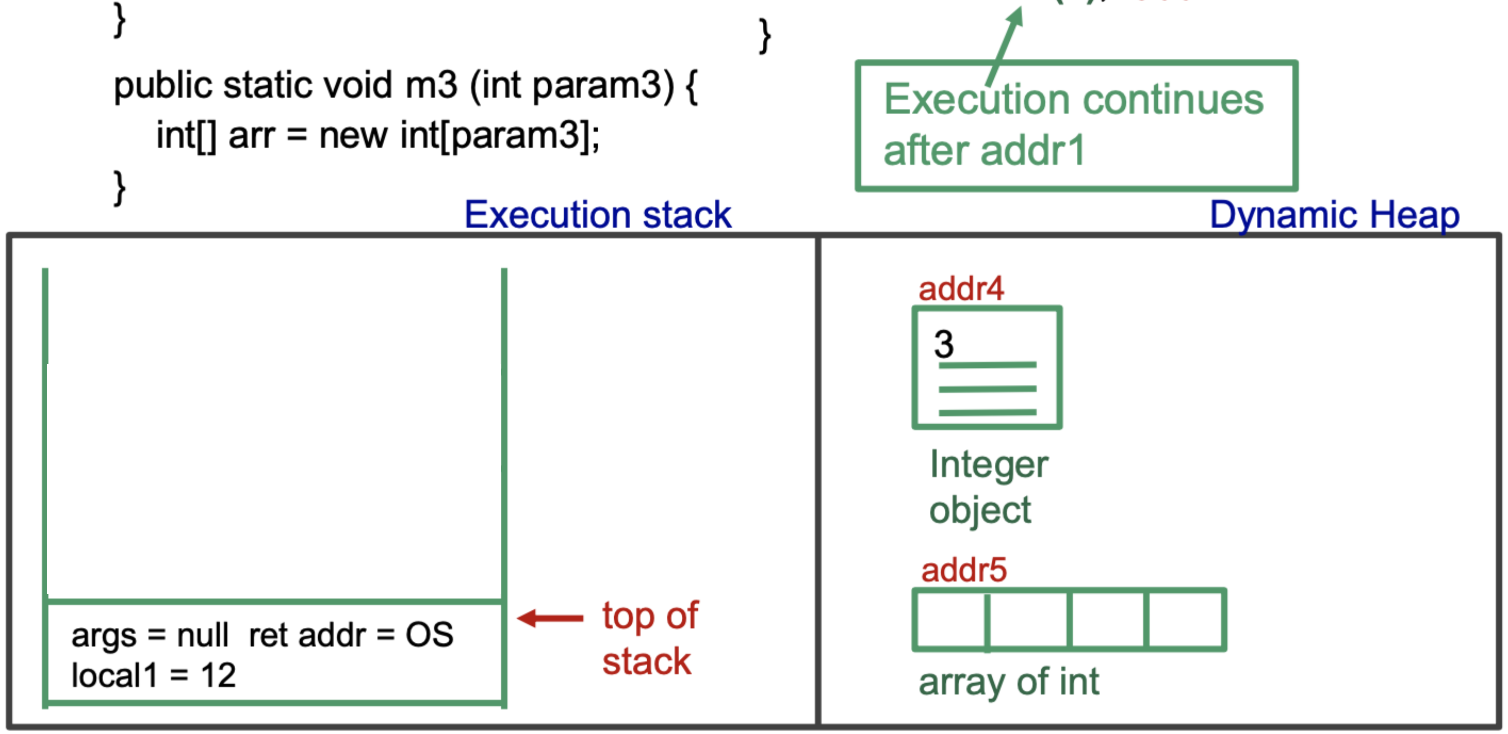
```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }

public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

Return value is computed and store in activation record
Execution stack
Dynamic Heap
param2 = 5 ret addr = addr1
local2 = 1 ret value = 12
i = addr4
args = null ret addr = OS
local1 =
top of stack
addr4
3
Integer object
addr5
array of int

Activation Records

```
    public static int m2 (int param2) {
        int local2 = 1;
        Integer i = new Integer(3);
addr2   m3(4);
addr3   return local2 + param2 + m4(3);
    }

    public static void m3 (int param3) {
        int[] arr = new int[param3];
    }
```

