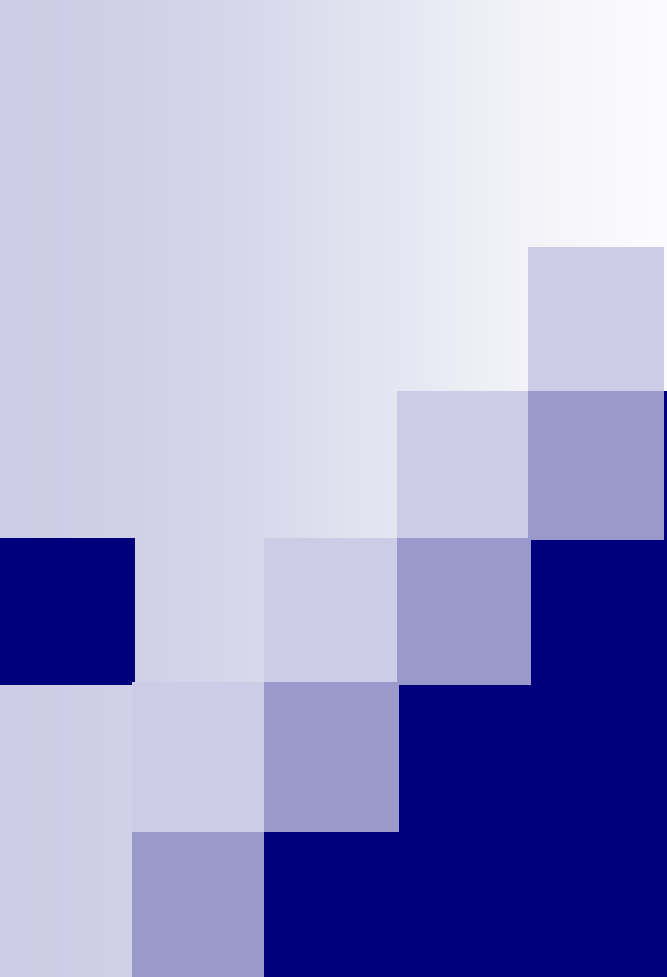




Recursion

Recursion

- A process by which a function calls itself repeatedly
 - Either directly.
 - X calls X
 - Or cyclically in a chain.
 - X calls Y, and Y calls X
- Used for repetitive computations in which each action is stated in terms of a previous result
$$\text{fact}(n) = n * \text{fact}(n-1)$$

- For a problem to be written in recursive form, two conditions are to be satisfied:
 - It should be possible to express the problem in recursive form
 - Solution of the problem in terms of solution of the **same** problem on smaller sized data
 - The problem statement must include a stopping/terminating condition
 - The direct solution of the problem for a small enough size

$$\begin{aligned} \text{fact}(n) &= 1, & \text{if } n = 0 \\ &= n * \text{fact}(n-1), & \text{if } n > 0 \end{aligned}$$

Stopping/Terminating
condition

Recursive definition

■ Examples:

□ Factorial:

$$\text{fact}(0) = 1$$

$$\text{fact}(n) = n * \text{fact}(n-1), \text{ if } n > 0$$

□ GCD:

$$\text{gcd}(m, m) = m$$

$$\text{gcd}(m, n) = \text{gcd}(m \% n, n), \text{ if } m > n$$

$$\text{gcd}(m, n) = \text{gcd}(n, n \% m), \text{ if } m < n$$

□ Fibonacci series (1,1,2,3,5,8,13,21,...)

$$\text{fib}(0) = 1$$

$$\text{fib}(1) = 1$$

$$\text{fib}(n) = \text{fib}(n-1) + \text{fib}(n-2), \text{ if } n > 1$$

Factorial

```
long int fact (int n)
{
    if (n == 1)
        return (1);
    else
        return (n * fact(n-1));
}
```

Factorial Execution

```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)
↓

```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)



```
if (4 == 1) return (1);  
else return (4 * fact(3));
```



```
long int fact (int n)  
{  
    if (n == 1) return (1);  
    else return (n * fact(n-1));  
}
```

Factorial Execution

fact(4)



if (4 == 1) return (1);
else return (4 * fact(3));



if (3 == 1) return (1);
else return (3 * fact(2));



```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)



if (4 == 1) return (1);
else return (4 * fact(3));



if (3 == 1) return (1);
else return (3 * fact(2));



if (2 == 1) return (1);
else return (2 * fact(1));



```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)



if (4 == 1) return (1);
else return (4 * fact(3));



if (3 == 1) return (1);
else return (3 * fact(2));



if (2 == 1) return (1);
else return (2 * fact(1));



if (1 == 1) return (1);

```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)



if (4 == 1) return (1);
else return (4 * fact(3));



if (3 == 1) return (1);
else return (3 * fact(2));

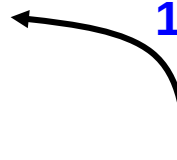


if (2 == 1) return (1);
else return (2 * fact(1));



if (1 == 1) return (1);

1



```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)



if (4 == 1) return (1);
else return (4 * fact(3));



if (3 == 1) return (1);
else return (3 * fact(2));



if (2 == 1) return (1);
else return (2 * fact(1));



if (1 == 1) return (1);

2

1

```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution

fact(4)

↓
if (4 == 1) return (1);
else return (4 * fact(3));

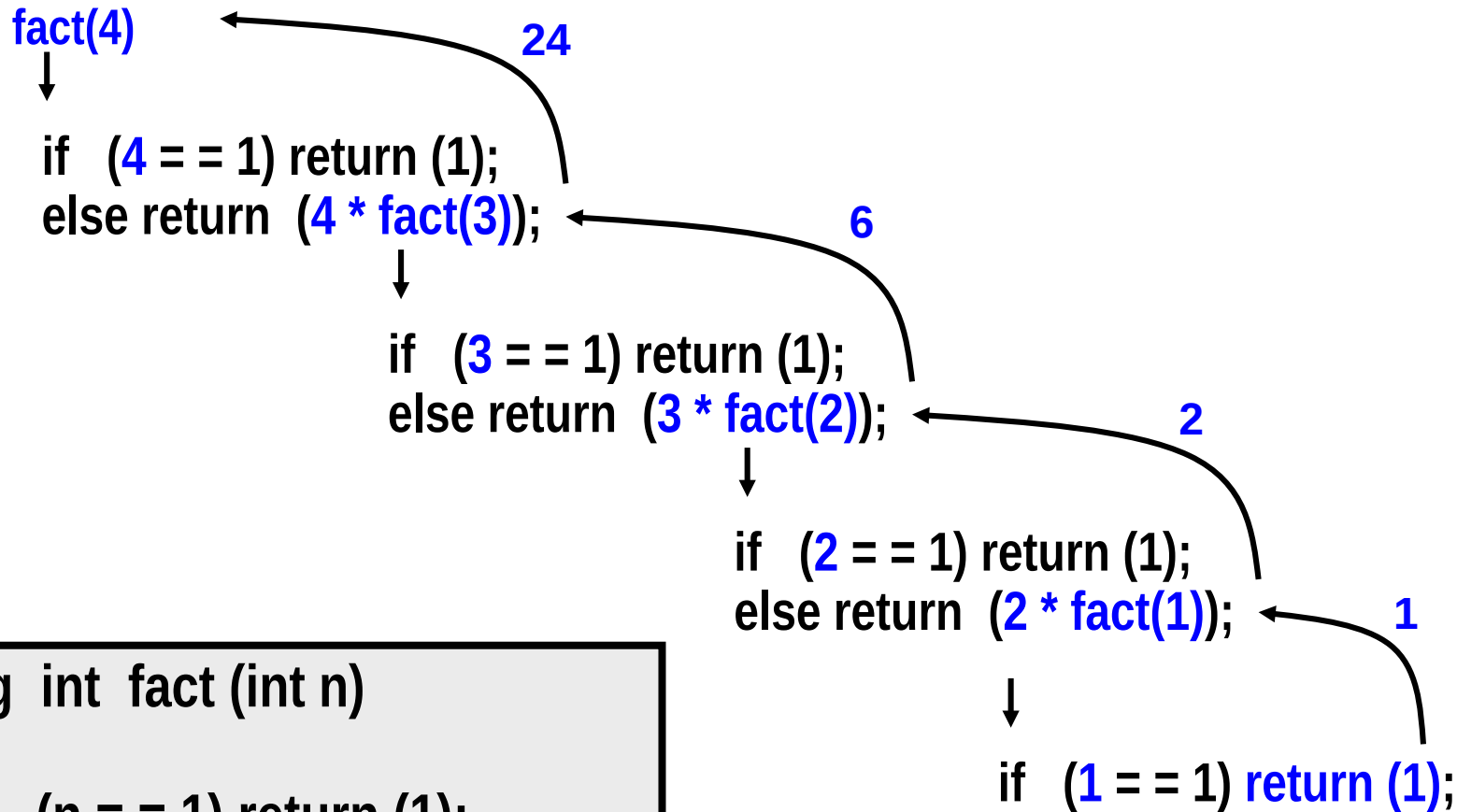
↓
if (3 == 1) return (1);
else return (3 * fact(2));

↓
if (2 == 1) return (1);
else return (2 * fact(1));

↓
if (1 == 1) return (1);

