

Advanced Algorithms Analysis and Design

By

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Lecture No 10

Measuring Complexity of Algorithms (Asymptotic Notations)

Today Covered

- Major Factors in Algorithms Design
- Complexity Analysis
- Growth of Functions
- Asymptotic Notations
- Usefulness of Notations
- Reflexivity, Symmetry, Transitivity Relations over Θ , Ω , O , ω and o
- Relation between Θ , Ω and O
- Various Examples Explaining each concept

Major Factors in Algorithms Design

1. Correctness

An **algorithm** is said to be **correct** if

- For every input, it **halts** with **correct** output.
- An **incorrect** algorithm might **not halt** at all OR
- It might **halt** with an answer **other than desired one**.
- **Correct algorithm** solves a computational problem

2. Algorithm Efficiency

Measuring efficiency of an algorithm,

- do its analysis i.e. growth rate.
- Compare efficiencies of different algorithms for the same problem.

Algorithms Growth Rate

Algorithm Growth Rates

- It measures algorithm efficiency

What means by efficient?

- If running time is bounded by polynomial in the input

Notations for Asymptotic performance

- How running time increases with input size
- O , Ω , Θ , etc. for asymptotic running time
- These notations defined in terms of functions whose domains are natural numbers
- convenient for worst case running time
- Algorithms, asymptotically efficient best choice

Complexity Analysis

- Algorithm analysis means predicting resources such as
 - computational time
 - memory
 - computer hardware etc
- Worst case analysis
 - Provides an upper bound on running time
 - An absolute guarantee
- Average case analysis
 - Provides the expected running time
 - Very useful, but treat with care: what is “average”?
 - Random (equally likely) inputs
 - Real-life inputs

Worst-case Analysis

Let us suppose that

- D_n = set of inputs of size n for the problem
- I = an element of D_n .
- $t(I)$ = number of basic operations performed on I
- Define a function W by

$$W(n) = \max\{t(I) \mid I \in D_n\}$$

called the worst-case complexity of the algorithm

- $W(n)$ is the maximum number of basic operations performed by the algorithm on any input of size n .
- Please note that the input, I , for which an algorithm behaves worst depends on the particular algorithm.

Average Complexity

- Let $\text{Pr}(I)$ be the probability that input I occurs.
- Then the average behavior of the algorithm is defined as

$$A(n) = \sum \text{Pr}(I) t(I), \quad \text{summation over all } I \in D_n$$

- We determine $t(I)$ by analyzing the algorithm, but $\text{Pr}(I)$ cannot be computed analytically.
- Average cost =

$$A(n) = \text{Pr}(\text{succ})A_{\text{succ}}(n) + \text{Pr}(\text{fail})A_{\text{fail}}(n)$$

- An element I in D_n may be thought as a set or equivalence class that affect the behavior of the algorithm

Worst Analysis computing average cost

- Take all possible inputs, compute their cost, take average

Asymptotic Notations Properties

- Categorize algorithms based on asymptotic growth rate e.g. linear, quadratic, polynomial, exponential
- Ignore small constant and small inputs
- Estimate upper bound and lower bound on growth rate of time complexity function
- Describe running time of algorithm as n grows to ∞ .
- Describes behavior of function within the limit.

Limitations

- not always useful for analysis on fixed-size inputs.
- All results are for *sufficiently large* inputs.

Asymptotic Notations

Asymptotic Notations Θ , O , Ω , o , ω

- We use Θ to mean “order exactly”,
- O to mean “order at most”,
- Ω to mean “order at least”,
- o to mean “tight upper bound”,
- ω to mean “tight lower bound”,

Define a *set* of functions: which is in practice used to compare two function sizes.

Big-Oh Notation (O)