```
public static int m4 (int param4) {
    return param4 * 2;
}

public static void main (String[] args) {
    int local1 = m2(5);  addr1
}
```

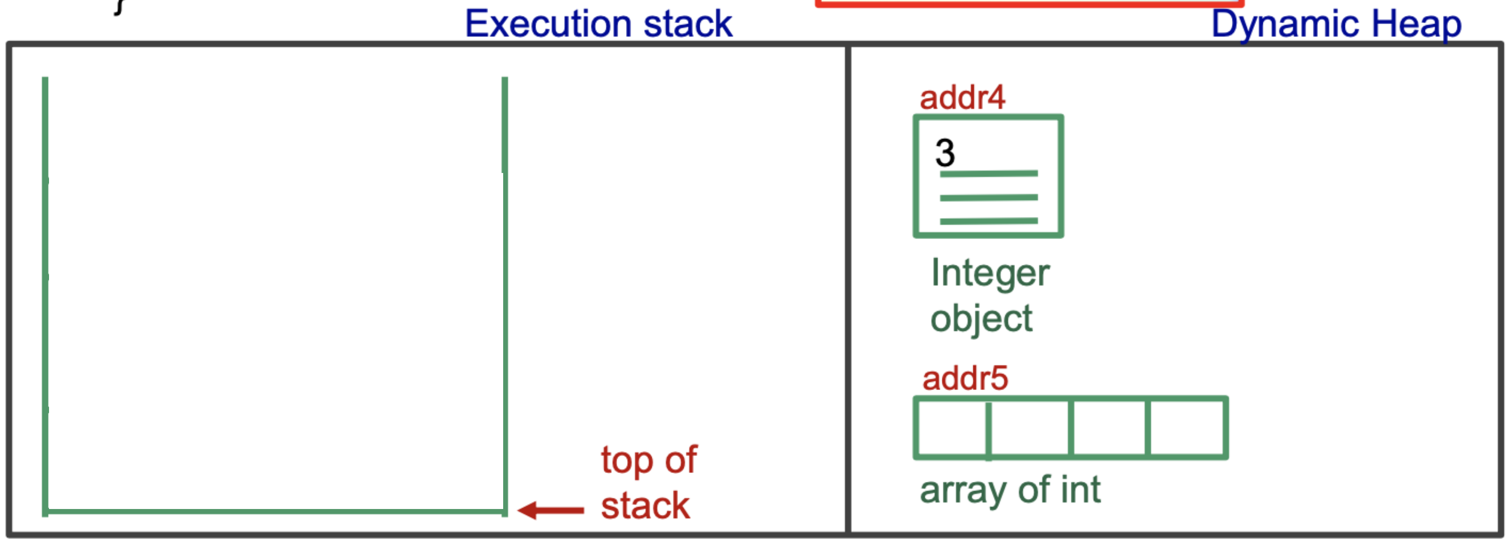


Activation Records

```
   public static int m2 (int param2) {
      int local2 = 1;
      Integer i = new Integer(3);
addr2 m3(4);
addr3 return local2 + param2 + m4(3);
   }

   public static void m3 (int param3) {
      int[] arr = new int[param3];
   }
```

```
public static int m4 (int param4) {
   return param4 * 2;
}

public static void main (String[] args) {
   int local1 = m2(5);  addr1
}
```

Program ends and control goes back to Operating System



Activation Records – Example 2

```
public class CallFrameDemo2 {
private static void printAll (String s1, String
s2, String s3) {
System.out.println(s1.toString( ));
System.out.println(s2.toString( ));
System.out.println(s3.toString( ));
}

public static void main (String args[ ]) {
String str1, str2, str3;
str1 = new String(" string 1 ");
str2 = new String(" string 2 ");
str3 = new String(" string 3 ");
printAll(str1, str2, str3);
  }
}
```

Activation Records – Example 2

Draw a picture of the execution stack and of the heap as the above program executes:

1. Activation record for main
2. Activation record for String constructor for str1 – then popped off
3. Activation record for String constructor for str2 – then popped off
4. Activation record for String constructor for str3 – then
5. popped off
6. Activation record for printAll
7. Activation record for toString for str1 – then popped off
8. Activation record for System.out.println – then popped off
9. etc.

Activation Records – Example 2

- What will be stored in the activation record for **main**?
  - Address to return to operating system
  - Variable **args**
  - Variable **str1**
    - Initial value?
    - Value after return from String constructor?
  - Variable **str2**
  - Variable **str3**
- What will be in the activation record for **printAll**?

Memory Deallocation

- What happens when a method returns?
  - On the execution stack:
    - The activation record is popped off when the method returns
    - So, that memory is deallocated

Memory Deallocation

- What happens to objects on the heap?
  - An object stays in the heap even if no variable is referencing it!
  - So, Java has automatic garbage collection
    - When memory runs low, objects that no longer have a variable referencing them are identified, and their memory is deallocated.

Recursive Definitions

Recursive Definition

- Defining something in terms of a smaller or simpler version of itself.
- A recursive definition consists of two parts:
  - The *base case*: this defines the *simplest* case or starting point
  - The *recursive part* is the general case that describes all the other cases in terms of smaller versions of itself.
  - Example:

```
// Recursive method to calculate factorial
public static int factorial(int n) {
  // Base case: if n is 1, return 1 (factorial of 1 is 1)
  if (n == 1) {return 1;}
  // Recursive part: n * factorial of (n - 1)
  else {return n * factorial(n - 1);}
}
```

base

recursive

Why is a base case needed in any recursive algorithm?

Recursion vs. Iteration

- What is iteration? Repetition, as in a loop
- What is recursion? Defining something in terms of a smaller or simpler version of itself (why smaller/simpler?)
- Recursion is a very powerful problem-solving technique.
- Many complex problems would be very difficult to solve without the use of recursion.

Example of Recursive Problem

- Consider the problem of computing the sum of all the numbers between 1 and n:

1 + 2 + 3 + 4 + … + n-1 + n

- Here is a simple iterative algorithm for this problem:

```
Algorithm sum (n)
total = 0
for i = 1 to n do
  total = total + i
return total
```

Example of Recursive Problem

- Consider the problem of computing the sum of all the numbers between 1 and n:

  1 + 2 + 3 + 4 + ... + n-1 + n

- Recursive definition:

```
sum of 1 to 1 => 1 (base case)
sum of 1 to n => n + the sum of 1 to n-1, for n > 1
```

$$\sum_{k=1}^{n} k = n + \sum_{k=1}^{n-1} k$$ (recursive case)

Recursive Algorithm

- Recursive definition:

```
sum of 1 to 1 => 1 (base case)
sum of 1 to n => n + the sum of 1 to n-1, for n > 1
```

- Recursive algorithm for this problem:

```
Algorithm sum(n)
In: Positive value n
Out: 1 + … + n
if n = 1 then return 1 // base case
else return n + sum(n-1) // recursive case
```

How Recursion Works

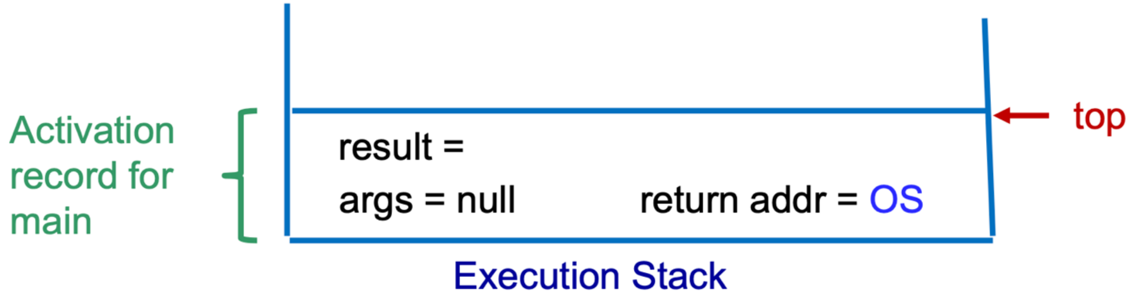
- Consider the following program

```
public static void main (String[] args) {int result = sum(4);} // addr 1
public static int sum (int n) {if (n == 1) return 1;
                              else return n + sum(n-1);} // addr2
```

- An **activation record** is created for the method main when the program is executed. This activation record stores:
  - The return address addr1
  - The variable result
  - The parameter args

How Recursion Works

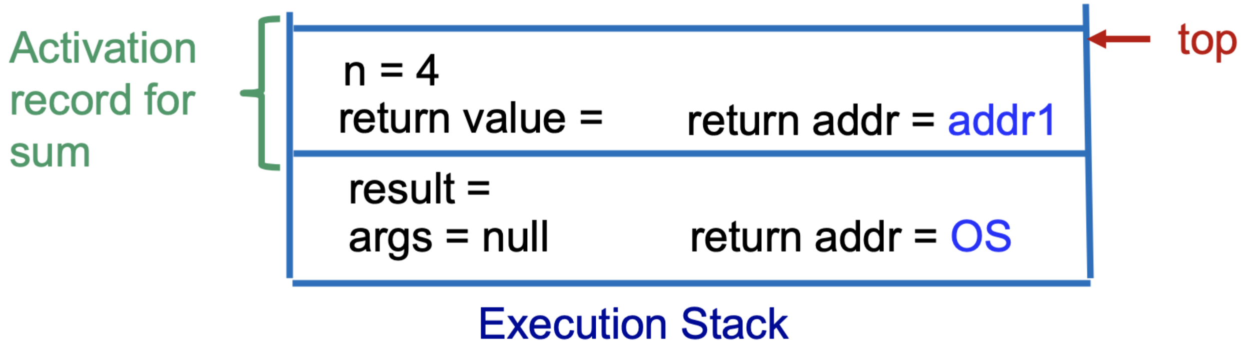
```
public static void main (String[] args)
{int result = sum(4);} // addr 1
public static int sum (int n) {
if (n == 1) return 1;
else return n + sum(n-1);} // addr2
```



- At this point, the execution stack looks like the following figure. We assume no parameter is passed to the main function, so args is null.
- The result variable has no value assigned to it yet, so we left its value blank. OS denotes the address of the virtual machine's instruction where the main method was invoked.

How Recursion Works

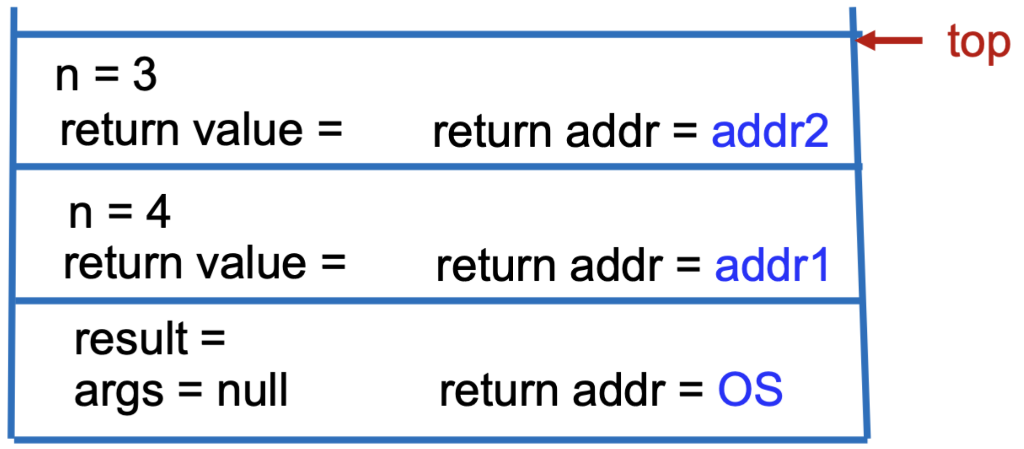
```
public static void main (String[] args)
{int result = sum(4);} // addr 1
public static int sum (int n) {
if (n == 1) return 1;
else return n + sum(n-1);} // addr2
```



- Once the activation record for the main function has been created and the values of the parameters and return address have been stored, the execution of the method main starts.
- The first and only statement of the main function invokes method **sum**(4). This creates another activation record, which is pushed into the execution stack, as shown above.

How Recursion Works (cont.)

