

## Slides

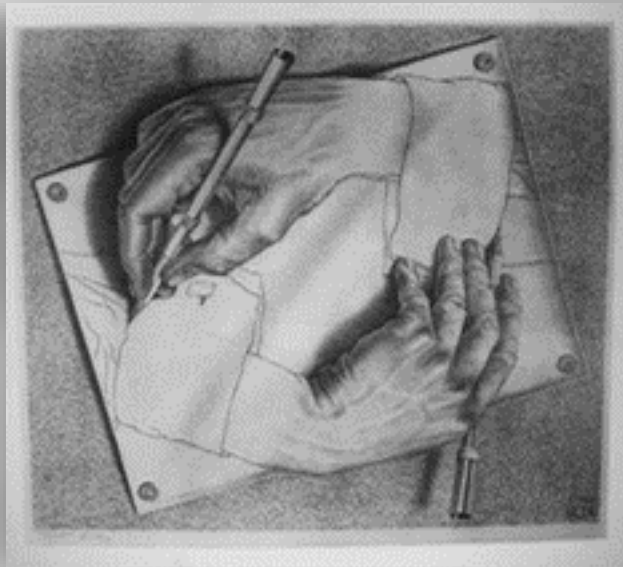
1. Table of Contents
2. Definitions
3. Simple Recursion
4. Recursive Execution Trace
5. Recursion Attributes
6. Recursive Array Summation
7. Recursive Array Summation Trace
8. Coding Recursively
9. Recursive Design
10. Avoiding Pitfalls
11. Middle Decomposition
12. Call Tree Traces
13. Edges & Center Decomposition
14. Recursive Sorting
15. Backtracking
16. Knapsack Solution
17. Runtime Stack
18. Knap Runtime Trace Snapshot
19. Storage Organization

## Recursion

- see **Recursion**
- a process in which the result of each repetition is dependent upon the result of the next repetition.
- Simplifies program structure at a cost of function calls

## Hofstadter's Law

- *“It always takes longer than you expect, even when you take into account Hofstadter's Law.”*



## *Sesquipedalian*

- *a person who uses words like sesquipedalian.*

## *Yogi Berra*

- *“Its déjà vu all over again.”*

A procedure or function which calls itself is a recursive routine.

