


Data Structures – Week #2

Algorithm Analysis
&
Sparse Vectors/Matrices
&
Recursion



Outline

- Performance of Algorithms
- Performance Prediction (Order of Algorithms)
- Examples
- Exercises
- Sparse Vectors/Matrices
- Recursion
- Recurrences

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Algorithm Analysis



Performance of Algorithms

- **Algorithm:** *a finite sequence of instructions* that the computer follows to solve a problem.
- Algorithms solving the *same problem* may *perform differently*. Depending on *resource requirements* an algorithm may be *feasible* or not. To find out whether or not an algorithm is usable or relatively better than another one solving the same problem, its resource requirements should be determined.
- The *process of determining the resource requirements of an algorithm* is called **algorithm analysis**.
- Two essential resources, hence, *performance criteria* of algorithms are
 - *execution or running time*
 - *memory space used*.



Performance Assessment - 1

- **Execution time** of an algorithm is hard to assess unless one knows
 - the *intimate details of the computer architecture*,
 - the operating system,
 - the compiler,
 - the quality of the program,
 - the current load of the system and
 - other factors.

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Performance Assessment - 2

- Two ways to assess performance of an algorithm
 - Execution time may be compared for a given algorithm using some special performance programs called *benchmarks* and evaluated as such.
 - *Growth rate* of *execution time* (or *memory space*) of an algorithm with the *growing input size* may be found.

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Performance Assessment - 3

- Here, we define the *execution time* or the *memory space* used as a *function of the input size*.
- By “*input size*” we mean
 - the number of elements to store in a data structure,
 - the number of records in a file etc...
 - the nodes in a LL or a tree or
 - the nodes as well as connections of a graph

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Assessment Tools

- We can use the concept the “*growth rate or order of an algorithm*” to assess both criteria. However, our main concern will be the execution time.
- We use *asymptotic notations* to symbolize the *asymptotic running time of an algorithm* in terms of the input size.

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Asymptotic Notations

- We use *asymptotic notations* to symbolize the *asymptotic running time of an algorithm* in terms of the input size.
- The following notations are frequently used in algorithm analysis:
 - O (Big Oh) Notation (*asymptotic upper bound*)
 - Ω (Omega) Notation (*asymptotic lower bound*)
 - Θ (Theta) Notation (*asymptotic tight bound*)
 - o (little Oh) Notation (*upper bound that is **not** asymptotically tight*)
 - ω (omega) Notation (*lower bound that is **not** asymptotically tight*)
- **Goal:** To find a function that asymptotically limits the execution time or the memory space of an algorithm.

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O -Notation (“Big Oh”)

Asymptotic Upper Bound

- Mathematically expressed, the “**Big Oh**” ($O()$) concept is as follows:
- Let $g: N \rightarrow R^*$ be an arbitrary function.
- $O(g(n)) = \{f: N \rightarrow R^* \mid (\exists c \in R^+)(\exists n_0 \in N)(\forall n \geq n_0) [f(n) \leq cg(n)]\}$,
 - where R^* is the set of nonnegative real numbers and R^+ is the set of strictly positive real numbers (excluding 0).

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O-Notation by words

Expressed by words; $O(g(n))$ is the set of all functions $f(n)$ mapping (\rightarrow) integers (N) to nonnegative real numbers (R^*) such that (|) there exists a positive real constant c ($\exists c \in R^+$) and there exists an integer constant n_0 ($\exists n_0 \in N$) such that for all values of n greater than or equal to the constant ($\forall n \geq n_0$), the function values of $f(n)$ are less than or equal to the function values of $g(n)$ multiplied by the constant c ($f(n) \leq cg(n)$).

- In other words, $O(g(n))$ is the set of all functions $f(n)$ bounded above by a positive real multiple of $g(n)$, provided n is sufficiently large (greater than n_0). $g(n)$ denotes the *asymptotic upper bound* for the running time $f(n)$ of an algorithm.