```
public static void main (String[] args)
{int result = sum(4);} // addr 1
public static int sum (int n) {
if (n == 1) return 1;
else return n + sum(n-1);} // addr2
```

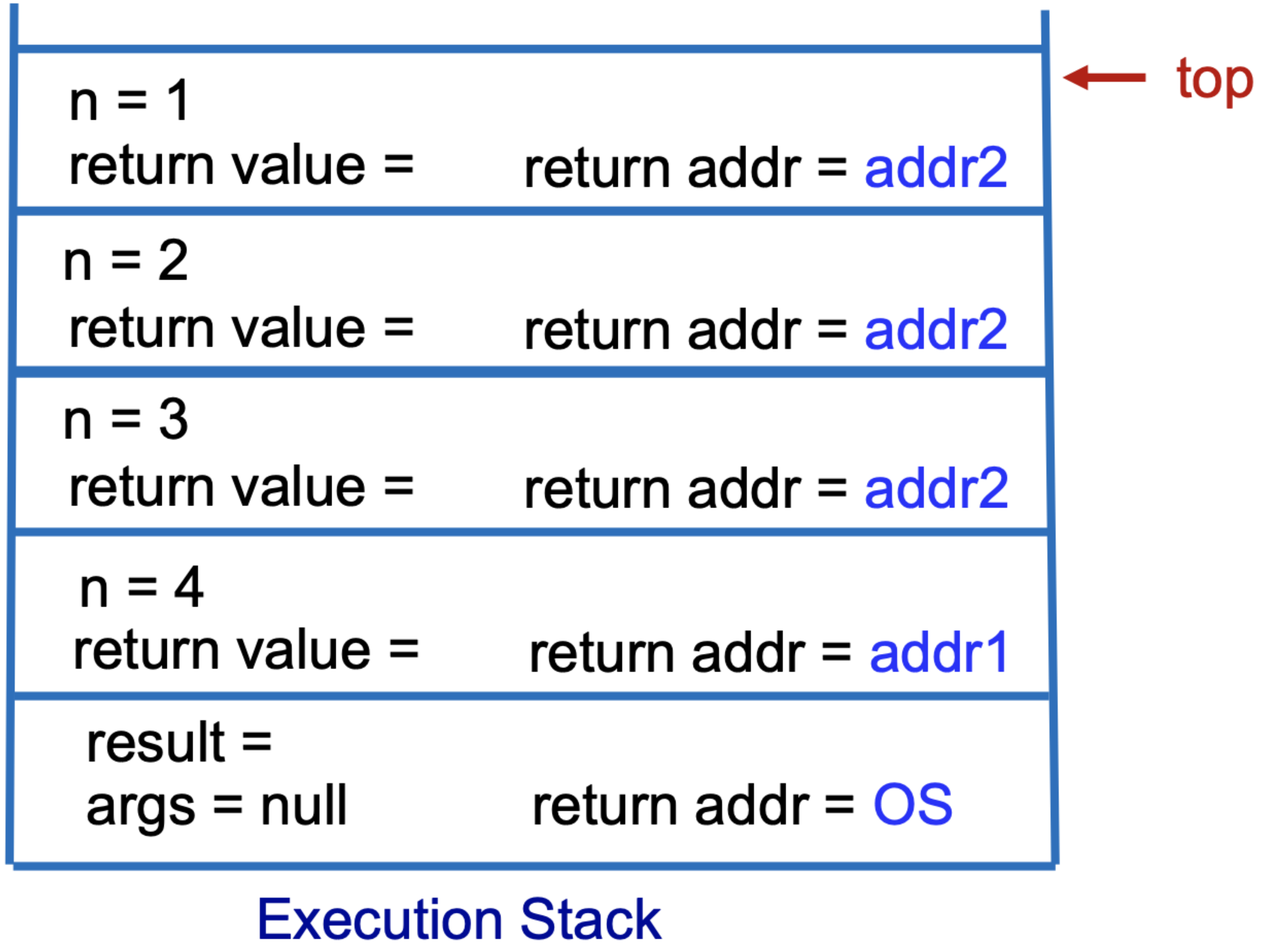


Execution Stack

- Once the activation record has been created, the execution of the method sum starts.
- Since n > 1, method sum (n-1) is invoked.
- A new activation record is created and pushed into the stack

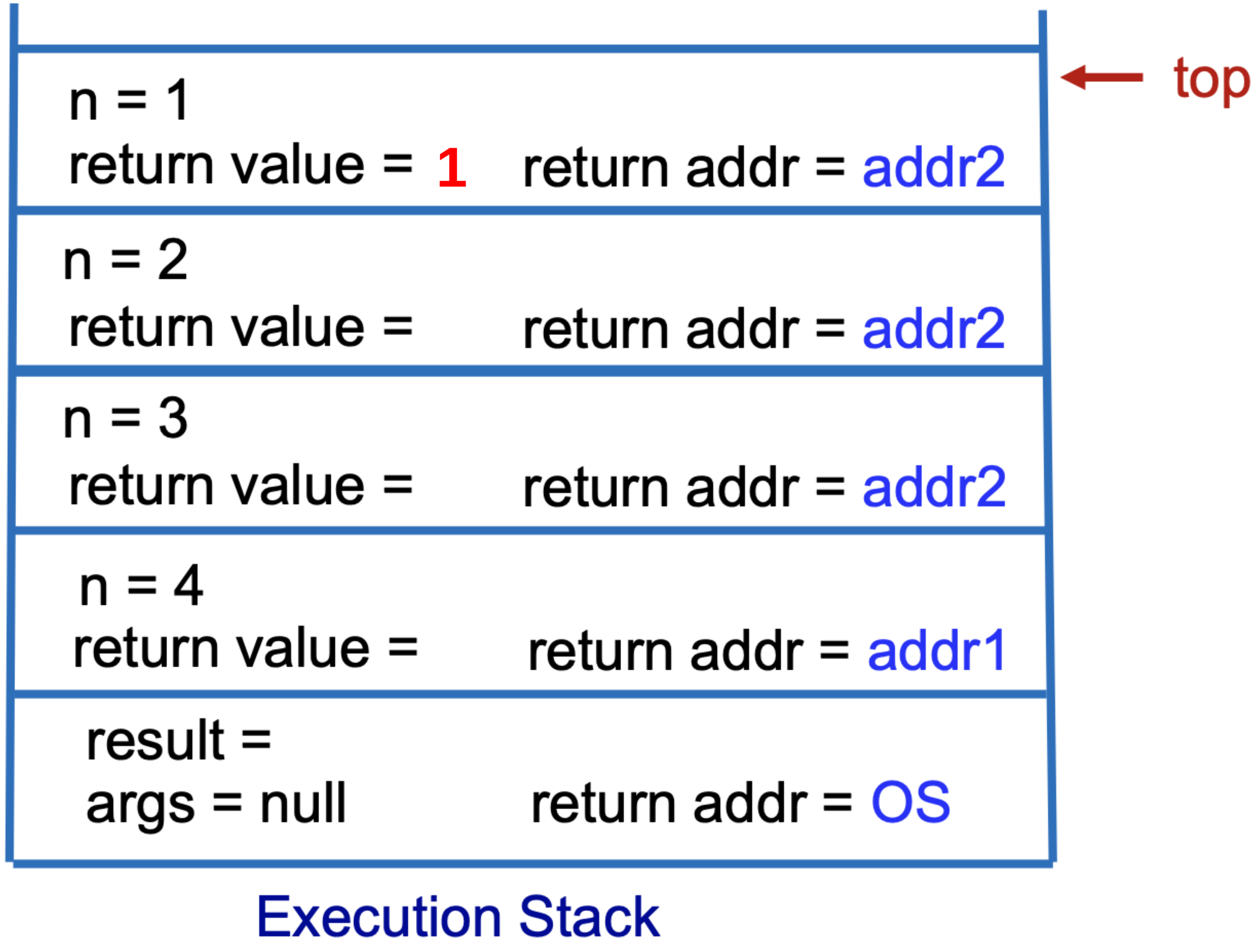
How Recursion Works (cont.)