Consider the following function, which computes

$$N! = 1 * 2 * \dots * N$$

```
int Factorial(int n) {
    int Product = 1,
        Scan    = 2;

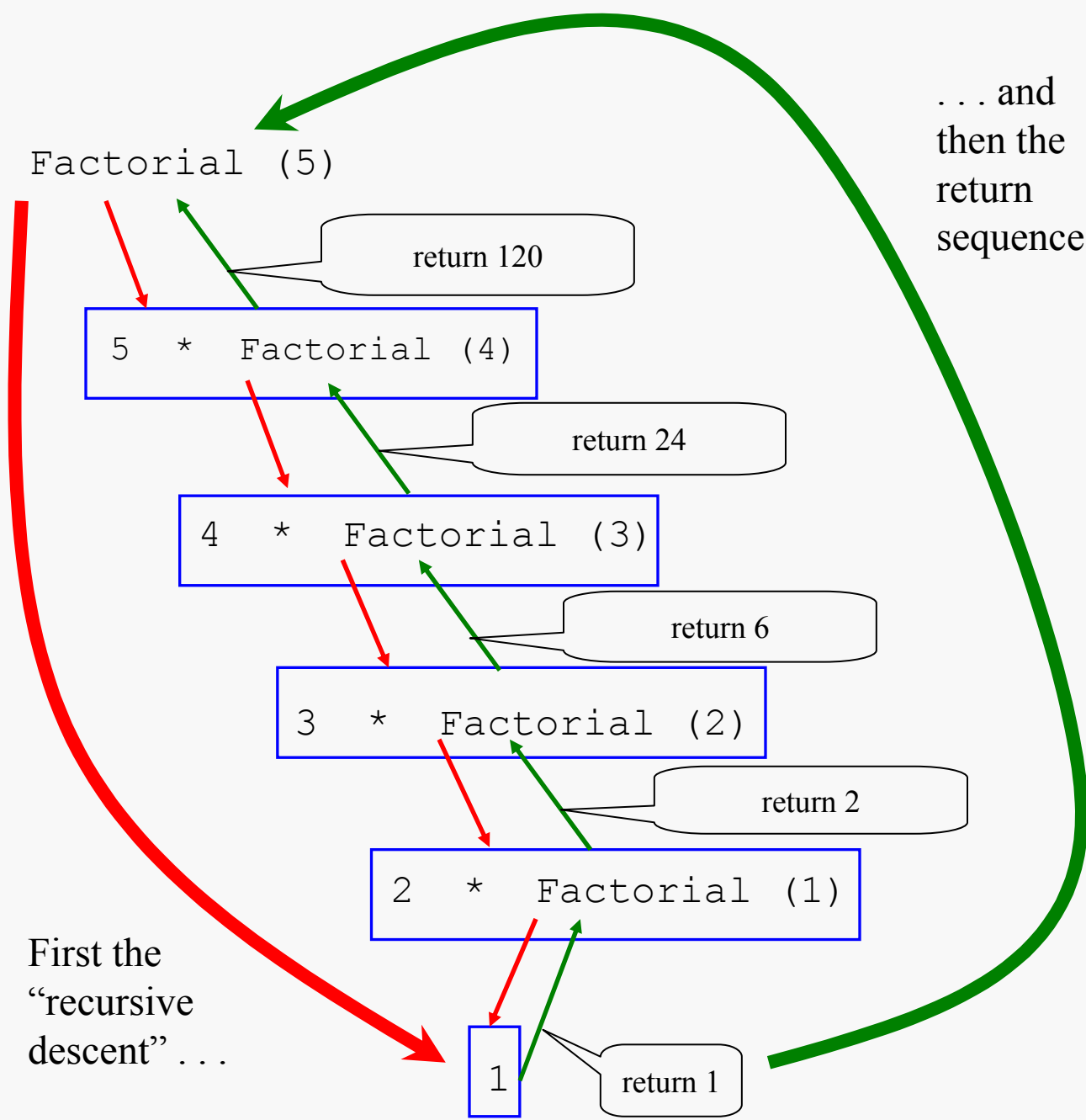
    while ( Scan <= n ) {
        Product = Product * Scan ;
        Scan = Scan + 1 ;
    }
    return (Product) ;
}
```

Now consider a recursive version of Factorial:

```
int Factorial(int n ) {
    if ( n > 1 )
        return( n * Factorial (n-1) );
    else
        return(1);
}
```

Factorial (5)

... and then the return sequence



First the “recursive descent” ...

- Every recursive algorithm can be implemented non-recursively.

recursion  $\Leftrightarrow$  iteration

- Eventually, the routine must not call itself, allowing the code to "back out".
- Recursive routines that call themselves continuously are termed:

infinite recursion  $\Leftrightarrow$  infinite loop

- Problem with this recursive factorial implementation?

**Negative numbers!**

- Recursion is inefficient at runtime.

Here is a recursive function that takes an array of integers and computes the sum of the elements:

```
// X[]      array of integers to be summed
// Start    start summing at this index . . .
// Stop     . . . and stop summing at this index
//
int SumArray(const int X[], int Start, int Stop) {
    // error check
    if (Start > Stop || Start < 0 || Stop < 0)
        return 0;
    else if (Start == Stop) // base case
        return X[Stop];
    else // recursion
        return (X[Start] + SumArray(X, Start + 1, Stop));
}
```

The call:

```
const int Size = 5;
int X[Size] = {37, 14, 22, 42, 19};
SumArray(X,0,Size- 1); // note Stop is last valid index
```

would result in the recursive trace:

```
SumArray(X, 0, 4) // return values:
                    // == 134
    return (X[0]+SumArray(X,1,4)) // == 37 + 97
        return (X[1]+SumArray(X,2,4)) // == 14 + 83
            return (X[2]+SumArray(X,3,4) ) // == 22 + 61
                return (X[3]+SumArray(X,4,4)) // == 42 + 19
                    return X[4] // == 19
```

## Mathematical Induction Model

- Solve the trivial "base" case(s).
- Restate general case in 'simpler' or 'smaller' terms of itself.