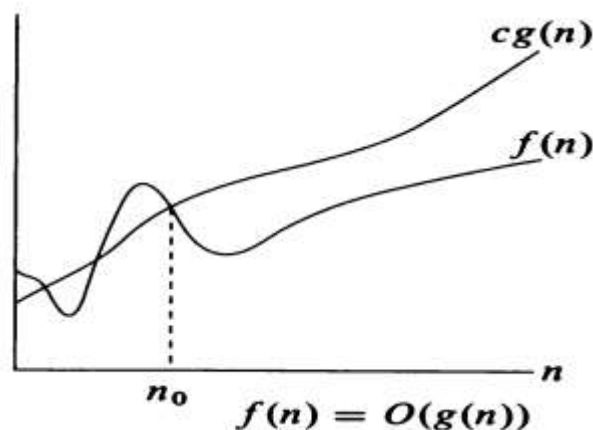
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O-Notation (“Big Oh”)

Asymptotic Upper Bound



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Θ -Notation (“Theta”)

Asymptotic Tight Bound

- Mathematically expressed, the “**Theta**” ($\Theta()$) concept is as follows:
- Let $g: N \rightarrow R^*$ be an arbitrary function.
- $\Theta(g(n)) = \{f: N \rightarrow R^* \mid (\exists c_1, c_2 \in R^+)(\exists n_0 \in N)(\forall n \geq n_0) [0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n)]\}$,
 - where R^* is the set of nonnegative real numbers and R^+ is the set of strictly positive real numbers (excluding 0).

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Θ -Notation by words

- **Expressed by words;** A function $f(n)$ belongs to the set $\Theta(g(n))$ if there exist positive real constants c_1 and c_2 ($\exists c_1, c_2 \in R^+$) such that it can be sandwiched between $c_1 g(n)$ and $c_2 g(n)$ ($[0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n)]$), for sufficiently large n ($\forall n \geq n_0$).
- In other words, $\Theta(g(n))$ is the set of all functions $f(n)$ tightly bounded below and above by a pair of positive real multiples of $g(n)$, provided n is sufficiently large (greater than n_0). $g(n)$ denotes the *asymptotic tight bound* for the running time $f(n)$ of an algorithm.

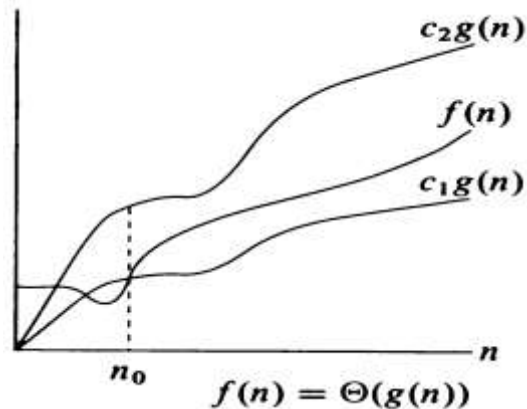
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Θ -Notation (“Theta”)

Asymptotic Tight Bound



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Ω -Notation (“Big-Omega”)

Asymptotic Lower Bound

- Mathematically expressed, the “Omega” ($\Omega()$) concept is as follows:
- Let $g: N \rightarrow R^*$ be an arbitrary function.
- $\Omega(g(n)) = \{f: N \rightarrow R^* \mid (\exists c \in R^+)(\exists n_0 \in N)(\forall n \geq n_0) [0 \leq cg(n) \leq f(n)]\}$,
 - where R^* is the set of nonnegative real numbers and R^+ is the set of strictly positive real numbers (excluding 0).

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Ω -Notation by words

- **Expressed by words;** A function $f(n)$ belongs to the set $\Omega(g(n))$ if there exists a positive real constant c ($\exists c \in \mathbf{R}^+$) such that $f(n)$ is less than or equal to $cg(n)$ ($[0 \leq cg(n) \leq f(n)]$), for sufficiently large n ($\forall n \geq n_0$).
- In other words, $\Omega(g(n))$ is the set of all functions $t(n)$ bounded below by a positive real multiple of $g(n)$, provided n is sufficiently large (greater than n_0). $g(n)$ denotes the *asymptotic lower bound* for the running time $f(n)$ of an algorithm.