- Then, two more invocations to the method sum with parameters 2 and 1 are made.
- After the last invocation, the execution stack looks like the figure given.



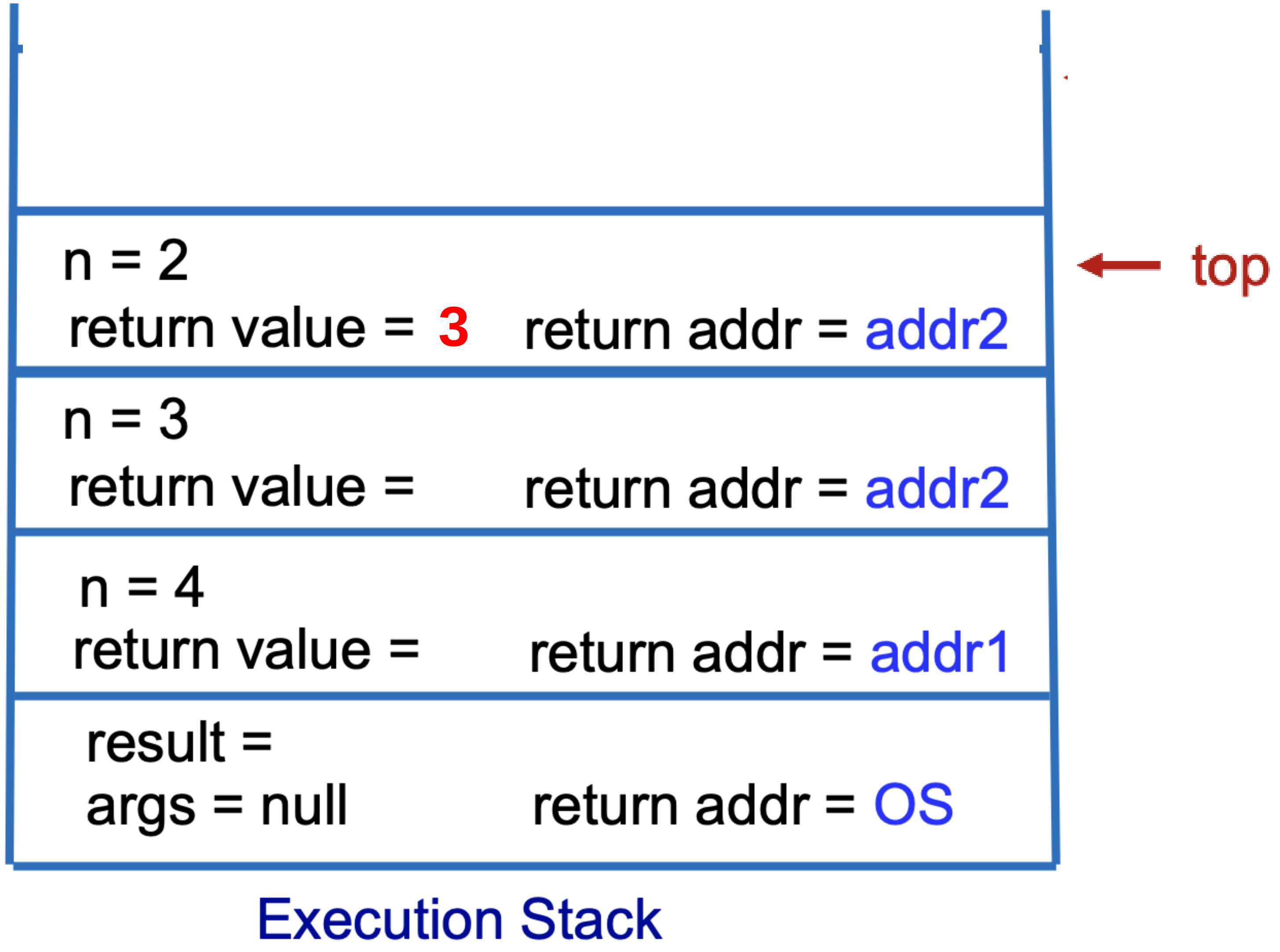
How Recursion Works (cont.)

- Since the value of n is 1 in the last invocation of the method sum, the statement return 1 (base case) is executed.
- The value 1 is stored in the **return value**.



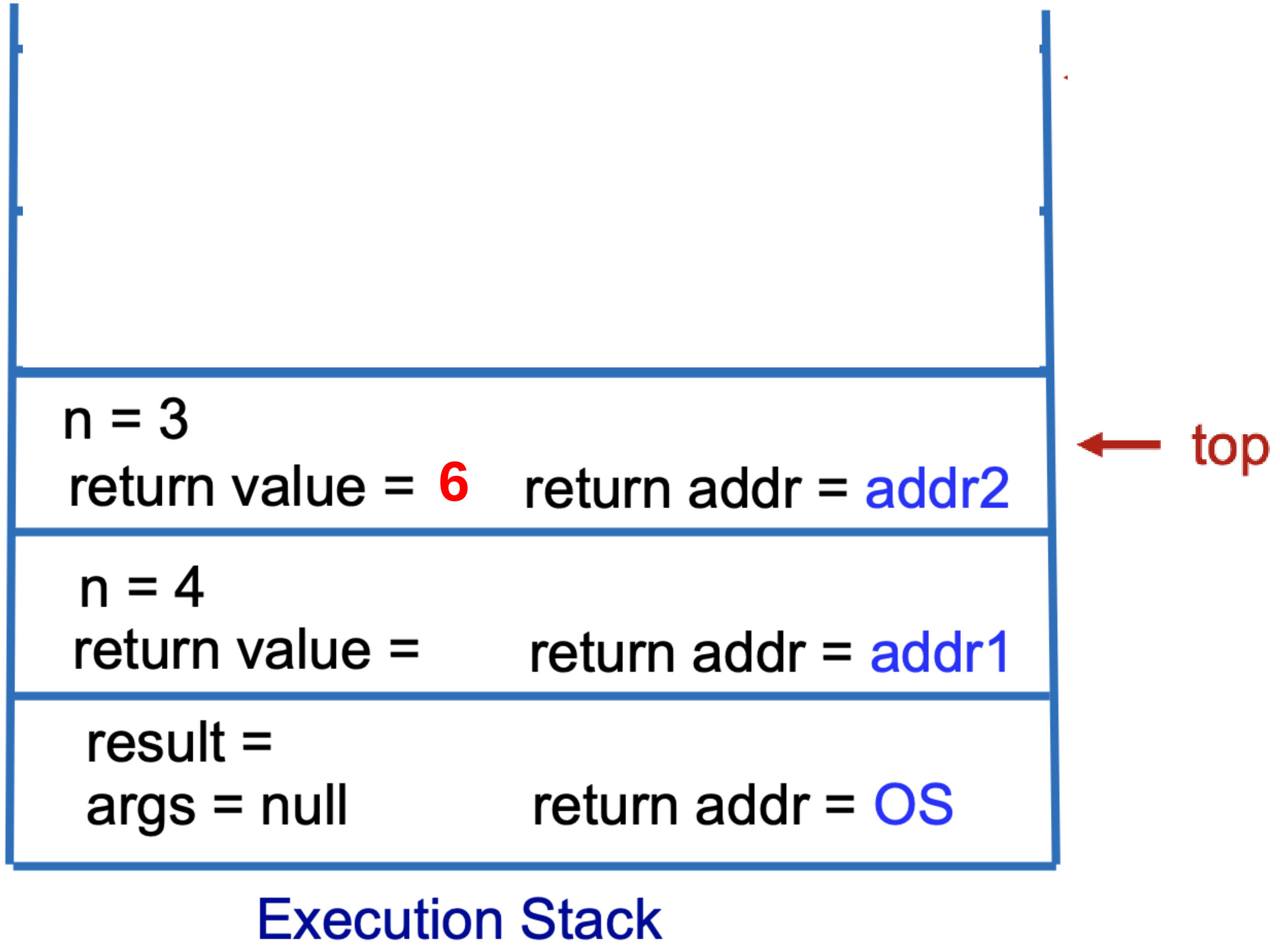
How Recursion Works (cont.)