## Array Sum Example

- Determine the size of a single linked list.

Base Case : array size =1, sum = the element

General Case : first element + Sum(Rest of Array)

```
// X[]      array of integers to be summed
// Start    start summing at this index . . .
// Stop     . . . and stop summing at this index
//
int SumArray(const int X[], int Start, int Stop) {
    // error check
    if (Start > Stop || Start < 0 || Stop < 0)
        return 0;
    else if (Start == Stop) // base case
        return X[Stop];
    else // recursion
        return (X[Start] + SumArray(X, Start + 1, Stop));
}
```

### Example of "tail recursion" (going up recursion).

**Tail recursive functions are characterized by the recursive call being the last statement in the function, (can easily be replaced by a loop).**

**Problem:**

- Code a function `void intComma( long )` that outputs the integer argument comma separated :

- e.g.,

the call:        `intComma ( 123456789 ) ;`

displays:       `123,456,789`

**Top-Down Design**

```
void intComma ( long num ) {  
    if (num is less than 1000)  
        display num  
    else  
        display comma separated digits above 1000  
        display comma  
        display digits below 1000  
}
```

**Code**

```
void intComma ( long num ) {  
    if (num < 1000)  
        cout << setw(3) << num;  
    else {  
        intComma(num / 1000);  
        cout << ',' << setw(3) << num % 1000;  
    }  
}
```

**Consider:**

```
intComma( 123456789 ) ;  
intComma( 1001 ) ;
```

## General Solution

```
void intComma ( long num ) {

    if (num < 0) {           // display sign for negatives
        cout << '-';
        num = -num;
    }

    if (num < 1000)
        cout << setw(3) << num;
    else {
        intComma(num / 1000);
        cout << ',';           // display digits
                               // separately
        num = num % 1000;     // for zeroes
        cout << (num / 100);
        num = num % 100;
        cout << (num / 10) << (num % 10);
    }
}
```

**Example of  
“going down”  
(head) recursion**

## Trace intComma(9087605430);

intComma(9087605430)  
 = intComma(9087605) and ...  
 = intComma(9087) and ...  
 = intComma(9) and ...  
 = intComma(9)

**output**

9

9,087

9,087,605

9,087,605,430

**alternatively**

```
string prefix =
    (num < 10 ) ? "00" :
    (num < 100) ? "0" : "";
cout << prefix << num;
```

**Problem:**

- Given an array of integers of n+1 elements code a function to return the index of the maximum value in the array.

**Solution:**

- Check if the middle element is the largest if so return its index otherwise return the index of either the largest element in the lower half or the largest element in the upper half, whichever is the larger of the two.

```
int rMax(const int ray[], int start, int end ) {  
  
    const int Unknown = -1;  
  
    int mid, h1max, h2max;  
  
    if (end < start) return Unknown;  
  
    mid = (start + end) / 2;  
    h1max = rMax(ray, start, mid-1); //left half  
    if (h1max == Unknown) h1max = start;  
    h2max = rMax(ray, mid+1, end); //right half  
    if (h2max == Unknown) h2max = end;  
    if ( (ray[mid] >= ray[h1max]) &&  
        (ray[mid] >= ray[h2max]) )  
        return mid;  
    else  
        return ( ray[h1max] > ray[h2max] ) ?  
                h1max : h2max );  
}
```