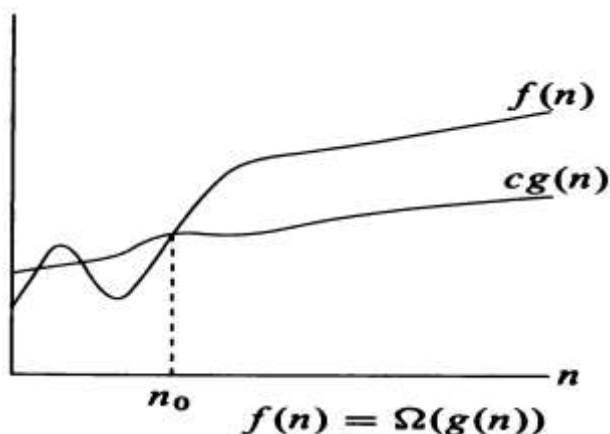
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Ω -Notation (“Big-Omega”)

Asymptotic Lower Bound



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o -Notation (“Little Oh”)

Upper bound NOT Asymptotically Tight

- “ o ” notation does not reveal whether the function $f(n)$ is a *tight asymptotic upper bound* for $t(n)$ ($t(n) \leq cf(n)$).
- “Little Oh” or o notation provides an *upper bound that strictly is NOT asymptotically tight*.
- Mathematically expressed;
- Let $f: N \rightarrow R^*$ be an arbitrary function.
- $o(f(n)) = \{t: N \rightarrow R^* \mid (\exists c \in R^+)(\exists n_0 \in N)(\forall n \geq n_0) [t(n) < cf(n)]\}$,
 - where R^* is the set of nonnegative real numbers and R^+ is the set of strictly positive real numbers (excluding 0).

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ω -Notation (“Little-Omega”)

Lower Bound NOT Asymptotically Tight

- ω concept relates to Ω concept in analogy to the relation of “little-Oh” concept to “big-Oh” concept.
- “Little Omega” or ω notation provides a *lower bound that strictly is NOT asymptotically tight*.
- Mathematically expressed, the “Little Omega” ($\omega()$) concept is as follows:
- Let $f: N \rightarrow R^*$ be an arbitrary function.
- $\omega(f(n)) = \{t: N \rightarrow R^* \mid (\exists c \in R^+)(\exists n_0 \in N)(\forall n \geq n_0) [cf(n) < t(n)]\}$,
 - where R^* is the set of nonnegative real numbers and R^+ is the set of strictly positive real numbers (excluding 0).

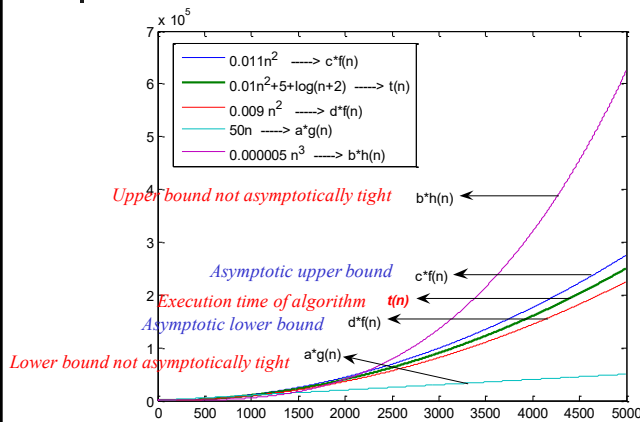
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Asymptotic Notations

Examples



$t(n) \in O(f(n))$
 $t(n) \in O(h(n))$

$t(n) \in \Theta(f(n))$
 $t(n) \notin \Theta(h(n))$
 $t(n) \notin \Theta(g(n))$

$t(n) \in \Omega(f(n))$
 $t(n) \in \Omega(g(n))$

$t(n) \in o(h(n))$
 $t(n) \notin o(f(n))$

$t(n) \in \omega(g(n))$
 $t(n) \notin \omega(f(n))$

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Execution time of various structures

- Simple Statement
 $O(1)$, executed within a constant amount of time
 irrespective to any change in input size.
- Decision (if) structure
 if (condition) $f(n)$ else $g(n)$
 $O(\text{if structure}) = \max(O(f(n)), O(g(n)))$
- Sequence of Simple Statements
 $O(1)$, since $O(f_1(n) + \dots + f_s(n)) = O(\max(f_1(n), \dots, f_s(n)))$

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Execution time of various structures

- $O(f_1(n) + \dots + f_s(n)) = O(\max(f_1(n), \dots, f_s(n)))$???