If $f, g: \mathbb{N} \rightarrow \mathbb{R}^+$, then we can define Big-Oh as

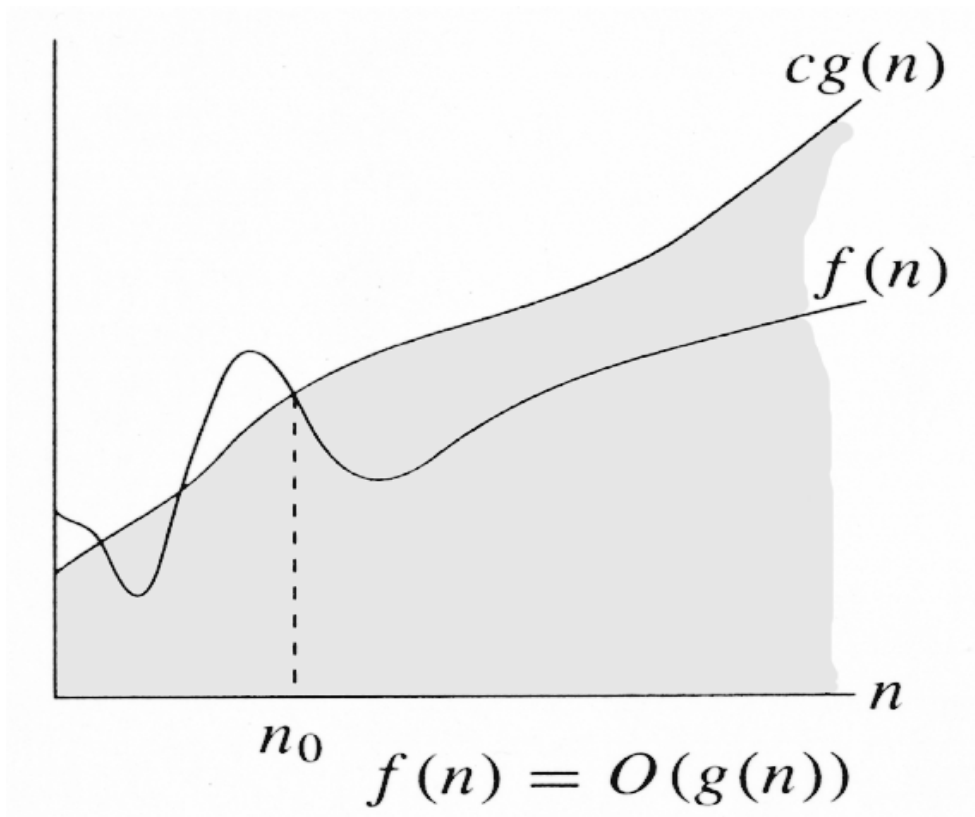
For a given function $g(n) \geq 0$, denoted by $O(g(n))$ the set of functions,
 $O(g(n)) = \{f(n): \text{there exist positive constants } c \text{ and } n_o \text{ such that}$
 $0 \leq f(n) \leq cg(n), \text{ for all } n \geq n_o\}$
 $f(n) = O(g(n))$ means function $g(n)$ is an asymptotically
upper bound for $f(n)$.

We may write $f(n) = O(g(n))$ OR $f(n) \in O(g(n))$

Intuitively:

Set of all functions whose *rate of growth* is the same as or lower than that of $g(n)$.

Big-Oh Notation



$$f(n) \in O(g(n))$$

$$\exists c > 0, \exists n_0 \geq 0 \text{ and } \forall n \geq n_0, 0 \leq f(n) \leq c \cdot g(n)$$

$g(n)$ is an *asymptotic upper bound* for $f(n)$.

Examples

Example 1: Prove that $2n^2 \in O(n^3)$

Proof:

Assume that $f(n) = 2n^2$, and $g(n) = n^3$

$f(n) \in O(g(n))$?

Now we have to find the existence of c and n_0

$$f(n) \leq c.g(n) \Leftrightarrow 2n^2 \leq c.n^3 \Leftrightarrow 2 \leq c.n$$

if we take, $c = 1$ and $n_0 = 2$ OR

$c = 2$ and $n_0 = 1$ then

$$2n^2 \leq c.n^3$$

Hence $f(n) \in O(g(n))$, $c = 1$ and $n_0 = 2$

Examples

Example 2: Prove that $n^2 \in O(n^2)$

Proof:

Assume that $f(n) = n^2$, and $g(n) = n^2$

Now we have to show that $f(n) \in O(g(n))$

Since

$f(n) \leq c.g(n) \Leftrightarrow n^2 \leq c.n^2 \Leftrightarrow 1 \leq c$, take, $c = 1$, $n_0 = 1$

Then

$n^2 \leq c.n^2$ for $c = 1$ and $n \geq 1$

Hence, $2n^2 \in O(n^2)$, where $c = 1$ and $n_0 = 1$

Examples

Example 3: Prove that $1000.n^2 + 1000.n \in O(n^2)$

Proof:

Assume that $f(n) = 1000.n^2 + 1000.n$, and $g(n) = n^2$

We have to find existence of c and n_0 such that

$$0 \leq f(n) \leq c.g(n) \quad \forall n \geq n_0$$

$$1000.n^2 + 1000.n \leq c.n^2 = 1001.n^2, \text{ for } c = 1001$$

$$1000.n^2 + 1000.n \leq 1001.n^2$$

$$\Leftrightarrow 1000.n \leq n^2 \Leftrightarrow n^2 \geq 1000.n \Leftrightarrow n^2 - 1000.n \geq 0$$

$$\Leftrightarrow n(n-1000) \geq 0, \text{ this true for } n \geq 1000$$

$$f(n) \leq c.g(n) \quad \forall n \geq n_0 \text{ and } c = 1001$$

Hence $f(n) \in O(g(n))$ for $c = 1001$ and $n_0 = 1000$

Examples

Example 4: Prove that $n^3 \notin O(n^2)$

Proof:

On contrary we assume that there exist some positive constants c and n_0 such that

$$0 \leq n^3 \leq c.n^2 \quad \forall n \geq n_0$$

$$0 \leq n^3 \leq c.n^2 \Leftrightarrow n \leq c$$

Since c is any fixed number and n is any arbitrary constant, therefore $n \leq c$ is not possible in general.

Hence our supposition is wrong and $n^3 \leq c.n^2$,
 $\forall n \geq n_0$ is not true for any combination of c and n_0 .

And hence, $n^3 \notin O(n^2)$

Some More Examples

1. $n^2 + n^3 = O(n^4)$
2. $n^2 / \log(n) = O(n \cdot \log n)$
3. $5n + \log(n) = O(n)$
4. $n^{\log n} = O(n^{100})$
5. $3^n = O(2^n \cdot n^{100})$
6. $n! = O(3^n)$
7. $n + 1 = O(n)$
8. $2^{n+1} = O(2^n)$
9. $(n+1)! = O(n!)$
10. $1 + c + c^2 + \dots + c^n = O(c^n)$ for $c > 1$
11. $1 + c + c^2 + \dots + c^n = O(1)$ for $c < 1$

Big-Omega Notation (Ω)

If $f, g: \mathbb{N} \rightarrow \mathbb{R}^+$, then we can define Big-Omega as

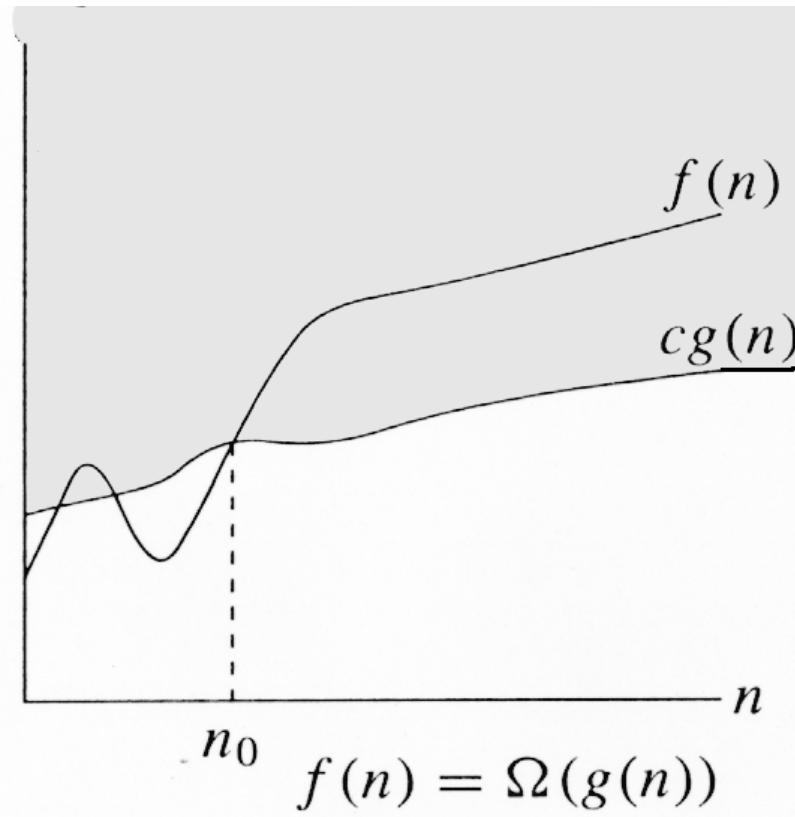
For a given function $g(n)$ denote by $\Omega(g(n))$ the set of functions,
 $\Omega(g(n)) = \{f(n) : \text{there exist positive constants } c \text{ and } n_0 \text{ such that}$
 $0 \leq cg(n) \leq f(n) \text{ for all } n \geq n_0\}$
 $f(n) \in \Omega(g(n))$, means that function $g(n)$ is an asymptotically
lower bound for $f(n)$.