- The method sum ends, and hence, an activation record is popped off the execution stack.
- The return address addr2 is recovered, and execution continues at the statement in that address: This call just finished, and it returned the value 1.
- Hence, n + sum(n-1) = 2 + 1 = 3 will be returned.

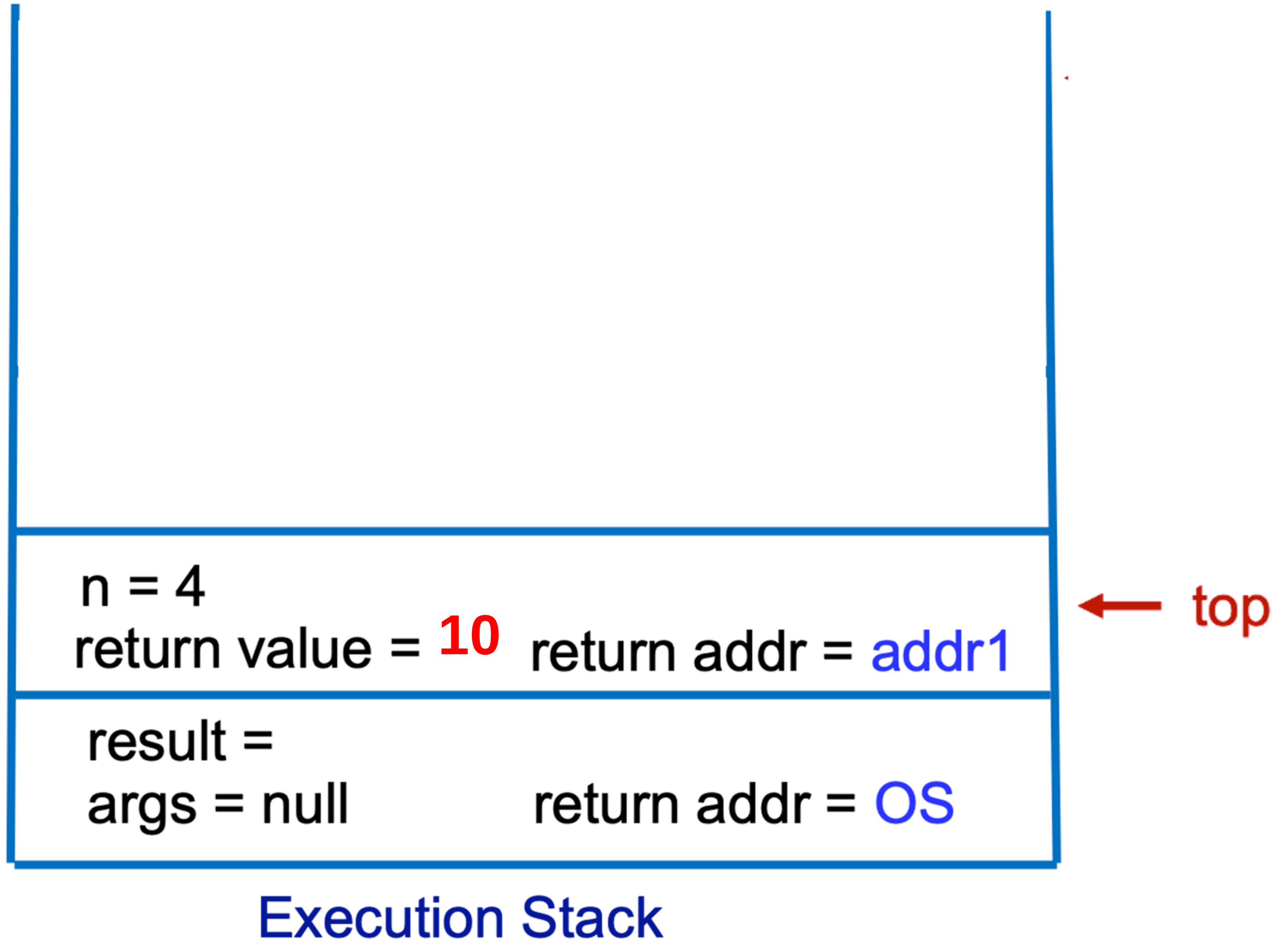


How Recursion Works (cont.)

- The next call returns the value 3, and an activation record is popped off the execution stack. The return address