- Proof:

$$t(n) \in O(f_1(n) + \dots + f_s(n)) \Rightarrow t(n) \leq c[f_1(n) + \dots + f_s(n)]$$

$$\leq sc * \max[f_1(n), \dots, f_s(n)], sc \text{ another constant.}$$

$$\Rightarrow t(n) \in O(\max(f_1(n), \dots, f_s(n)))$$

Hence, hypothesis follows.

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Execution Time of Loop Structures

- Loop structures' execution time depends upon whether or not their index bounds are related to the input size.
- Assume n is the number of input records
- for ($i=0$; $i \leq n$; $i++$) {statement block}, $O(?)$
- for ($i=0$; $i \leq m$; $i++$) {statement block}, $O(?)$

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Examples

Find the execution time $t(n)$ in terms of n !

```
for (i=0; i<=n; i++)
  for (j=0; j<=n; j++)
    statement block;
```

```
for (i=0; i<=n; i++)
  for (j=0; j<=i; j++)
    statement block;
```

```
for (i=0; i<=n; i++)
  for (j=1; j<=n; j*=2)
    statement block;
```

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Exercises

Find the number of times the statement block is executed!


```
for (i=0; i<=n; i++)
  for (j=1; j<=i; j*=2)
    statement block;
```

```
for (i=1; i<=n; i*=3)
  for (j=1; j<=n; j*=2)
    statement block;
```


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Sparse Vectors and Matrices



Motivation

- In numerous applications, we may have to process vectors/matrices which mostly contain trivial information (i.e., most of their entries are zero!). This type of vectors/matrices are defined to be *sparse*.
- Storing *sparse* vectors/matrices as usual (e.g., matrices in a 2D array or a vector a regular 1D array) causes wasting memory space for storing trivial information.
- **Example:** What is the *space requirement* for a matrix $m_{n \times n}$ with only *non-trivial information in its diagonal* if
 - it is stored in a 2D array;
 - in some other way? Your suggestions?

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Sparse Vectors and Matrices

- This fact brings up the question:

May the vector/matrix be stored in MM avoiding waste of memory space?

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Sparse Vectors and Matrices

- Assuming that the vector/matrix is *static* (i.e., it is not going to change throughout the execution of the program), we should study *two cases*:

1. Non-trivial information is placed in the vector/matrix *following a specific order*;
2. Non-trivial information is *randomly* placed in the vector/matrix.

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Case 1: Info. follows an order

- Example structures:
 - Triangular matrices (upper or lower triangular matrices)
 - Symmetric matrices
 - Band matrices
 - Any other types ...?

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Triangular Matrices

$$m = \begin{bmatrix} m_{11} & m_{12} & m_{13} & \cdots & m_{1n} \\ 0 & m_{22} & m_{23} & \cdots & m_{2n} \\ 0 & 0 & m_{33} & \cdots & m_{3n} \\ 0 & 0 & 0 & \ddots & \vdots \\ 0 & 0 & 0 & 0 & m_{nn} \end{bmatrix}$$

Upper Triangular Matrix

$$m = \begin{bmatrix} m_{11} & 0 & 0 & \cdots & 0 \\ m_{21} & m_{22} & 0 & \cdots & 0 \\ m_{31} & m_{32} & m_{33} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & m_{n3} & \cdots & m_{nn} \end{bmatrix}$$

Lower Triangular Matrix

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Symmetric and Band Matrices

$$m = \begin{bmatrix} m_{11} & m_{12} & m_{13} & \cdots & m_{1n} \\ m_{12} & m_{22} & m_{23} & \cdots & m_{2n} \\ m_{13} & m_{23} & m_{33} & \cdots & m_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ m_{1n} & m_{2n} & m_{3n} & \cdots & m_{nn} \end{bmatrix}$$

Symmetric Matrix

$$m = \begin{bmatrix} m_{11} & m_{12} & 0 & \cdots & 0 \\ m_{21} & m_{22} & m_{23} & \cdots & 0 \\ 0 & m_{32} & m_{33} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & m_{n-1,n} \\ 0 & 0 & \cdots & m_{n,n-1} & m_{nn} \end{bmatrix}$$

Band Matrix

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Case 1: How to Efficiently Store...