**Example of  
“splitting  
into halves”  
recursion**

**“Unknown” checks ensure that indices are within array subscript range**



### Problem:

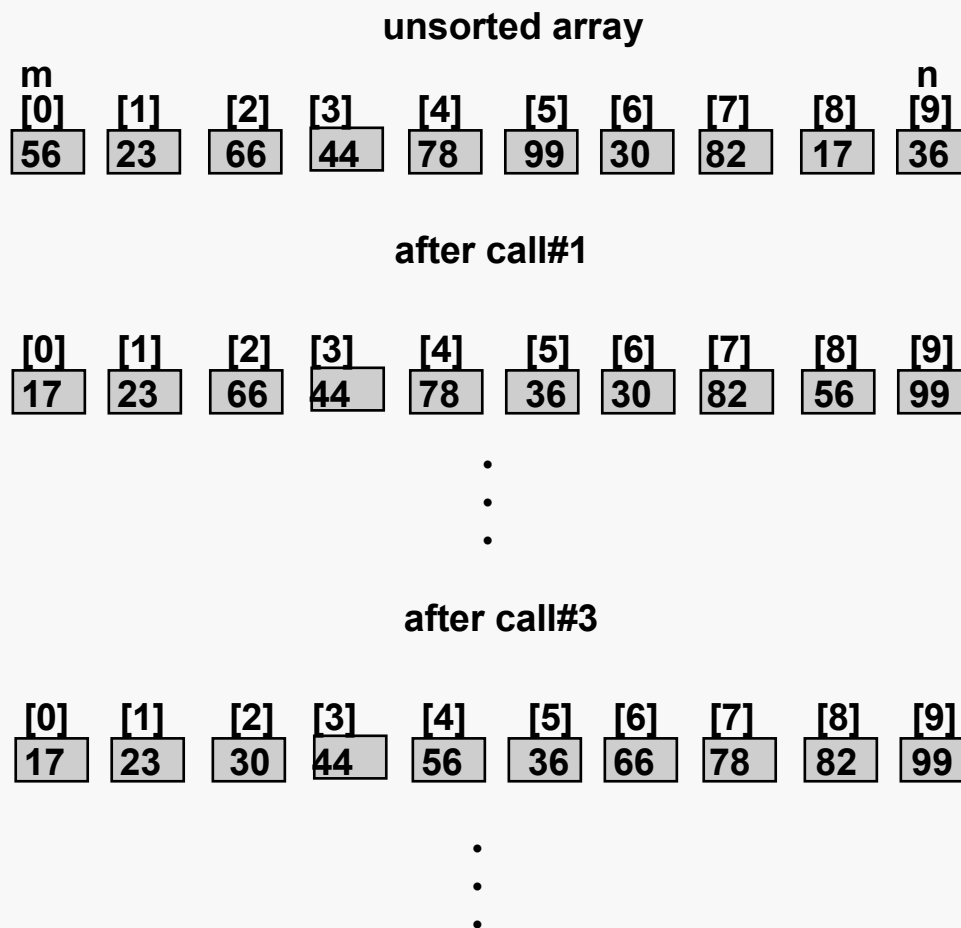
- sort a subset, (m:n), of an array of integers (ascending order)

### Solution:

- Find the smallest and largest values in the subset of the array (m:n) and swap the smallest with the m<sup>th</sup> element and swap the largest with the n<sup>th</sup> element, (i.e. order the edges).
- Sort the center of the array (m+1: n-1).

**Variation of the "selection" sort algorithm**

### Solution Trace



```

void duplexSelection(int ray[], int start,
                    int end ) {
    int mini = start, maxi = end;

    if (start < end) { //start==end => 1 element to sort

        findMiniMaxi( ray, start, end, mini, maxi);
        swapEdges(ray, start, end, mini, maxi);
        duplexSelection( ray, start+1, end-1);
    }
}

```

```

void findMiniMaxi( const int ray[], int start, int end,
                  int& mini, int& maxi) {

    if (start < end) { //subset to search exists

        if (ray[start] < ray[mini]) mini = start;
        else if (ray[start] > ray[maxi]) maxi = start;
        findMiniMaxi( ray, start+1, end, mini, maxi);
    }
}

```

```

void swapEdges(int ray[], int start, int end,
               int mini, int maxi)
{
    //check for swap interference
    if ( (mini == end) && (maxi == start) ) {
        swap( ray[start], ray[end] );
    } //check for low 1/2 interference
    else if (maxi == start) {
        swap( ray[maxi], ray[end] );
        swap( ray[mini], ray[start] );
    } // (mini == end) || no interference
    else {
        swap( ray[mini], ray[start] );
        swap( ray[maxi], ray[end] );
    }
}

```

```

void swap
( int& x, int& y)
{
    int tmp= x ;
    x = y ;
    y = tmp ;
}

```

## Knapsack Problem (*very weak form*)

- Given an integer total, and an integer array, determine if any collection of array elements within a subset of the array sum up to total.
- Assume the array contains only positive integers.