```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Factorial Execution



```
long int fact (int n)
{
    if (n == 1) return (1);
    else return (n * fact(n-1));
}
```

Example: Finding max in an array

```
int findMax(int A[ ], int n)
{
    int temp;
    if (n==1)
    {
        return A[0];
    }
    temp = findMax(A, n-1);
    if (A[n-1] > temp)
        return A[n-1];
    else return temp;
}
```

Terminating condition. Small size problem that you know how to solve directly without calling any functions

Recursive call. Find the max in the first $n-1$ elements (exact same problem, just solved on a smaller array).

Important things to remember

- Think how the whole problem (finding max of n elements in A) can be solved if you can solve the exact same problem on a smaller problem (finding max of first $n-1$ elements of the array). **But then, do NOT think how the smaller problem will be solved,** just call the function recursively and assume it will be solved.
- When you write a recursive function
 - First write the terminating/base condition
 - Then write the rest of the function
 - Always double-check that you have both

Back to Factorial: Look at the variable addresses (a slightly different program) !

```
int main()
{
    int x,y;
    scanf("%d",&x);
    y = fact(x);
    printf ("M: x= %d, y = %d\n", x,y);
    return 0;
}

int fact(int data)
{ int val = 1;
  printf("F: data = %d, &data = %u \n
    &val = %u\n", data, &data, &val);
  if (data>1) val = data*fact(data-1);
  return val;
}
```

Output

4

F: data = 4, &data = 3221224528

&val = 3221224516

F: data = 3, &data = 3221224480

&val = 3221224468

F: data = 2, &data = 3221224432

&val = 3221224420

F: data = 1, &data = 3221224384

&val = 3221224372

M: x= 4, y = 24

- 
- The memory addresses for the variable data are different in different calls!
 - They are not the same variable.
 - Each function call will have its own set of variables, even if the name of the variable is the same as it is the same function being called
 - Change made to one will not be seen by the calling function on return

```

int main()
{
    int x,y;
    scanf("%d",&x);
    y = fact(x);
    printf ("M: x= %d, y = %d\n", x,y);
    return 0;
}

int fact(int data)
{
    int val = 1, count = 0;
    if (data>1) val = data*fact(data-1);
    count++;
    printf("count = %d, data = %d\n",
count, data);
    return val;
}

```

Output

```

4
count = 1, data = 1
count = 1, data = 2
count = 1, data = 3
count = 1, data = 4
M: x= 4, y = 24

```

- Count did not change even though ++ done!
- Each call does it on its own copy, lost on return

Fibonacci Numbers

Fibonacci recurrence:

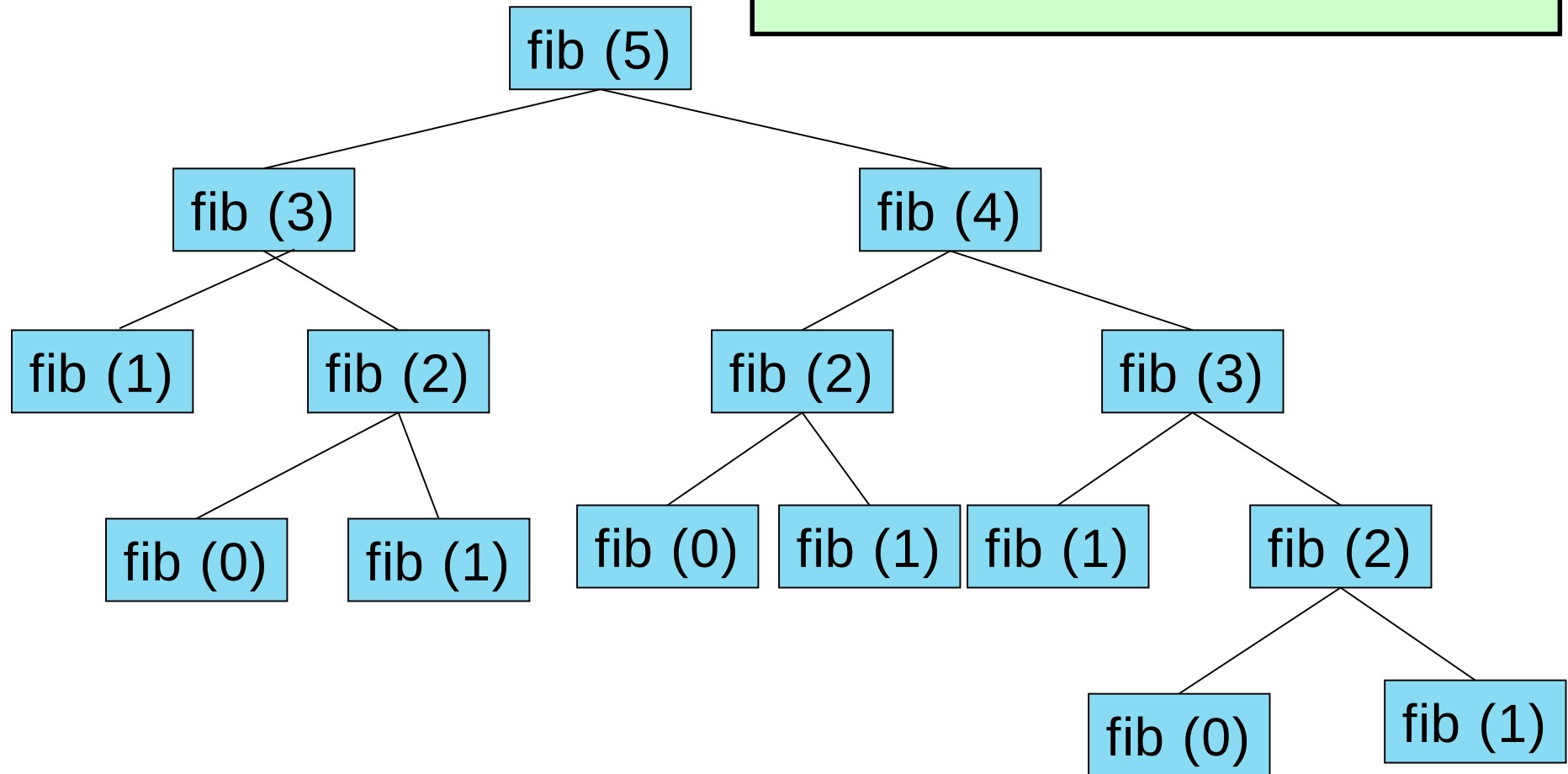
**fib(n) = 1 if n = 0 or 1;
 = fib(n - 2) + fib(n - 1)
 otherwise;**

```
int fib (int n) {  
    if (n == 0 or n == 1)  
        return 1;    [Base]  
    return fib(n-2) + fib(n-1) ;  
                        [Recursive]  
}
```

```
int fib (int n)  {  
    if (n == 0 || n == 1)  
        return 1;  
    return fib(n-2) + fib(n-1) ;  
}
```