- Store only the non-trivial information in a *1-dim* array *a*;
- Find a function *f* mapping the indices of the *2-dim* matrix (i.e., *i* and *j*) to the index *k* of *1-dim* array *a*,

or

$$f : N_0^2 \rightarrow N_0$$

such that

$$k = f(i, j)$$

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Case 2: How to Efficiently Store...

- Store only the non-trivial information in a l -dim array a along with the entry coordinates.
- Example:

$$a \quad \begin{array}{|c|c|c|c|c|c|c|} \hline a;0,0 & b;1,1 & f;1,n-1 & c;2,1 & g;i,j & e;n-1,0 & d;n-1,2 \\ \hline \end{array}$$

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Recursion



Recursion

Definition:

Recursion is a mathematical concept referring to programs or functions calling or using itself.

A *recursive function* is a functional piece of code that invokes or calls itself.

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Recursion

Concept:

- A recursive function divides the problem into two conceptual pieces:
 - a piece that the function knows how to solve (**base case**),
 - a piece that is very similar to, but *a little simpler than*, the original problem, hence still unknown how to solve by the function (**call(s) of the function to itself**).

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Recursion... cont'd

- **Base case:** the simplest version of the problem that is *not further reducible*. The function actually knows how to solve this version of the problem.
- To make the recursion feasible, the latter piece must be slightly simpler.

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Recursion Examples

- **Towers of Hanoi**
- Story: According to the legend, the life on the world will end when Buddhist monks in a Far-Eastern temple move 64 disks stacked on a peg in a decreasing order in size to another peg. They are allowed to move one disk at a time and a larger disk can never be placed over a smaller one.

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Towers of Hanoi... cont'd

Algorithm:

```

Hanoi(n,i,j)
// moves n smallest rings from rod i to rod j
F0A0  if (n > 0) {
        //moves top n-1 rings to intermediary rod (6-i-j)
F0A2  Hanoi(n-1,i,6-i-j);
        //moves the bottom (nth largest) ring to rod j
F0A5  move i to j
        // moves n-1 rings at rod 6-i-j to destination rod j
F0A8  Hanoi(n-1,6-i-j,j);
F0AB  }

```

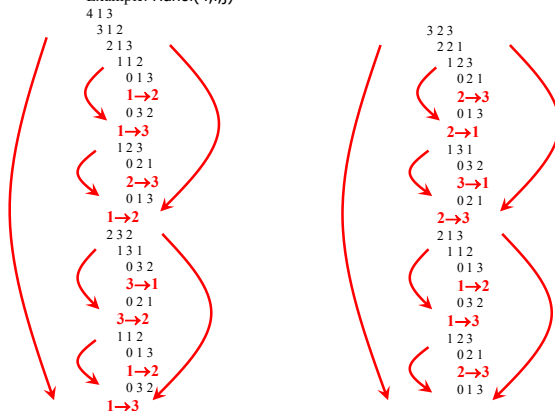
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Towers of Hanoi... cont'd