We may write $f(n) \in \Omega(g(n))$ OR $f(n) \in \Omega(g(n))$

Intuitively:

Set of all functions whose *rate of growth* is the same as or higher than that of $g(n)$.

Big-Omega Notation



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

$$\exists c > 0, \exists n_0 \geq 0, \forall n \geq n_0, f(n) \geq c \cdot g(n)$$

$g(n)$ is an *asymptotically lower bound* for $f(n)$.

Examples

Example 1: Prove that $5.n^2 \in \Omega(n)$

Proof:

Assume that $f(n) = 5.n^2$, and $g(n) = n$

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

We have to find the existence of c and n_0 s.t.

$$c.g(n) \leq f(n) \quad \forall n \geq n_0$$

$$c.n \leq 5.n^2 \Leftrightarrow c \leq 5.n$$

if we take, $c = 5$ and $n_0 = 1$ then

$$c.n \leq 5.n^2 \quad \forall n \geq n_0$$

And hence $f(n) \in \Omega(g(n))$, for $c = 5$ and $n_0 = 1$

Examples

Example 2: Prove that $5.n + 10 \in \Omega(n)$

Proof:

Assume that $f(n) = 5.n + 10$, and $g(n) = n$

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

We have to find the existence of c and n_0 s.t.

$$c.g(n) \leq f(n) \quad \forall n \geq n_0$$

$$c.n \leq 5.n + 10 \Leftrightarrow c.n \leq 5.n + 10.n \Leftrightarrow c \leq 15.n$$

if we take, $c = 15$ and $n_0 = 1$ then

$$c.n \leq 5.n + 10 \quad \forall n \geq n_0$$

And hence $f(n) \in \Omega(g(n))$, for $c = 15$ and $n_0 = 1$

Examples

Example 3: Prove that $100.n + 5 \notin \Omega(n^2)$

Proof:

Let $f(n) = 100.n + 5$, and $g(n) = n^2$

Assume that $f(n) \in \Omega(g(n))$?

Now if $f(n) \in \Omega(g(n))$ then there exist c and n_0 s.t.

$$c.g(n) \leq f(n) \quad \forall n \geq n_0 \quad \Leftrightarrow$$

$$c.n^2 \leq 100.n + 5 \quad \Leftrightarrow$$

$$c.n \leq 100 + 5/n \quad \Leftrightarrow$$

$n \leq 100/c$, for a very large n , which is not possible

And hence $f(n) \notin \Omega(g(n))$

Theta Notation (Θ)

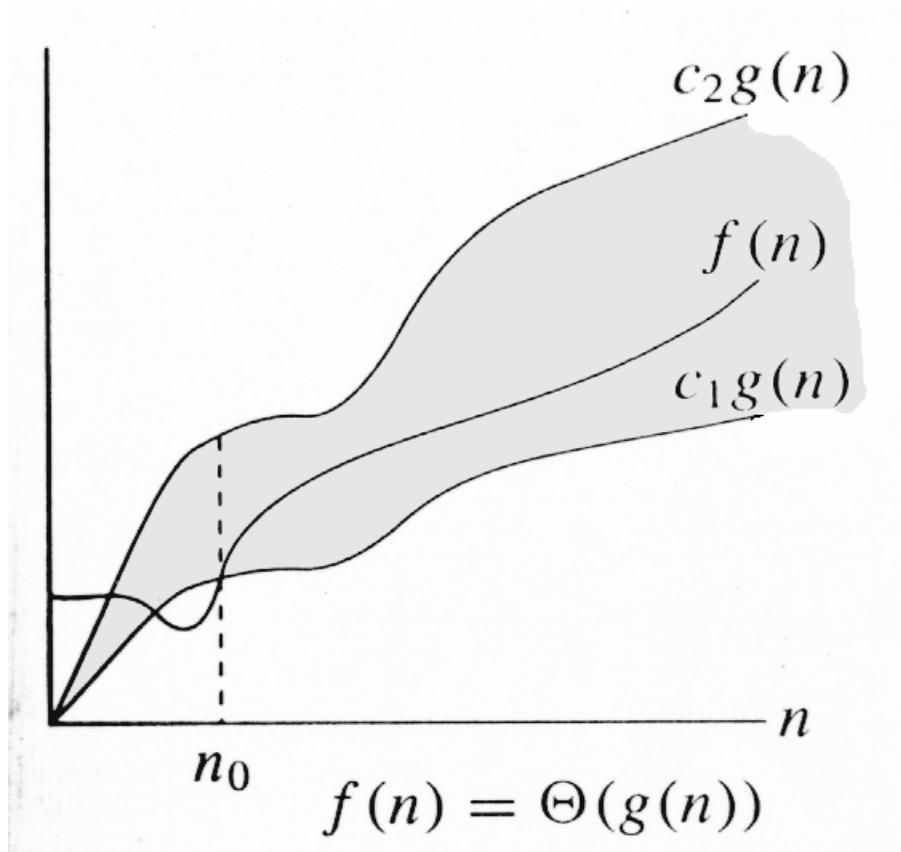
If $f, g: \mathbb{N} \rightarrow \mathbb{R}^+$, then we can define Big-Theta as