addr2 is recovered, and execution continues with the statement in that address.
- The value n + sum(n-1) = 3 + 3 = 6 will be returned.

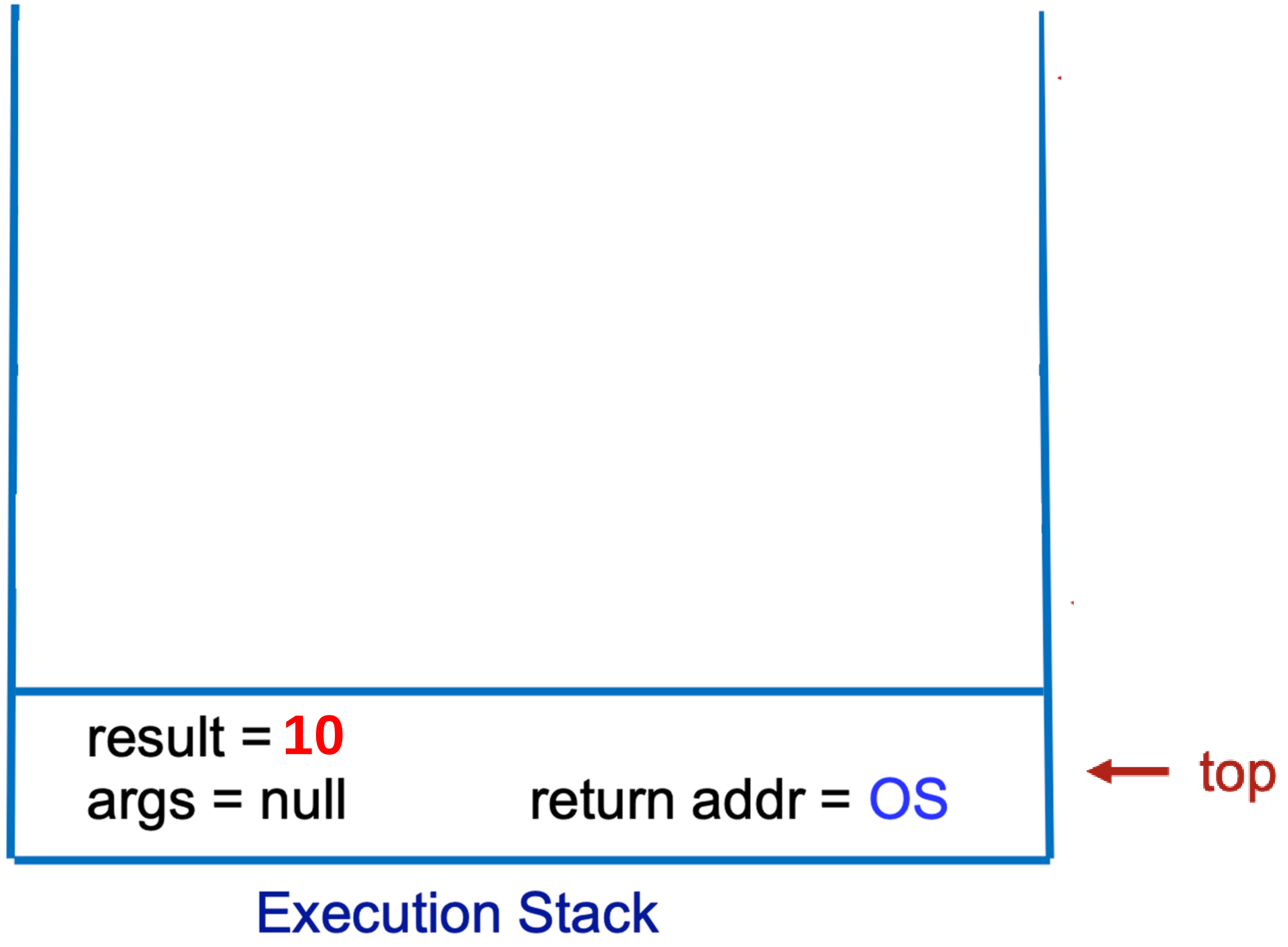


How Recursion Works (cont.)



How Recursion Works (cont.)

```
public static void main
(String[] args) {int result =
sum(4);} // addr 1
```



Recursion vs. Iteration

- Every recursive algorithm can also be written as an **iterative** algorithm. However, the algorithm could be much more complex and require the use of an auxiliary stack or other data structures to simulate the execution stack.
- Thus, just because we can use recursion to solve a problem does not mean we should!
- Would you use iteration or recursion to compute the sum of 1 to n? Why?

Recursion vs. Iteration

- Recursion often uses more memory and can lead to stack overflow errors if the recursive depth is too large. Sometimes, an iterative (loop-based) solution is faster and more memory-efficient.

Thank you