## Special Base Cases

- total = 0 :
  - † solution: the collection of no elements adds up to 0.
- total < 0 :
  - † solution: no collection adds to sum.
- start of subset index > end of subset index :
  - † solution: no such collection can exist.



## Inductive Step

- Check if a collection exists containing the first subset element.
  - † Does a collection exist for total - ray[ subset start ] from subset start + 1 to end of subset?
- If no collection exists containing ray[ subset start ] check for a collection for total from subset start + 1 to the end of the subset.

**Backtracking step. Function searches for alternative solution “undoing” previous possible solution search work.**

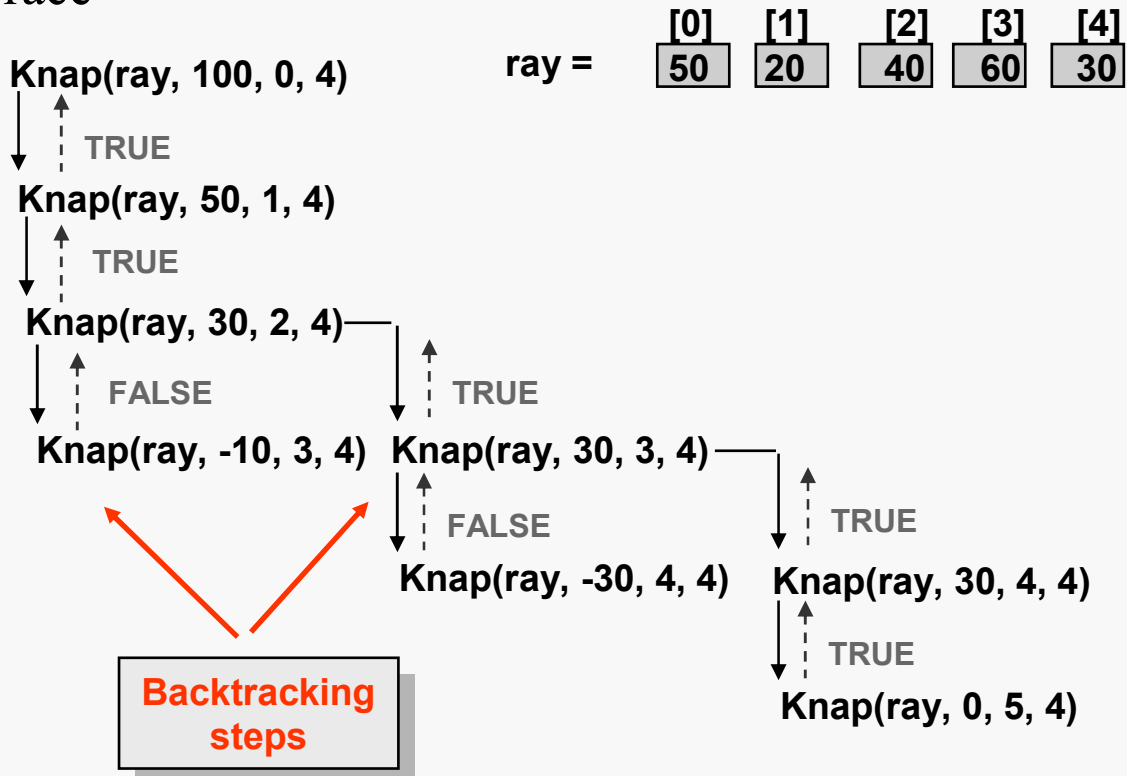
## Knap **backtracking** function

```
bool Knap (const int ray[], int total, int start, int end)
{
    if (total == 0) // empty collection adds up to 0
        return true;
    if ( (total < 0) || (start > end) ) //no such
        return false; //collection exists

    //check for collection containing ray[start]
    if (Knap(ray, total-ray[start], start+1, end))
        return true;

    // check for collection w/o ray[start]
    return (Knap(ray, total, start+1, end));
}
```