For a given function $g(n)$ denoted by $\Theta(g(n))$ the set of functions,
 $\Theta(g(n)) = \{f(n): \text{there exist positive constants } c_1, c_2 \text{ and } n_o \text{ such that}$
 $0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \text{ for all } n \geq n_o\}$
 $f(n) = \Theta(g(n))$ means function $f(n)$ is equal to $g(n)$ to within a constant factor, and $g(n)$ is an asymptotically tight bound for $f(n)$.

We may write $f(n) = \Theta(g(n))$ OR $f(n) \in \Theta(g(n))$

Intuitively: Set of all functions that have same *rate of growth* as $g(n)$.

Theta Notation



$$f(n) \in \Theta(g(n))$$

$$\exists c_1 > 0, c_2 > 0, \exists n_0 \geq 0, \forall n \geq n_0, c_2 \cdot g(n) \leq f(n) \leq c_1 \cdot g(n)$$

We say that $g(n)$ is an asymptotically tight bound for $f(n)$.

Theta Notation

Example 1: Prove that $\frac{1}{2}.n^2 - \frac{1}{2}.n = \Theta(n^2)$

Proof

Assume that $f(n) = \frac{1}{2}.n^2 - \frac{1}{2}.n$, and $g(n) = n^2$

$f(n) \in \Theta(g(n))$?

We have to find the existence of c_1 , c_2 and n_0 s.t.

$$c_1.g(n) \leq f(n) \leq c_2.g(n) \quad \forall n \geq n_0$$

Since, $\frac{1}{2} n^2 - \frac{1}{2} n \leq \frac{1}{2} n^2 \quad \forall n \geq 0$ if $c_2 = \frac{1}{2}$ and

$$\frac{1}{2} n^2 - \frac{1}{2} n \geq \frac{1}{2} n^2 - \frac{1}{2} n \cdot \frac{1}{2} n \quad (\forall n \geq 2) = \frac{1}{4} n^2, \quad c_1 = \frac{1}{4}$$

Hence $\frac{1}{2} n^2 - \frac{1}{2} n \leq \frac{1}{2} n^2 \leq \frac{1}{2} n^2 - \frac{1}{2} n$

$$c_1.g(n) \leq f(n) \leq c_2.g(n) \quad \forall n \geq 2, c_1 = \frac{1}{4}, c_2 = \frac{1}{2}$$

Hence $f(n) \in \Theta(g(n)) \Rightarrow \frac{1}{2}.n^2 - \frac{1}{2}.n = \Theta(n^2)$

Theta Notation

Example 2: Prove that $a.n^2 + b.n + c = \Theta(n^2)$ where a, b, c are constants and $a > 0$

Proof

If we take $c_1 = \frac{1}{4}.a$, $c_2 = \frac{7}{4}.a$ and

$$n_0 = 2.\max((|b|/a), \sqrt{(|c|/a)})$$

Then it can be easily verified that

$$0 \leq c_1.g(n) \leq f(n) \leq c_2.g(n), \forall n \geq n_0, c_1 = \frac{1}{4}.a, c_2 = \frac{7}{4}.a$$

$$\text{Hence } f(n) \in \Theta(g(n)) \Rightarrow a.n^2 + b.n + c = \Theta(n^2)$$

Hence any polynomial of degree 2 is of order $\Theta(n^2)$

Theta Notation

Example 1: Prove that $2.n^2 + 3.n + 6 \notin \Theta(n^3)$

Proof: Let $f(n) = 2.n^2 + 3.n + 6$, and $g(n) = n^3$
we have to show that $f(n) \notin \Theta(g(n))$

On contrary assume that $f(n) \in \Theta(g(n))$ i.e.

there exist some positive constants c_1 , c_2 and n_0
such that: $c_1.g(n) \leq f(n) \leq c_2.g(n)$

$$c_1.g(n) \leq f(n) \leq c_2.g(n) \Leftrightarrow c_1.n^3 \leq 2.n^2 + 3.n + 6 \leq c_2.n^3 \Leftrightarrow$$

$$c_1.n \leq 2 + 3/n + 6/n^2 \leq c_2.n \Rightarrow$$

$$c_1.n \leq 2 \leq c_2.n, \text{ for large } n \Rightarrow$$

$$n \leq 2/c_1 \leq c_2/c_1.n \text{ which is not possible}$$

$$\text{Hence } f(n) \notin \Theta(g(n)) \Rightarrow 2.n^2 + 3.n + 6 \notin \Theta(n^3)$$

Little-Oh Notation

o -notation is used to denote an upper bound that is not asymptotically tight.