Fibonacci recurrence:

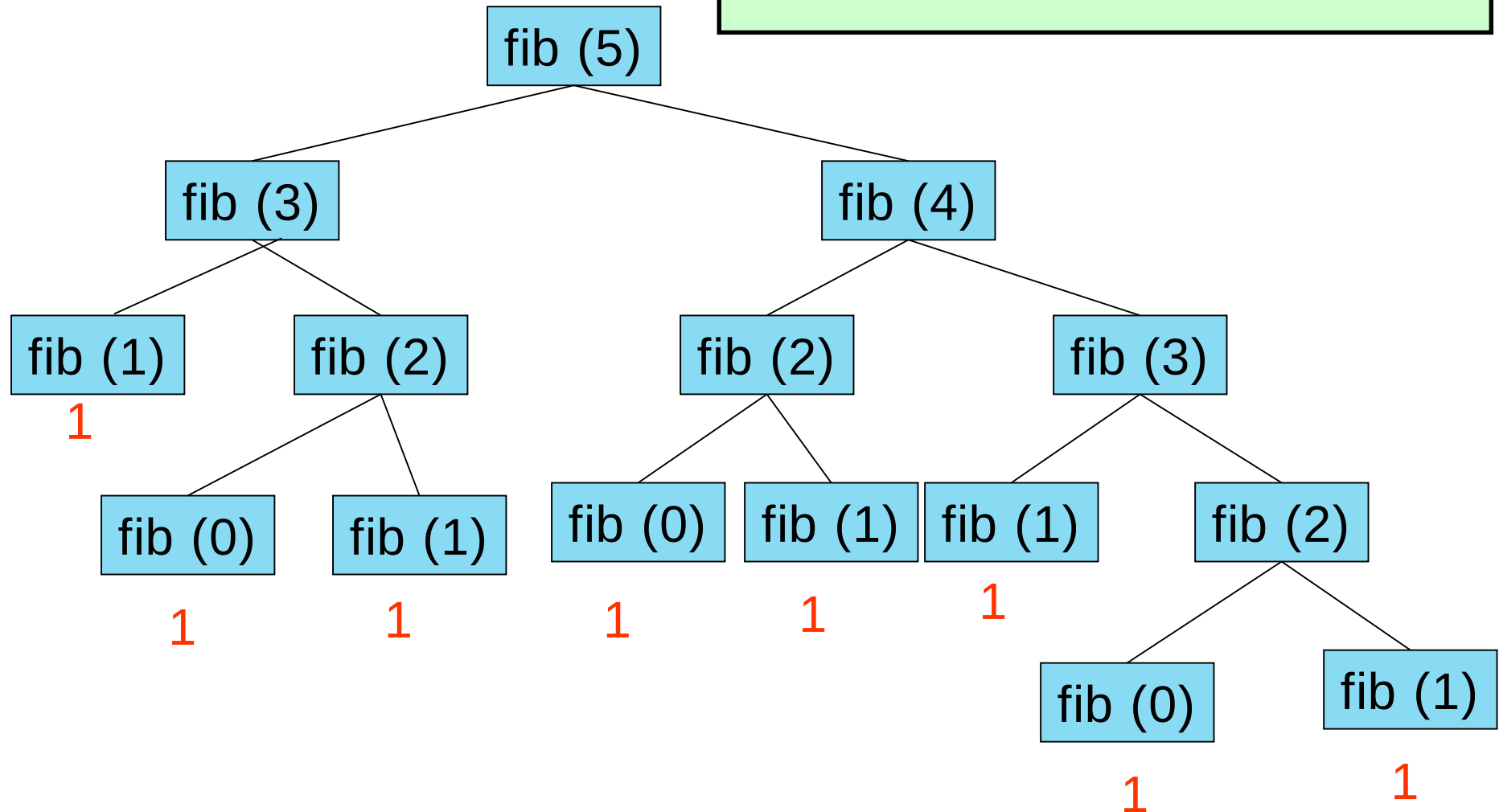
$\text{fib}(n) = 1$ if $n = 0$ or 1 ;
 $= \text{fib}(n - 2) + \text{fib}(n - 1)$
otherwise;



```
int fib (int n) {  
    if (n == 0 || n == 1)  
        return 1;  
    return fib(n-2) + fib(n-1);  
}
```

Fibonacci recurrence:

$\text{fib}(n) = 1$ if $n = 0$ or 1 ;
 $= \text{fib}(n - 2) + \text{fib}(n - 1)$
otherwise;



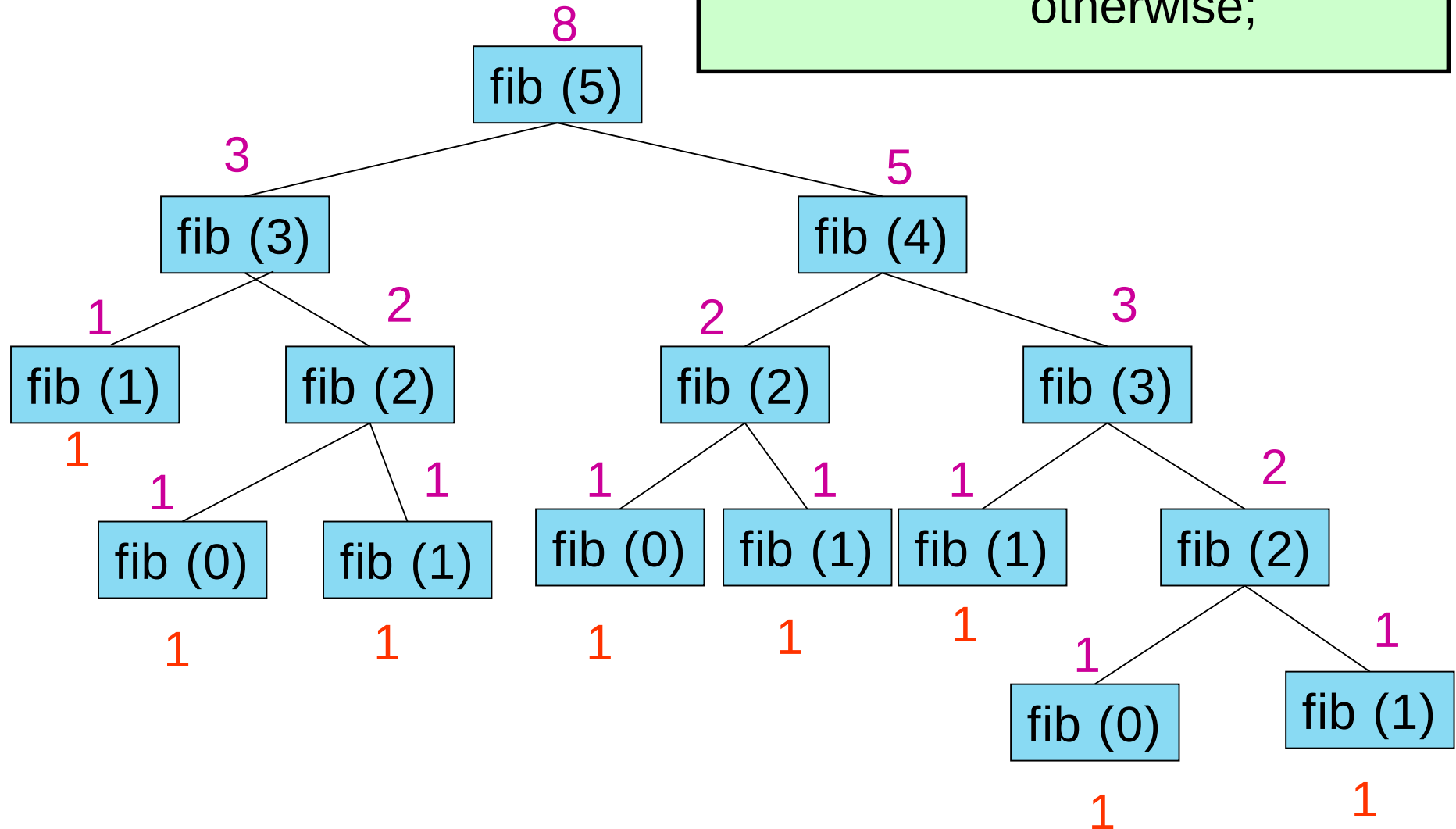
```

int fib (int n)  {
    if (n==0 || n==1)
        return 1;
    return fib(n-2) + fib(n-1) ;
}