## Trace

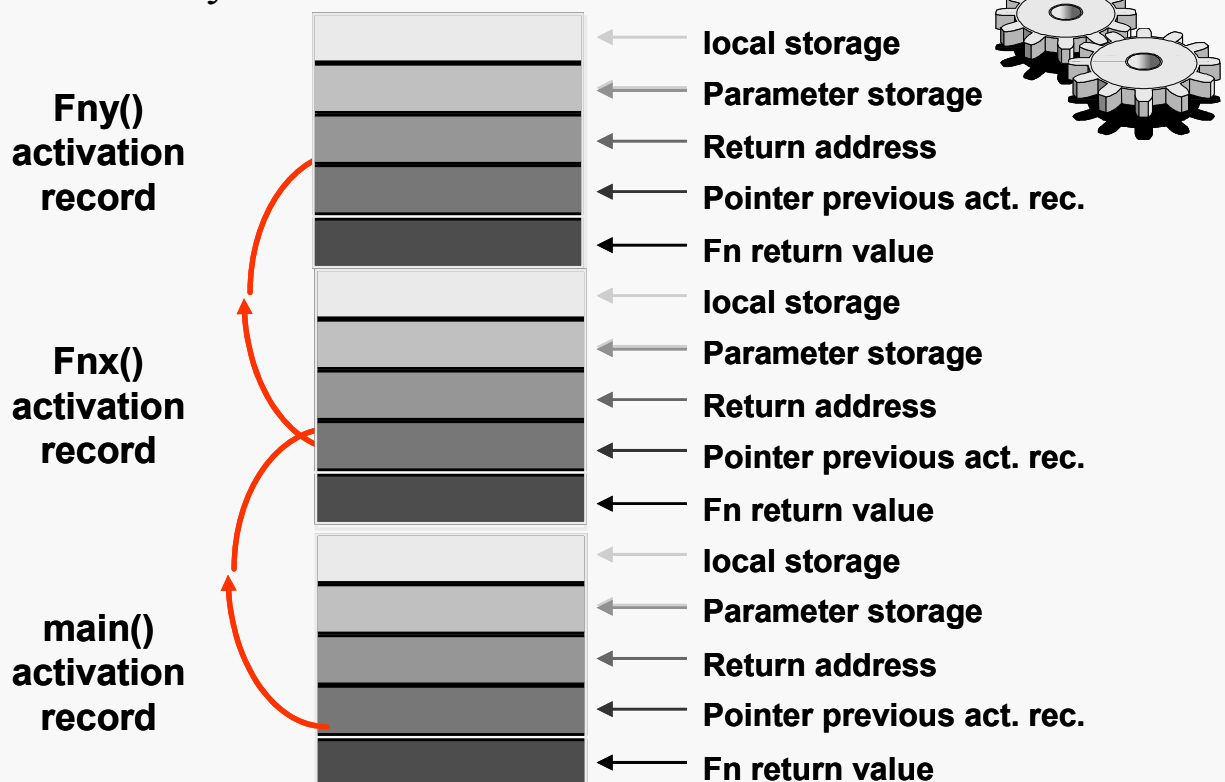


## Recursion Underpinnings

- Every instance of a function execution (call) creates an **Activation Record, (frame)** for the function.
- Activation records hold required execution information for functions:
  - † Return value for the function
  - † Pointer to activation record of calling function
  - † Return memory address, (calling instruction address)
  - † Parameter storage
  - † Local variable storage