For a given function $g(n) \geq 0$, denoted by $o(g(n))$ the set of functions,

$$o(g(n)) = \left\{ f(n) : \text{for any positive constants } c, \text{ there exists a constant } n_o \right. \\ \left. \text{such that } 0 \leq f(n) < cg(n) \text{ for all } n \geq n_o \right\}$$

$f(n)$ becomes insignificant relative to $g(n)$ as n approaches infinity

e.g., $2n = o(n^2)$ but $2n^2 \neq o(n^2)$. $\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = 0$

$g(n)$ is an upper bound for $f(n)$, not asymptotically tight

Examples

Example 1: Prove that $2n^2 \in o(n^3)$

Proof:

Assume that $f(n) = 2n^2$, and $g(n) = n^3$
 $f(n) \in o(g(n))$?

Now we have to find the existence n_0 for any c
 $f(n) < c.g(n)$ this is true
 $\Leftrightarrow 2n^2 < c.n^3 \Leftrightarrow 2 < c.n$

This is true for any c , because for any arbitrary c
we can choose n_0 such that the above inequality
holds.

Hence $f(n) \in o(g(n))$

Examples

Example 2: Prove that $n^2 \notin o(n^2)$

Proof:

Assume that $f(n) = n^2$, and $g(n) = n^2$

Now we have to show that $f(n) \notin o(g(n))$

Since

$$f(n) < c.g(n) \Leftrightarrow n^2 < c.n^2 \Leftrightarrow 1 \leq c,$$

In our definition of small o , it was required to prove for any c but here there is a constraint over c .

Hence, $n^2 \notin o(n^2)$, where $c = 1$ and $n_0 = 1$

Examples

Example 3: Prove that $1000.n^2 + 1000.n \notin o(n^2)$

Proof:

Assume that $f(n) = 1000.n^2 + 1000.n$, and $g(n) = n^2$
we have to show that $f(n) \notin o(g(n))$ i.e.

We assume that for any c there exist n_0 such that
 $0 \leq f(n) < c.g(n) \quad \forall n \geq n_0$

$$1000.n^2 + 1000.n < c.n^2$$

If we take $c = 2001$, then, $1000.n^2 + 1000.n < 2001.n^2$

$$\Leftrightarrow 1000.n < 1001.n^2 \quad \text{which is not true}$$

Hence $f(n) \notin o(g(n))$ for $c = 2001$

Little-Omega Notation

Little- ω notation is used to denote a lower bound that is not asymptotically tight.

For a given function $g(n)$, denote by $\omega(g(n))$ the set of all functions.

$\omega(g(n)) = \{f(n) : \text{for any positive constants } c, \text{ there exists a constant } n_o \text{ such that } 0 \leq cg(n) < f(n) \text{ for all } n \geq n_o\}$

$f(n)$ becomes arbitrarily large relative to $g(n)$ as n approaches infinity

$$\lim_{n \rightarrow \infty} \frac{f(n)}{g(n)} = \infty$$

$$\text{e.g., } \frac{n^2}{2} = \omega(n) \text{ but } \frac{n^2}{2} \neq \omega(n^2).$$

Examples

Example 1: Prove that $5.n^2 \in \omega(n)$

Proof:

Assume that $f(n) = 5.n^2$, and $g(n) = n$
 $f(n) \in \Omega(g(n))$?

We have to prove that for any c there exists n_0 s.t.,
 $c.g(n) < f(n) \quad \forall n \geq n_0$
 $c.n < 5.n^2 \Leftrightarrow c < 5.n$

This is true for any c , because for any arbitrary c
e.g. $c = 1000000$, we can choose $n_0 = 1000000/5$
 $= 200000$ and the above inequality does hold.

And hence $f(n) \in \omega(g(n))$,

Examples

Example 2: Prove that $5.n + 10 \notin \omega(n)$

Proof:

Assume that $f(n) = 5.n + 10$, and $g(n) = n$
 $f(n) \notin \Omega(g(n))$?