```

Fibonacci recurrence:

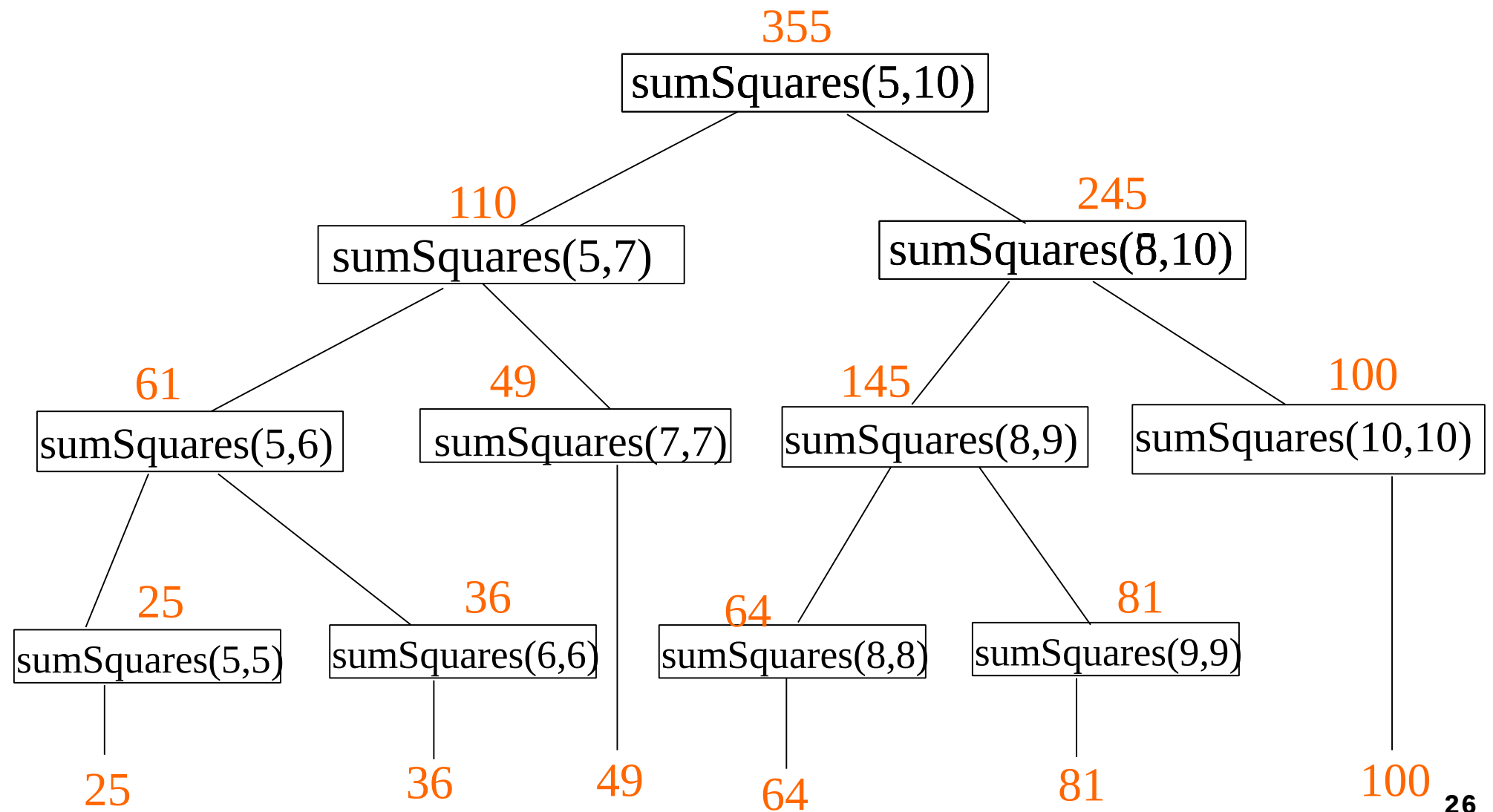
$\text{fib}(n) = 1$ if $n = 0$ or 1 ;
 $= \text{fib}(n - 2) + \text{fib}(n - 1)$
 otherwise;



Example: Sum of Squares

```
int sumSquares (int m, int n)
{
    int middle ;
    if (m == n) return(m*m);
    else
    {
        middle = (m+n)/2;
        return (sumSquares(m,middle)
                + sumSquares(middle+1,n));
    }
}
```

Annotated Call Tree



Example: Printing the digits of an Integer in Reverse

- Print the last digit, then print the remaining number in reverse
 - Ex: If integer is 743, then reversed is print 3 first, then print the reverse of 74

```
void printReversed(int i)
{
    if (i < 10) {
        printf("%d\n", i); return;
    }
    else {
        printf("%d", i%10);
        printReversed(i/10);
    }
}
```

Counting Zeros in a Positive Integer

- Check last digit from right
 - If it is 0, number of zeros = 1 + number of zeroes in remaining part of the number
 - If it is non-0, number of zeros = number of zeroes in remaining part of the number

```
int zeros(int number)
{
    if(number<10) return 0;
    if (number%10 == 0)
        return(1+zeros(number/10));
    else
        return(zeros(number/10));
}
```

Example: Binary Search

- Searching for an element k in a sorted array A with n elements
- Idea:
 - Choose the middle element $A[n/2]$
 - If $k == A[n/2]$, we are done
 - If $k < A[n/2]$, search for k between $A[0]$ and $A[n/2 - 1]$
 - If $k > A[n/2]$, search for k between $A[n/2 + 1]$ and $A[n-1]$
 - Repeat until either k is found, or no more elements to search
- Requires less number of comparisons than linear search in the worst case ($\log_2 n$ instead of n)

```
int binsearch(int A[ ], int low, int high, int k)
{
    int mid;
    printf("low = %d, high = %d\n", low, high);
    if (low > high)
        return 0;
    mid = (low + high)/2;
    printf("mid = %d, A[%d] = %d\n\n", mid, mid, A[mid]);
    if (A[mid] == k)
        return 1;
    else {
        if (A[mid] > k)
            return (binsearch(A, low, mid-1, k));
        else
            return(binsearch(A, mid+1, high, k));
    }
}
```



```
int main()
{
    int A[25], n, k, i, found;

    scanf("%d", &n);
    for (i=0; i<n; i++) scanf("%d", &A[i]);
    scanf("%d", &k);
    found = binsearch(A, 0, n-1, k);
    if (found == 1)
        printf("%d is present in the array\n", k);
    else
        printf("%d is not present in the array\n", k);
}
```

Output

8

9 11 14 17 19 20 23 27

21

low = 0, high = 7

mid = 3, A[3] = 17

low = 4, high = 7

mid = 5, A[5] = 20

low = 6, high = 7

mid = 6, A[6] = 23

low = 6, high = 5

21 is not present in the array

8

9 11 14 17 19 20 23 27

14

low = 0, high = 7

mid = 3, A[3] = 17

low = 0, high = 2

mid = 1, A[1] = 11

low = 2, high = 2

mid = 2, A[2] = 14

14 is present in the array

Static Variables

- Declared using the static keyword
- Static variables stay in existence rather than coming and going everytime the function is called
- Example: Counting number of 0's in an array

```
int main() {  
  
    int A[] = {1, 0, 0, 4, 5, 0};  
    cntZero(A, 10, 1);  
    return 0;  
}
```

```
void cntZero(int A[], int n, int print)
{
    int i;
    static int count = 0;
    printf("Called with: n=%d, count = %d\n", n, count);
    printf("&n=%p, &count = %p\n\n", &n, &count);
    if (n == 1) {
        if (A[0] == 0) count++;
        return;
    }
    if (A[n-1] == 0) count++;
    cntZero(A, n-1, 0);
    if (print == 1)
        printf("n=%d, No. of zeros = %d\n", n, count);
    return;
}
```