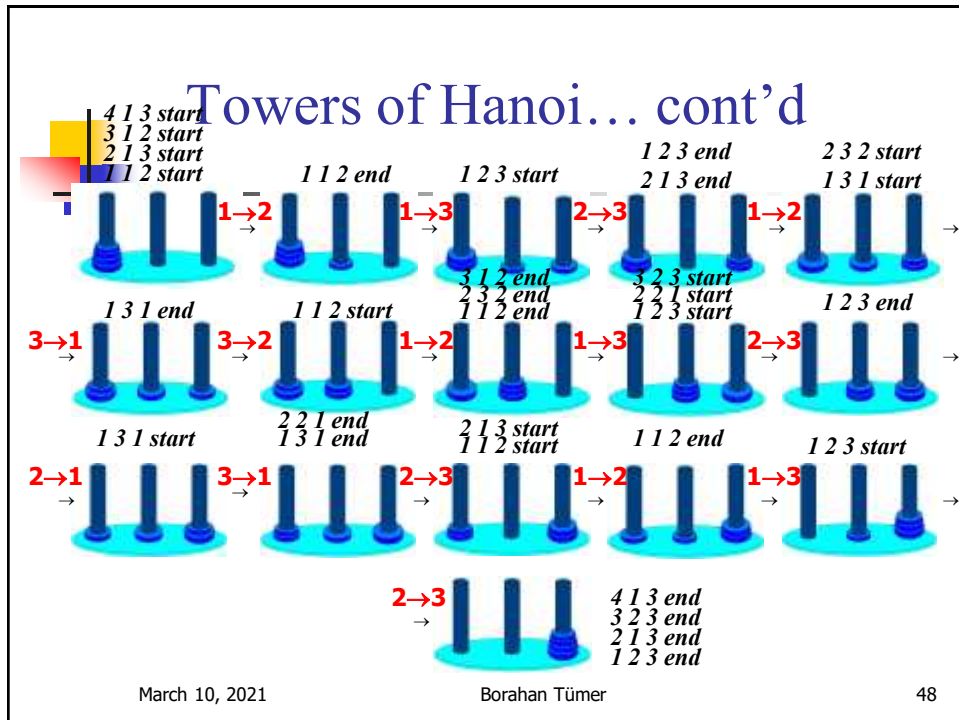
Example: Hanoi(4,i,j)