## Runtime Stack

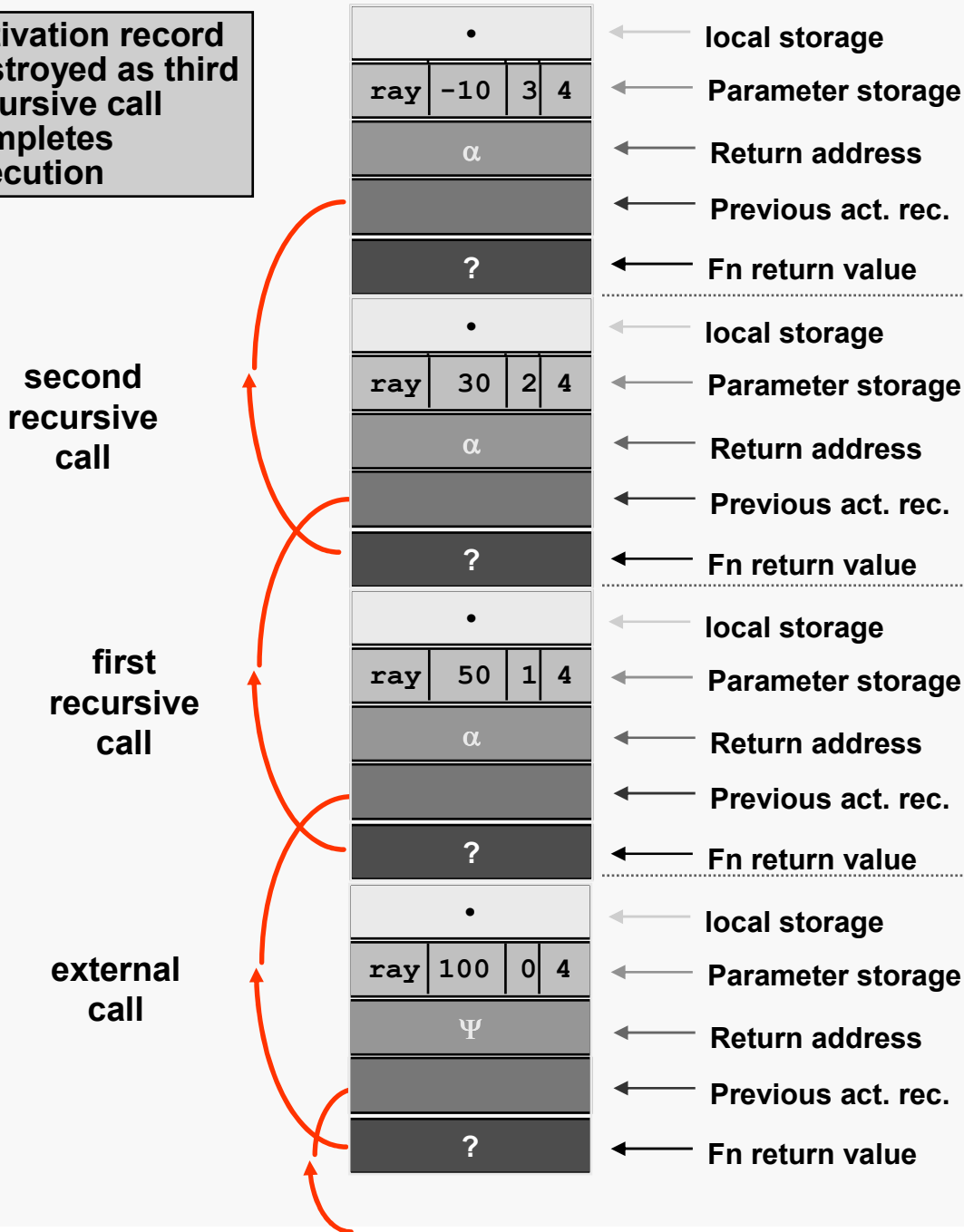
- Activation records are created and stored in an area of memory termed the “**runtime stack**”.