Output

```
Called with: n=6, count= 0
&n=0x7ffe074392c4, &count= 0x40401c
Called with: n=5, count= 1
&n=0x7ffe074392a4, &count= 0x40401c
Called with: n=4, count= 1
&n=0x7ffe07439284, &count= 0x40401c
Called with: n=3, count= 1
&n=0x7ffe07439264, &count= 0x40401c
Called with: n=2, count= 2
&n=0x7ffe07439244, &count= 0x40401c
Called with: n=1, count= 3
&n=0x7ffe07439224, &count= 0x40401cn=6,
```

No. of zeros = 3

Another Example

```
int Fib (int, int);

int main()
{
    int n;
    scanf("%d", &n);
    if (n == 0 || n == 1)
        printf("F(%d) = %d \n", n, 1);
    else
        printf("F(%d) = %d \n", n,
            Fib(n,2));
    return 0;
}
```

```
int Fib(int n, int i)
{
    static int m1, m2;
    int res, temp;
    if (i==2) {m1 =1; m2=1;}
    if (n == i) res = m1+ m2;
    else
    {   temp = m1;
        m1 = m1+m2;
        m2 = temp;
        res = Fib(n, i+1);
    }
    return res;
}
```

Static Variables: See the addresses!

```
int Fib(int n, int i)
{
    static int m1, m2;
    int res, temp;
    if (i==2) {m1 =1; m2=1;}
    printf("F: m1=%d, m2=%d, n=%d,
           i=%d\n", m1,m2,n,i);
    printf("F: &m1=%u, &m2=%u\n",
           &m1,&m2);
    printf("F: &res=%u, &temp=%u\n",
           &res,&temp);
    if (n == i) res = m1+ m2;
    else { temp = m1; m1 = m1+m2;
          m2 = temp;
          res = Fib(n, i+1);  }
    return res;
}
```

Output

```
5
F: m1=1, m2=1, n=5, i=2
F: &m1=134518656, &m2=134518660
F: &res=3221224516, &temp=3221224512
F: m1=2, m2=1, n=5, i=3
F: &m1=134518656, &m2=134518660
F: &res=3221224468, &temp=3221224464
F: m1=3, m2=2, n=5, i=4
F: &m1=134518656, &m2=134518660
F: &res=3221224420, &temp=3221224416
F: m1=5, m2=3, n=5, i=5
F: &m1=134518656, &m2=134518660
F: &res=3221224372, &temp=3221224368
F(5) = 8
```

Common Errors in Writing Recursive Functions

- Non-terminating Recursive Function (Infinite recursion)

- No base case

```
int badFactorial(int x) {  
    return x * badFactorial(x-1);  
}
```

- The base case is never reached

```
int anotherBadFactorial(int x) {  
    if(x == 0)  
        return 1;  
    else  
        return x*(x-1)*anotherBadFactorial(x-2);  
    // When x is odd, base case never reached!!  
}
```

```
int badSum2(int x)  
{  
    if(x==1) return 1;  
    return(badSum2(x--));  
}
```

Common Errors in Writing Recursive Functions

- Mixing up loops and recursion

```
int anotherBadFactorial(int x) {  
    int i, fact = 0;  
    if (x == 0)  
        return 1;  
    else {  
        for (i=x; i>0; i=i-1) {  
            fact = fact + x*anotherBadFactorial(x-1);  
        }  
        return fact;  
    }  
}
```

- In general, if you have recursive function calls within a loop, think carefully if you need it. Most recursive functions you will see in this course will not need this

Recursion vs. Iteration

- Repetition
 - Iteration: explicit loop
 - Recursion: repeated function calls
- Termination
 - Iteration: loop condition fails
 - Recursion: base case recognized
- Both can have infinite loops
- Balance
 - Choice between performance (iteration) and good software engineering (recursion).

- 
- Every recursive program can also be written without recursion
 - Recursion is used for programming convenience, not for performance enhancement
 - Sometimes, if the function being computed has a nice recursive form, then a recursive code may be more readable

How are function calls implemented?

- The following applies in general, with minor variations that are implementation dependent
 - The system maintains a stack in memory
 - Stack is a last-in first-out structure
 - Two operations on stack, push and pop
 - Whenever there is a function call, the activation record gets pushed into the stack
 - Activation record consists of the return address in the calling program, the return value from the function, and the local variables inside the function

```

int main()
{
    .....
    x = gcd (a, b);
    .....
}

```

```

int gcd (int x, int y)
{
    .....
    .....
    return (result);
}

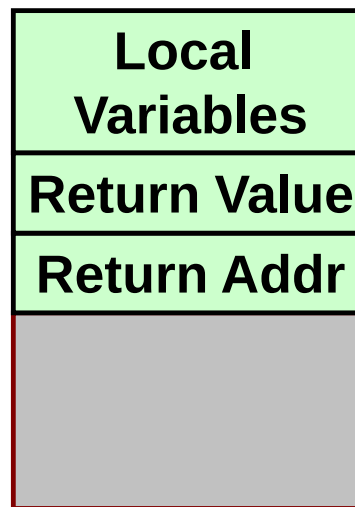
```

STACK

Activation
record



Before call



After call



After return

```
int main()
```

```
{
```

```
.....
```

```
x = ncr (a, b);
```

```
.....
```

```
}
```

```
int ncr (int n, int r)
```

```
{
```

```
return (fact(n)/  
        fact(r)/fact(n-r));
```

```
}
```

```
int fact (int n)
```

```
{
```

```
.....
```

```
return (result);
```

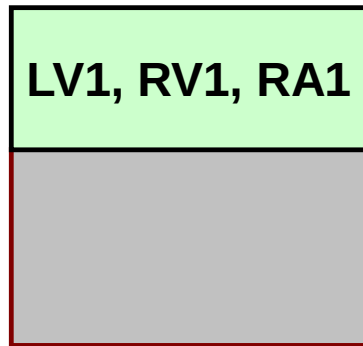
```
}
```

3 times

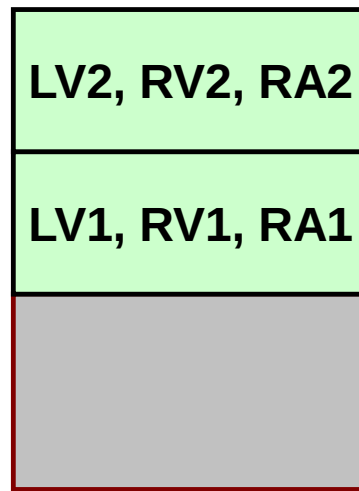
3 times



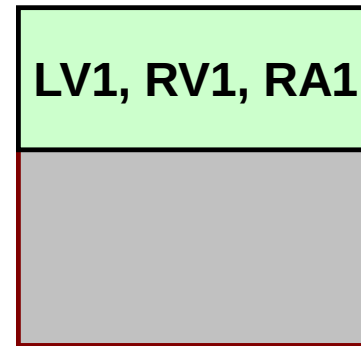
Before call



Call ncr



Call fact



fact returns



ncr returns

What happens for recursive calls?