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Recursion Examples

- **Fibonacci Series**
 - $t_n = t_{n-1} + t_{n-2}; t_0=0; t_1=1$
- **Algorithm**

```

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

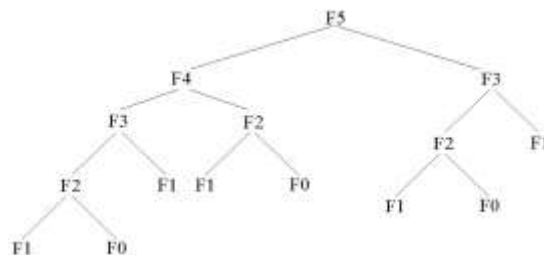
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Fibonacci Series... cont'd

- Tree of recursive function calls for fib(5)
- Any problems???



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Fibonacci Series... cont'd

- Redundant function calls slow the execution down.
- A **lookup table** used to store the Fibonacci values already computed saves redundant function executions and speeds up the process.
- **Homework**: Write fib(n) with a lookup table!

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Recurrences



Recurrences or Difference Equations

- **Homogeneous Recurrences**
- Consider $a_0 t_n + a_1 t_{n-1} + \dots + a_k t_{n-k} = 0$.
- The recurrence
 - contains t_i values which we are looking for.
 - is a linear recurrence (i.e., t_i values appear alone, no powered values, divisions or products)
 - contains constant coefficients (i.e., a_i).
 - is homogeneous (i.e., RHS of equation is 0).



Homogeneous Recurrences

We are looking for solutions of the form:

$$t_n = x^n$$

Then, we can write the recurrence as

$$a_0 x^n + a_1 x^{n-1} + \dots + a_k x^{n-k} = 0$$

- This k^{th} degree equation is the **characteristic equation (CE)** of the recurrence.

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Homogeneous Recurrences

If $r_i, i=1, \dots, k$, are k distinct roots of $a_0 x^k + a_1 x^{k-1} + \dots + a_k = 0$,
then

$$t_n = \sum_{i=1}^k c_i r_i^n$$


If $r_i, i=1, \dots, k$, is a single root of multiplicity k , then

$$t_n = \sum_{i=1}^k c_i n^{i-1} r^n$$

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Inhomogeneous Recurrences

Consider

- $a_0 t_n + a_1 t_{n-1} + \dots + a_k t_{n-k} = b^n p(n)$
- where b is a constant; and $p(n)$ is a polynomial in n of degree d .

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Inhomogeneous Recurrences

Generalized Solution for Recurrences

Consider a general equation of the form

$$(a_0 t_n + a_1 t_{n-1} + \dots + a_k t_{n-k}) = b_1^n p_1(n) + b_2^n p_2(n) + \dots$$

We are looking for solutions of the form:

$$t_n = x^n$$

Then, we can write the recurrence as

$$(a_0 x^k + a_1 x^{k-1} + \dots + a_k)(x - b_1)^{d_1+1} (x - b_2)^{d_2+1} \dots = 0$$

where d_i is the polynomial degree of polynomial $p_i(n)$.

This is the **characteristic equation (CE)** of the recurrence.

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Generalized Solution for Recurrences

If $r_i, i=1, \dots, k$, are k distinct roots of

$$(a_0 x^k + a_1 x^{k-1} + \dots + a_k) = 0$$

$$t_n = \sum_{i=1}^k c_i r_i^n + \underbrace{c_{k+1} b_1^n + c_{k+2} n b_1^n + \dots + c_{k+1+d_1} n^{d_1-1} b_1^n}_{\text{from } (x-b_1)^{d_1+1}} +$$

$$\dots + \underbrace{c_{k+2+d_1} b_2^n + c_{k+3+d_1} n b_2^n + \dots + c_{k+2+d_1+d_2} n^{d_2-1} b_2^n}_{\text{from } (x-b_2)^{d_2+1}} + \dots$$

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Examples

Homogeneous Recurrences

Example 1.

$$t_n + 5t_{n-1} + 4t_{n-2} = 0; \text{ sol'ns of the form } t_n = x^n$$

$$x^n + 5x^{n-1} + 4x^{n-2} = 0; \text{ (CE) } n-2 \text{ trivial sol'ns (i.e., } x_{1, \dots, n-2} = 0)$$

$$(x^2 + 5x + 4) = 0; \text{ characteristic equation (simplified CE)}$$

$$x_1 = -1; x_2 = -4; \text{ nontrivial sol'ns}$$

$$\Rightarrow t_n = c_1(-1)^n + c_2(-4)^n; \text{ general sol'n}$$

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Examples

Homogeneous Recurrence

Example 2.

$$t_n - 6t_{n-1} + 12t_{n-2} - 8t_{n-3} = 0; \quad t_n = x^n$$

$$x^n - 6x^{n-1} + 12x^{n-2} - 8x^{n-3} = 0; \quad n-3 \text{ trivial sol'n's}$$

$$\text{CE: } (x^3 - 6x^2 + 12x - 8) = (x-2)^3 = 0; \text{ by polynomial division}$$

$$x_1 = x_2 = x_3 = 2; \text{ roots not distinct!!!}$$

$$\Rightarrow t_n = c_1 2^n + c_2 n 2^n + c_3 n^2 2^n; \text{ general sol'n}$$

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Examples

Homogeneous Recurrence

Example 3.

$$t_n = t_{n-1} + t_{n-2}; \text{ Fibonacci Series}$$

$$x^n - x^{n-1} - x^{n-2} = 0; \Rightarrow \text{CE: } x^2 - x - 1 = 0;$$

$$x_{1,2} = \frac{1 \pm \sqrt{5}}{2}; \text{ distinct roots!!!}$$

$$\Rightarrow t_n = c_1 \left(\frac{1 + \sqrt{5}}{2} \right)^n + c_2 \left(\frac{1 - \sqrt{5}}{2} \right)^n; \text{ general sol'n!!}$$