We have to find the existence n_0 for any c , s.t.

$$c.g(n) < f(n) \quad \forall n \geq n_0$$

$c.n < 5.n + 10$, if we take $c = 16$ then

$16.n < 5.n + 10 \Leftrightarrow 11.n < 10$ is not true for any positive integer.

Hence $f(n) \notin \omega(g(n))$

Examples

Example 3: Prove that $100.n \notin \omega(n^2)$

Proof:

Let $f(n) = 100.n$, and $g(n) = n^2$

Assume that $f(n) \in \omega(g(n))$

Now if $f(n) \in \omega(g(n))$ then there n_0 for any c s.t.

$c.g(n) < f(n) \quad \forall n \geq n_0$ this is true

$\Leftrightarrow c.n^2 < 100.n \Leftrightarrow c.n < 100$

If we take $c = 100$, $n < 1$, not possible

Hence $f(n) \notin \omega(g(n))$ i.e. $100.n \notin \omega(n^2)$

Usefulness of Notations

- It is not always possible to determine behaviour of an algorithm using Θ -notation.
- For example, given a problem with n inputs, we may have an algorithm to solve it in $a.n^2$ time when n is even and $c.n$ time when n is odd. OR
- We may prove that an algorithm never uses more than $e.n^2$ time and never less than $f.n$ time.
- In either case we can neither claim $\Theta(n)$ nor $\Theta(n^2)$ to be the order of the time usage of the algorithm.
- Big O and Ω notation will allow us to give at least partial information

Reflexive Relation

Definition:

- Let X be a non-empty set and R is a relation over X then R is said to be reflexive if

$$(a, a) \in R, \forall a \in X,$$

Example 1:

- Let P be a set of all persons, and S be a relation over P such that if $(x, y) \in S$ then x has same sign as y .
- Of course this relation is reflexive because

$$(x, x) \in S, \quad \forall a \in P,$$

Example 2:

- Let P be a set of all persons at VU and let T be a relation over P such that if $(x, y) \in T$ then x is teacher of y . This relation is not reflexive because

$$(x, x) \notin T, \forall a \in X$$

Reflexivity Relations over Θ , Ω , O

Example 1

Since, $0 \leq c_1 f(n) \leq f(n) \leq c_2 f(n) \quad \forall n \geq n_0 = 1$, if $c_1 = c_2 = 1$

Hence $f(n) = \Theta(f(n))$

Example 2

Since, $0 \leq f(n) \leq cf(n) \quad \forall n \geq n_0 = 1$, if $c = 1$

Hence $f(n) = O(f(n))$

Example 3

Since, $0 \leq cf(n) \leq f(n) \quad \forall n \geq n_0 = 1$, if $c = 1$

Hence $f(n) = \Omega(f(n))$

Note: All the relations, Θ , Ω , O , are reflexive

Reflexivity Relations over o , ω

Example

As we can not prove that $f(n) < f(n)$, for any n , and for all $c > 0$

Therefore

1. $f(n) \neq o(f(n))$ and
2. $f(n) \neq \omega(f(n))$

Note :

Hence small o and small ω are not reflexive relations

Symmetry over Ω

Definition:

- Let X be a non-empty set and R is a relation over X then R is said to be symmetric if
$$\forall a, b \in X, (a, b) \in R \Rightarrow (b, a) \in R$$

Example 1:

- Let P be a set of persons, and S be a relation over P such that if $(x, y) \in S$ then x has the same sign as y .
- This relation is symmetric because
$$(x, y) \in S \Rightarrow (y, x) \in S$$

Example 2:

- Let P be a set of all persons, and B be a relation over P such that if $(x, y) \in B$ then x is brother of y .
- This relation is not symmetric because
$$(\text{Anwer, Sadia}) \in B \Rightarrow (\text{Saida, Brother}) \notin B$$

Symmetry over Θ

Property : prove that

$$f(n) = \Theta(g(n)) \Leftrightarrow g(n) = \Theta(f(n))$$

Proof

- Since $f(n) = \Theta(g(n))$ i.e. $f(n) \in \Theta(g(n)) \Rightarrow$
 \exists constants $c_1, c_2 > 0$ and $n_0 \in \mathbb{N}$ such that
$$0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \quad \forall n \geq n_0 \quad (1)$$
$$(1) \Rightarrow 0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \Rightarrow 0 \leq f(n) \leq c_2 g(n)$$
$$\Rightarrow 0 \leq (1/c_2) f(n) \leq g(n) \quad (2)$$
$$(1) \Rightarrow 0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \Rightarrow 0 \leq c_1 g(n) \leq f(n)$$
$$\Rightarrow 0 \leq g(n) \leq (1/c_1) f(n) \quad (3)$$