- What we have seen
 - Space for activation record is allocated on the stack when a function call is made
 - Space allocated for activation record is de-allocated on the stack when the function returns
- In recursion, a function calls itself
 - Several function calls going on, with none of the function calls returning back
 - Space for activation records allocated on the stack continuously
 - Large stack space required

- Space for activation records are de-allocated, when the termination condition of recursion is reached
- We shall illustrate the process by an example of computing factorial
 - Activation record looks like:

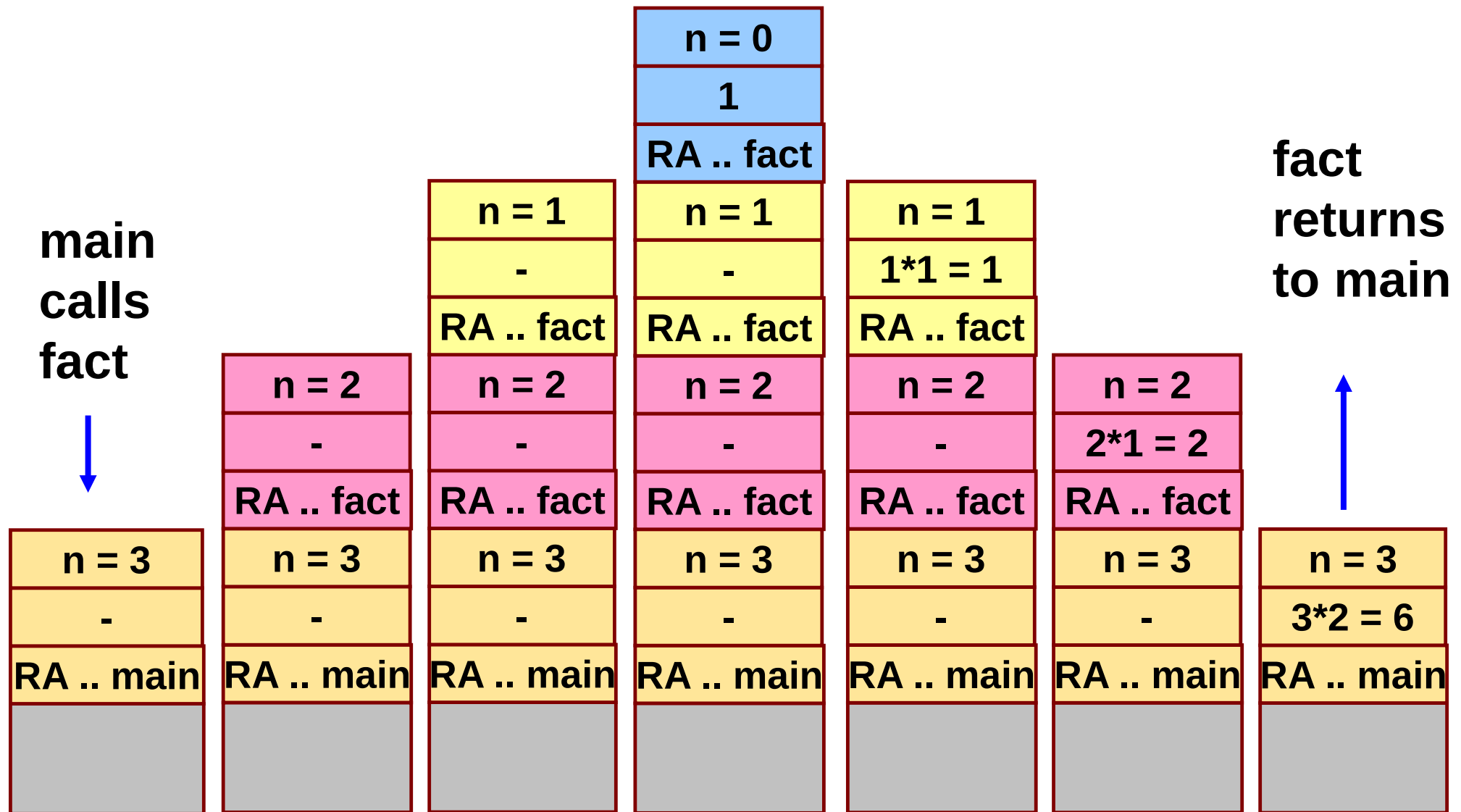
Local Variables
Return Value
Return Addr

Example:: main() calls fact(3)

```
int main()
{
    int n;
    n = 3;
    printf ("%d \n", fact(n) );
    return 0;
}
```

```
int fact (int n)
{
    if (n == 0)
        return (1);
    else
        return (n * fact(n-1));
}
```

TRACE OF THE STACK DURING EXECUTION

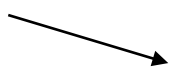


Do Yourself

- Trace the activation records for the following version of Fibonacci sequence

```
int f (int n)
{
    int a, b;
    if (n < 2) return (n);
    else {
        a = f(n-1);
        b = f(n-2);
        return (a+b);
    }
}
```

X



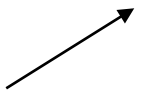
Y



Local Variables (n, a, b)
Return Value
Return Addr (either main, or X, or Y)

```
void main() {
    printf("Fib(4) is: %d \n", f(4));
}
```

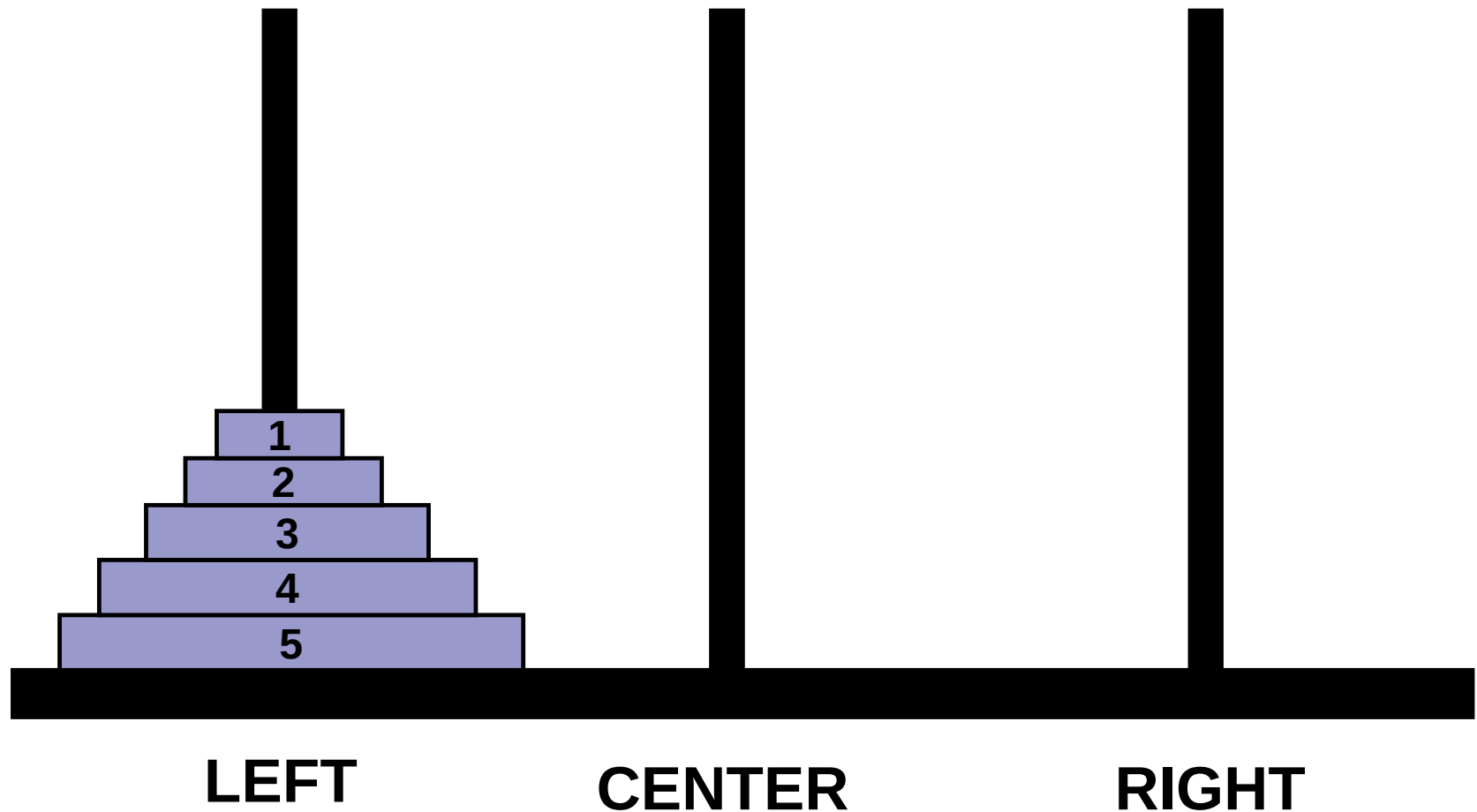
main





Additional Example

Towers of Hanoi Problem



- 
- Initially all the disks are stacked on the LEFT pole
 - Required to transfer all the disks to the RIGHT pole
 - Only one disk can be moved at a time.
 - A larger disk cannot be placed on a smaller disk
 - CENTER pole is used for temporary storage of disks