We find coefficients c_i using initial values t_0 and t_1 of Fibonacci series on the next slide!!!

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Examples

Example 3... cont'd

We use as many t_i values

as c_i

$$t_0 = 0 = c_1 \left(\frac{1+\sqrt{5}}{2} \right)^0 + c_2 \left(\frac{1-\sqrt{5}}{2} \right)^0 = c_1 + c_2 = 0 \Rightarrow c_1 = -c_2$$

$$t_1 = 1 = c_1 \left(\frac{1+\sqrt{5}}{2} \right)^1 + c_2 \left(\frac{1-\sqrt{5}}{2} \right)^1 = c_1 \left(\frac{1+\sqrt{5}}{2} \right) - c_1 \left(\frac{1-\sqrt{5}}{2} \right) \Rightarrow c_1 = \frac{1}{\sqrt{5}}, \quad c_2 = -\frac{1}{\sqrt{5}}$$

Check it out using t_2 !!!

$$\Rightarrow t_n = \frac{1}{\sqrt{5}} \left(\frac{1+\sqrt{5}}{2} \right)^n - \frac{1}{\sqrt{5}} \left(\frac{1-\sqrt{5}}{2} \right)^n$$

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Examples

Example 3... cont'd

What do n and t_n represent?

n is the location and t_n the value of any Fibonacci number in the series.

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Examples

Example 4.

$$t_n = 2t_{n-1} - 2t_{n-2}; \quad n \geq 2; \quad t_0 = 0; \quad t_1 = 1;$$

$$\text{CE: } x^2 - 2x + 2 = 0;$$

Complex roots: $x_{1,2} = 1 \pm i$

As in differential equations, we represent the complex roots as a vector in polar coordinates by a combination of a real radius r and a complex argument θ :

$$z = r * e^{i\theta};$$

Here,

$$1+i = \sqrt{2} * e^{(\pi/4)i}$$

$$1-i = \sqrt{2} * e^{(-\pi/4)i}$$

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Examples

Example 4... cont'd

Solution:

$$t_n = c_1 (2)^{n/2} e^{(n\pi/4)i} + c_2 (2)^{n/2} e^{(-n\pi/4)i};$$

From initial values $t_0 = 0, t_1 = 1$,

$$t_n = 2^{n/2} \sin(n\pi/4); \quad (\text{prove that!!!})$$

Hint:

$$e^{i\theta} = \cos \theta + i \sin \theta$$

$$e^{in\theta} = (\cos \theta + i \sin \theta)^n = \cos n\theta + i \sin n\theta$$

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Examples

Inhomogeneous Recurrences

Example 1. (From Example 3)

We would like to know **how many times fib(n)** on page 22 **is executed in terms of n** . To find out:

1. choose a barometer in **fib(n)**;
2. devise a formula to count up the number of times the barometer is executed.

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Examples

Example 1 ... cont'd

In **fib(n)**, the only statement is the *if* statement.

Hence, **if condition** is chosen as the **barometer**.

Suppose **fib(n)** takes t_n time units to execute, where the barometer takes one time unit and the function calls **fib(n-1)** and **fib(n-2)**, t_{n-1} and t_{n-2} , respectively. Hence, the recurrence to solve is

$$t_n = t_{n-1} + t_{n-2} + 1$$

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Examples

Example 1... cont'd

$t_n - t_{n-1} - t_{n-2} = 1$; inhomogeneous recurrence

The homogeneous part comes directly from Fibonacci Series example on page 52.

RHS of recurrence is 1 which can be expressed as $1^n x^0$. Then, from the equation on page 48,

CE: $(x^2 - x - 1)(x - 1) = 0$; from page 49,

$$t_n = c_1 \left(\frac{1+\sqrt{5}}{2} \right)^n + c_2 \left(\frac{1-\sqrt{5}}{2} \right)^n + c_3 1^n$$

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Examples

Example 1... cont'd

$$t_n = c_1 \left(\frac{1+\sqrt{5}}{2} \right)^n + c_2 \left(\frac{1-\sqrt{5}}{2} \right)^n + c_3$$

Now, we have to find c_1, \dots, c_3 .

Initial values: for both $n=0$ and $n=1$, if condition is checked once and no recursive calls are done.

For $n=2$, if condition is checked once and recursive calls $\text{fib}(1)$ and $\text{fib}(0)$ are done.

$$\Rightarrow t_0 = t_1 = 1 \text{ and } t_2 = t_0 + t_1 + 1 = 3.$$

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Examples

Example 1 ... cont'd

$$t_n = c_1 \left(\frac{1+\sqrt{5}}{2} \right)^n + c_2 \left(\frac{1-\sqrt{5}}{2} \right)^n + c_3; \quad t_0 = t_1 = 1, t_2 = 3$$

$$c_1 = \frac{\sqrt{5}+1}{\sqrt{5}}; \quad c_2 = \frac{\sqrt{5}-1}{\sqrt{5}}; \quad c_3 = -1$$

$$t_n = \left\lfloor \frac{\sqrt{5}+1}{\sqrt{5}} \right\rfloor \left(\frac{1+\sqrt{5}}{2} \right)^n + \left\lfloor \frac{\sqrt{5}-1}{\sqrt{5}} \right\rfloor \left(\frac{1-\sqrt{5}}{2} \right)^n - 1;$$

Here, t_n provides the number of times the barometer is executed in terms of n . Practically, this number also gives the number of times `fib(n)` is called.