A pair of glasses with a dark frame and light-colored lenses is resting on a piece of white paper. The background is a soft, out-of-focus yellow and orange gradient.

Data Structures

Chapter 1

1. Recursion

2. Performance Analysis

- Space Complexity
- Time Complexity
- Step Count

3. Asymptotic Analysis

Performance Analysis

- The program we write should
 1. meet the specification.
 2. work correctly.
 3. be documented properly.
 4. run effectively
 5. be readable.
 6. **use the storage effectively – space**
 7. **run timely – time**
- } space & time complexity

The **space complexity** of a program is the amount of **memory** that it needs to run to completion.

The **time complexity** of a program is the amount of computer **time** that it needs to run to completion.

Performance Analysis

- **Space complexity:**
- Fixed space requirements : \mathbf{c}
 - that do not depend on input size, simple or fixed-size variables
- Variable space requirements : $S_p(I)$
 - that depend on the instance I , stack, variable

The total space requirement for the program P :

$$S(P) = \mathbf{c} + S_p(I)$$

where \mathbf{c} is a constant for fixed space and variable space for the instance I .

We are concerned about only $S_p(I)$, but **not \mathbf{c} . Why?**

Because we usually **compare** the algorithms of the programs.

Performance Analysis

- Space complexity: $S(P) = c + S_p(I)$
- Example: $S_{\text{sum}}(n) = ?$

Program sum

```
float sum(float list[], int n) {  
    float total = 0;  
    for (int i=0; i<n; i++)  
        total += list[i];  
    return total;  
}
```

$S_{\text{sum}}(n) = 0$ since the C/C++ passes list[] by its address.

Performance Analysis

- Space complexity: $S(P) = c + S_p(I)$
- Example: $S_{\text{rsum}}(n) = ?$

Program rsum

```
float rsum(float list[], int n) {  
    if (n)  
        return rsum(list, n-1) + list[n-1];  
    return 0;  
}
```

Program rsum

```
float rsum(float list[], int n) {  
    if (n)  
        return rsum(list, n-1) + list[n];  
    return 0;  
}
```

Performance Analysis

- Space complexity: $S(P) = c + S_p(I)$
- Example: $S_{\text{rsum}}(n) = ?$

Program rsum

```
float rsum(float list[], int n) {  
    if (n)  
        return rsum(list, n-1) + list[n-1];  
    return 0;  
}
```

The variable space requirement are for **two** parameters and **one** return address are saved in the system stack **per recursive call**:

$$\text{sizeof}(n) + \text{list[] address} + \text{return address} = 12$$

← assuming 32 bit address

Performance Analysis

- Space complexity: $S(P) = c + S_p(I)$
- Example: $S_{\text{rsum}}(n=\text{MAX_SIZE}) = ?$

Program rsum

```
float rsum(float list[], int n) {  
    if (n)  
        return rsum(list, n-1) + list[n-1];  
    return 0;  
}
```

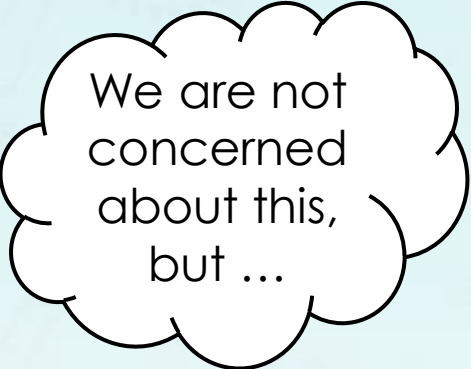
The variable space requirement are for **two** parameters and **one** return address are saved in the system stack **per recursive call**:

$$\text{sizeof}(n) + \text{list[]} \text{ address} + \text{return address} = 12$$

$$S_{\text{rsum}}(n) = 12 * n$$

Performance Analysis

- **Time complexity:** The time taken by the program P:
 - $T(P) = \text{compile time } c + \text{execution time } T_p(n)$
- Similarly, we are concerned about only $T_p(n)$, but not c .
- **Example:** $T_p(n) = c_a \text{ADD}(n) + c_s \text{SUB}(n) + c_l \text{LDA}(n) + c_{st} \text{STA}(n)$
 - where n – number of execution, c for constant time for operation
- **Program step:** a meaningful program segment whose execution time is independent of the instance characteristics.
- **Example:**
 - $a = 2;$
 - $a = 2 * b + 3 * c/d - e + f/g/a/b/c;$



We are not concerned about this, but ...