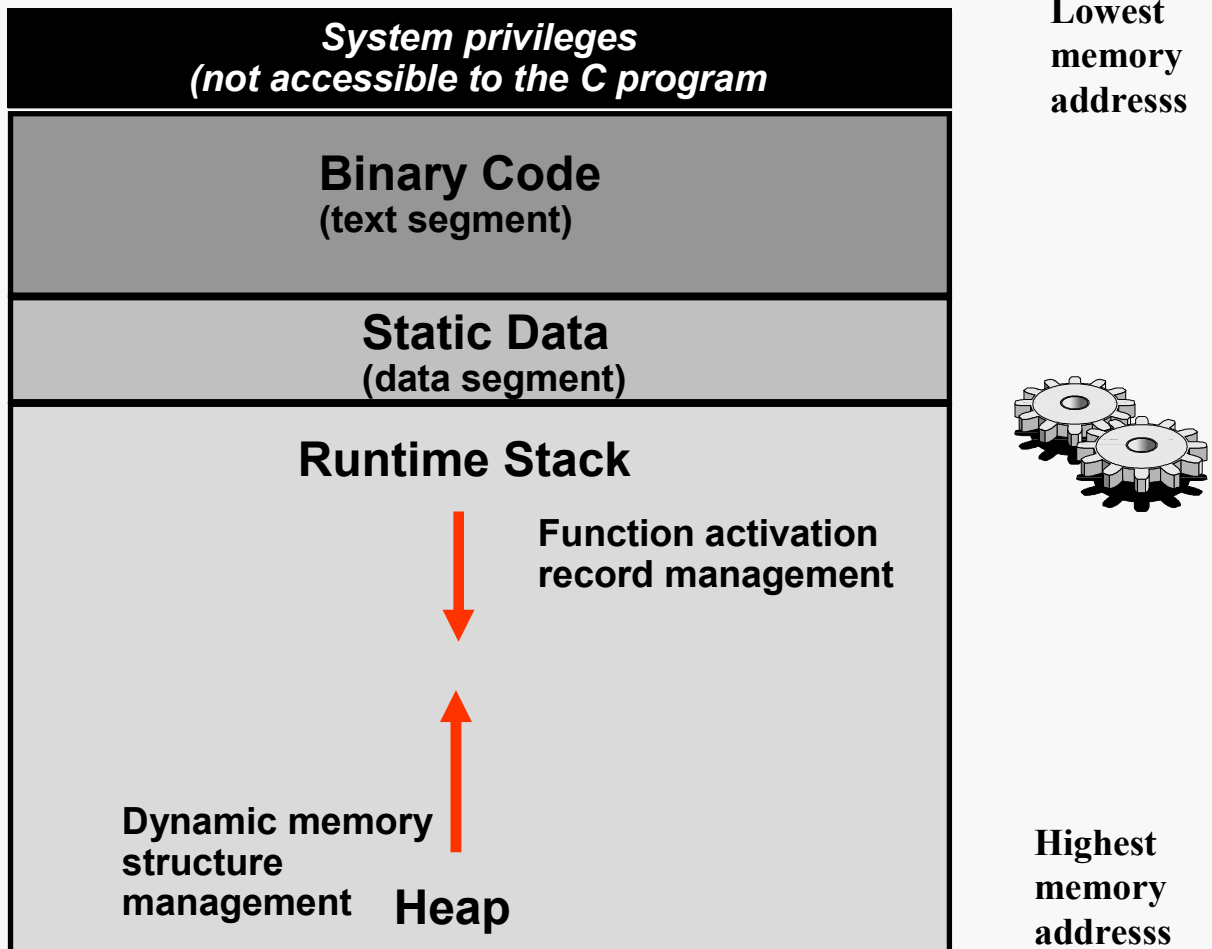
### First backtrack step(during fourth call)

- Let first recursive call in knap be at address  $\alpha$
- Let second recursive call in knap be at address  $\beta$

Activation record destroyed as third recursive call completes execution



## Typical C++ program execution memory model



## Storage Corruption

- Infinite regression results in a collision between the “run-time” stack & heap termed a “run-time” stack overflow error.
- Illegal pointer de-references (garbage, dangling-references) often result in memory references outside the operating system allocated partition, (segment) for the C program resulting in a “segmentation error” (GPF - access violation) and core dump.