- Recursive statement of the general problem of n disks

- Step 1:

- Move the top $(n-1)$ disks from LEFT to CENTER

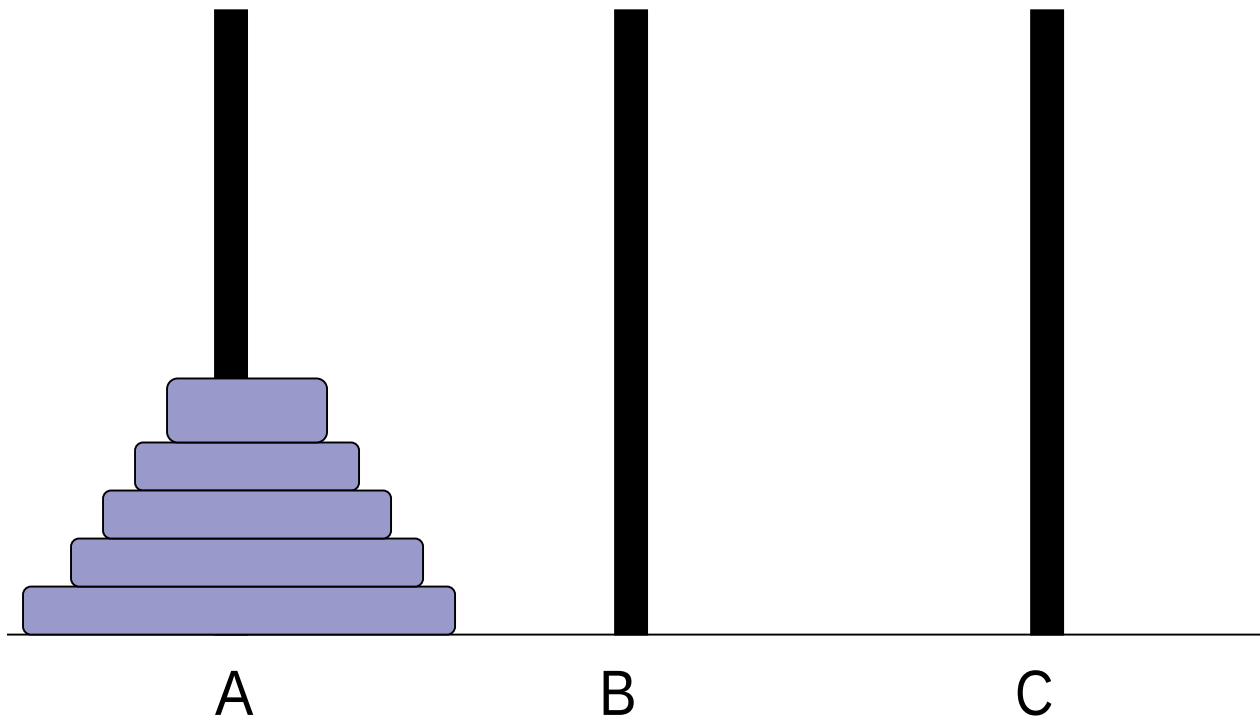
- Step 2:

- Move the largest disk from LEFT to RIGHT

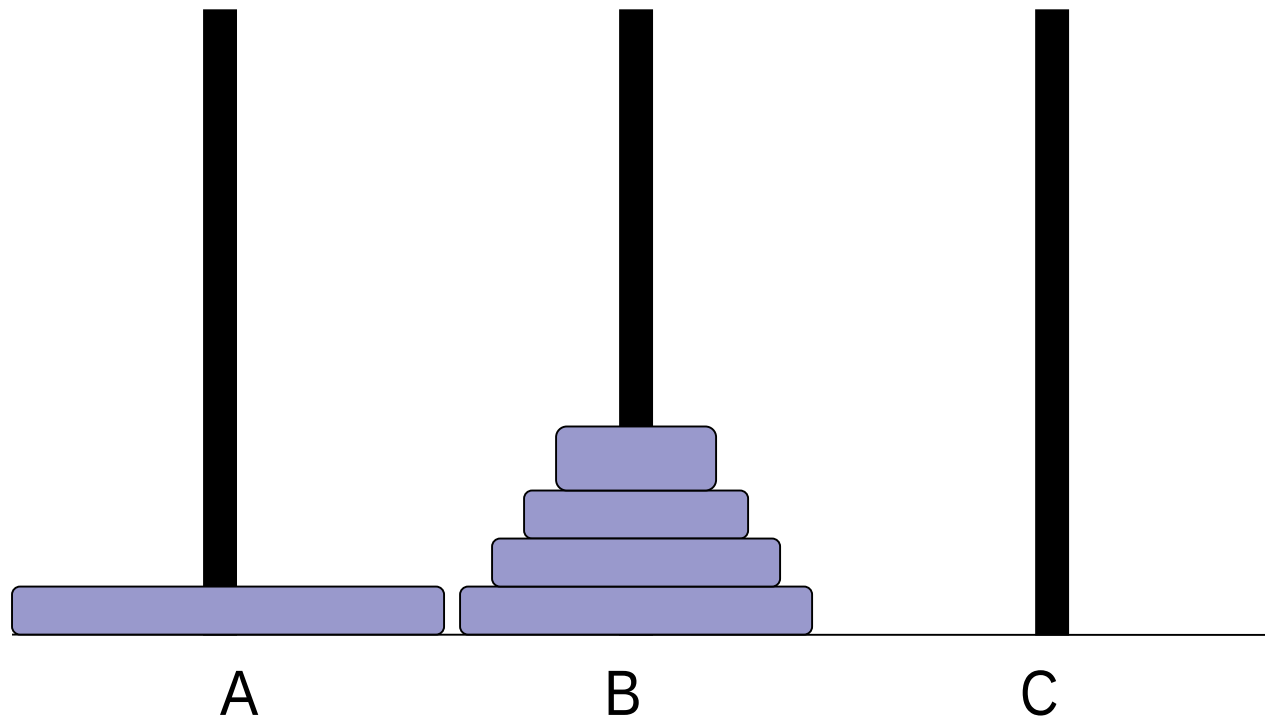
- Step 3:

- Move the $(n-1)$ disks from CENTER to RIGHT

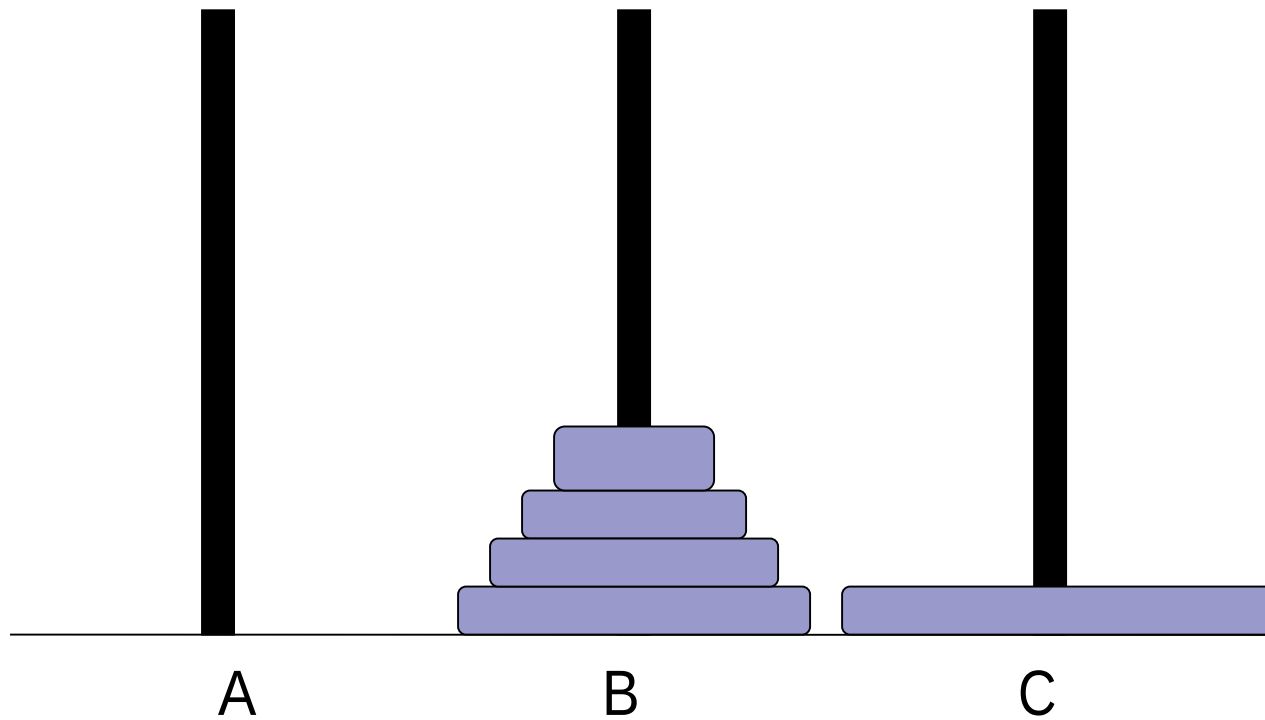
Tower of Hanoi



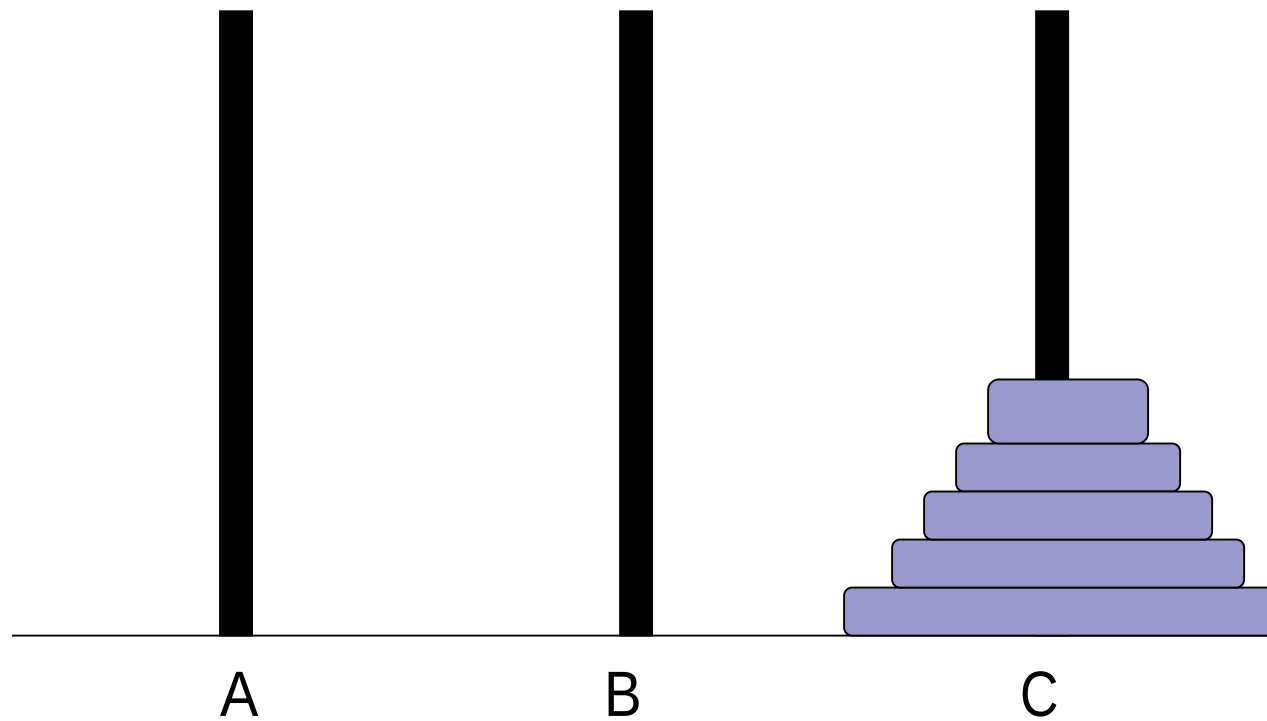
Tower of Hanoi



Tower of Hanoi



Tower of Hanoi



Towers of Hanoi function

```
void towers (int n, char from, char to, char aux)
{
    /* Base Condition */
    if (n==1) {
        printf ("Disk 1 : %c →  &c \n", from, to) ;
        return ;
    }
    /* Recursive Condition */
    towers (n-1, from, aux, to) ;
    .....
    .....
}
```

Towers of Hanoi function

```
void towers (int n, char from, char to, char aux)
{
    /* Base Condition */
    if (n==1) {
        printf ("Disk 1 : %c → %c \n", from, to) ;
        return ;
    }
    /* Recursive Condition */
    towers (n-1, from, aux, to) ;
    printf ("Disk %d : %c → %c\n", n, from, to) ;
    .....
}
```

Towers of Hanoi function

```
void towers (int n, char from, char to, char aux)
{
    /* Base Condition */
    if (n==1) {
        printf ("Disk 1 : %c → %c \n", from, to) ;
        return ;
    }
    /* Recursive Condition */
    towers (n-1, from, aux, to) ;
    printf ("Disk %d : %c → %c\n", n, from, to) ;
    towers (n-1, aux, to, from) ;
}
```

TOH runs

```
void towers(int n, char from, char to, char aux)
{ if (n==1)
  { printf ("Disk 1 : %c -> %c \n", from, to) ;
    return ;
  }
  towers (n-1, from, aux, to) ;
  printf ("Disk %d : %c -> %c\n", n, from, to) ;
  towers (n-1, aux, to, from) ;
}

int main()
{ int n;
  scanf("%d", &n);
  towers(n,'A','C','B');
  return 0;
}
```

Output

```
3
Disk 1 : A -> C
Disk 2 : A -> B
Disk 1 : C -> B
Disk 3 : A -> C
Disk 1 : B -> A
Disk 2 : B -> C
Disk 1 : A -> C
```

More TOH runs

```
void towers(int n, char from, char to, char aux)
{ if (n==1)
  { printf ("Disk 1 : %c -> %c \n", from, to) ;
    return ;
  }
  towers (n-1, from, aux, to) ;
  printf ("Disk %d : %c -> %c\n", n, from, to) ;
  towers (n-1, aux, to, from) ;
}

int main()
{ int n;
  scanf ("%d", &n);
  towers(n,'A','C','B');
  return 0;
}
```

Output

4

Disk 1 : A -> B

Disk 2 : A -> C

Disk 1 : B -> C

Disk 3 : A -> B

Disk 1 : C -> A

Disk 2 : C -> B

Disk 1 : A -> B

Disk 4 : A -> C

Disk 1 : B -> C

Disk 2 : B -> A

Disk 1 : C -> A

Disk 3 : B -> C

Disk 1 : A -> B

Disk 2 : A -> C

Disk 1 : B -> C

Practice Problems

1. Write a recursive function to search for an element in an array
2. Write a recursive function to count the digits of a positive integer (do also for sum of digits)
3. Write a recursive function to reverse a null-terminated string
4. Write a recursive function to convert a decimal number to binary
5. Write a recursive function to check if a string is a palindrome or not
6. Write a recursive function to copy one array to another

Note:

- For each of the above, write the main functions to call the recursive function also
- Practice problems are just for practicing recursion, recursion is not necessarily the most efficient way of doing them