⇒ 1 step!!

⇒ 1 step!!

Performance Analysis

- **Example:** How many **program steps** required?

Program	sum	$2n+3$
<pre>float sum(float list[], int n) { float total = 0; for (int i=0; i<n; i++) total += list[i]; return total; }</pre>		<div>1</div> <div>$n+1$</div> <div>n</div> <div>1</div>

Performance Analysis

- **Example:** How many **program steps** required?

Program rsum	$2n+2$
<pre>float rsum(float list[], int n) { if (n) return rsum(list, n-1) + list[n-1]; return 0; }</pre>	$n+1$ n 1

Performance Analysis

■ Comparison:

Program sum

```
float sum(float list[], int n) {  
    float total = 0;  
    for (int i=0; i<n; i++)  
        total += list[i];  
    return total;  
}
```

Program rsum

```
float rsum(float list[], int n) {  
    if (n)  
        return rsum(list, n-1) + list[n-1];  
    return 0;  
}
```

$$2n + 3 > 2n + 2$$

$$\text{sum} > \text{rsum}$$

$$T_{\text{iterative}} > T_{\text{recursive}}$$

Performance Analysis

- **Example:** How many **program steps** required?

Program	sum of matrix
<pre>void add(int a[][MAX_SIZE], int b[][MAX_SIZE], int c[][MAX_SIZE], int rows, int cols) { for(int i=0; i<rows; i++) for(int j=0; j<cols; j++) c[i][j] = a[i][j] + b[i][j]; }</pre>	<pre>rows + 1 rows * (cols+1) rows * cols</pre>

step count = **2 rows*cols + 2 rows + 1**

Step Count Example 1:

- What is **the exact number of times** `sum++` executed?

	Step count
<pre>int sum = 0; for (int i = 1; i <= n*n; i++) for (int j = 1; j <= i; j++) sum++;</pre>	<pre>1 n * n + 1 2 + 3 + ... + n*n+1 ?</pre>

Useful formulas:

$$1 + 2 + 3 + \dots + N = N(N+1)/2$$

$$1 + 2 + 4 + 8 + \dots + 2^n = 2^{n+1} - 1$$

Step Count Example 2:

- What is **the exact number of times** `sum++` executed?

	Step count
<pre>int sum = 0; for (int i = 1; i <= n; i++) for (int j = n; j >= i; j--) sum++;</pre>	<pre>1 n + 1 (n+1) + (n) + (n-1) + ... + 2 ?</pre>

Useful formulas:

$$1 + 2 + 3 + \dots + N = N(N+1)/2$$

$$1 + 2 + 4 + 8 + \dots + 2^n = 2^{n+1} - 1$$

Step Count Example 3:

- What is **the exact number of times** `sum++` executed?

	Step count
<pre>int sum = 0; while (n >= 1) { sum++; n /= 2; }</pre>	$n / 2^k = 1$

We have to find the smallest k such that $n / 2^k = 1$

$$n / 2^k = 1$$

$$n = 2^k$$

$$\log(n) = \log(2^k)$$

$$\log(n) = k$$

Step Count Example 4:

- Compute the following series:

a) $1 + 2 + 3 + \dots + 9 + 10 =$

b) $1 + 2 + 3 + \dots + (N - 1) + N =$

c) $1 + 2 + 4 + \dots + 16 =$

Useful formulas:

$$1 + 2 + 3 + \dots + N = N(N+1)/2$$

$$1 + 2 + 4 + 8 + \dots + 2^n = 2^{n+1} - 1$$

Step Count Exercise 1:

- What is **the exact number of times** `sum++` executed?

<pre>int sum = 0; for (int i = 10; i < n + 5; i += 2) sum++;</pre>	

<pre>int sum = 0; for (int i = 1; i < n; i *= 2) sum++; for (int i = n; i > 1; i /= 2) sum++;</pre>	

Step Count Exercise 2:

- What is **the exact number of times** `sum++` executed?

<pre>int sum = 0; for (int i = 10; i < n; i++) for (int j = 0; j < n; i += 2) sum++;</pre>	
---	--

<pre>for (i = 0; i < n; i++) for (j = 0; j < 100; j++) sum++;</pre>	
---	--

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