Symmetry over Θ

From (2),(3): $0 \leq (1/c_2)f(n) \leq g(n) \wedge 0 \leq g(n) \leq (1/c_1)f(n)$

$$\Rightarrow 0 \leq (1/c_2)f(n) \leq g(n) \leq (1/c_1)f(n)$$

Suppose that $1/c_2 = c_3$, and $1/c_1 = c_4$,

Now the above equation implies that

$$0 \leq c_3f(n) \leq g(n) \leq c_4f(n), \forall n \geq n_0$$

$$\Rightarrow g(n) = \Theta(f(n)), \forall n \geq n_0$$

Hence it proves that,

$$f(n) = \Theta(g(n)) \Leftrightarrow g(n) = \Theta(f(n))$$

Exercise:

prove that big O, big omega Ω , little ω , and little o, do not satisfy the symmetry property.

Transitivity

Definition:

- Let X be a non-empty set and R is a relation over X then R is said to be transitive if

$$\forall a, b, c \in X, (a, b) \in R \wedge (b, c) \in R \Rightarrow (a, c) \in R$$

Example 1:

- Let P be a set of all persons, and B be a relation over P such that if $(x, y) \in B$ then x is brother of y .
- This relation is transitive this is because
$$(x, y) \in B \wedge (y, z) \in B \Rightarrow (x, z) \in B$$

Example 2:

- Let P be a set of all persons, and F be a relation over P such that if $(x, y) \in F$ then x is father of y .
- Of course this relation is not a transitive one this is because if $(x, y) \in F \wedge (y, z) \in F \Rightarrow (x, z) \notin F$

Transitivity Relation over Θ , Ω , O , o and ω

Prove the following

1. $f(n) = \Theta(g(n)) \ \& \ g(n) = \Theta(h(n)) \Rightarrow f(n) = \Theta(h(n))$
2. $f(n) = O(g(n)) \ \& \ g(n) = O(h(n)) \Rightarrow f(n) = O(h(n))$
3. $f(n) = \Omega(g(n)) \ \& \ g(n) = \Omega(h(n)) \Rightarrow f(n) = \Omega(h(n))$
4. $f(n) = o(g(n)) \ \& \ g(n) = o(h(n)) \Rightarrow f(n) = o(h(n))$
5. $f(n) = \omega(g(n)) \ \& \ g(n) = \omega(h(n)) \Rightarrow f(n) = \omega(h(n))$

Note

It is to be noted that all these algorithms complexity measuring notations are in fact relations which satisfy the transitive property.

Transitivity Relation over Θ

Property 1

$$f(n) = \Theta(g(n)) \ \& \ g(n) = \Theta(h(n)) \Rightarrow f(n) = \Theta(h(n))$$

Proof

- Since $f(n) = \Theta(g(n))$ i.e. $f(n) \in \Theta(g(n)) \Rightarrow$
 \exists constants $c_1, c_2 > 0$ and $n_{01} \in \mathbb{N}$ such that
$$0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n) \quad \forall n \geq n_{01} \quad (1)$$
- 2. Now since $g(n) = \Theta(h(n))$ i.e. $g(n) \in \Theta(h(n)) \Rightarrow$
 \exists constants $c_3, c_4 > 0$ and $n_{02} \in \mathbb{N}$ such that
$$0 \leq c_3 h(n) \leq g(n) \leq c_4 h(n) \quad \forall n \geq n_{02} \quad (2)$$
- 3. Now let us suppose that $n_0 = \max(n_{01}, n_{02})$

Transitivity Relation over Θ

4. Now we have to show that $f(n) = \Theta(h(n))$ i.e. we have to prove that

\exists constants $c_5, c_6 > 0$ and $n_0 \in \mathbb{N}$ such that

$$0 \leq c_5 h(n) \leq f(n) \leq c_6 h(n) \quad ?$$

$$(2) \Rightarrow 0 \leq c_3 h(n) \leq g(n) \leq c_4 h(n)$$

$$\Rightarrow 0 \leq c_3 h(n) \leq g(n) \quad (3)$$

$$(1) \Rightarrow 0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n)$$

$$\Rightarrow 0 \leq c_1 g(n) \leq f(n)$$

$$\Rightarrow 0 \leq g(n) \leq (1/c_1) f(n) \quad (4)$$

$$\text{From (3) and (4), } 0 \leq c_3 h(n) \leq g(n) \leq (1/c_1) f(n)$$

$$\Rightarrow 0 \leq c_1 c_3 h(n) \leq f(n) \quad (5)$$

Transitivity Relation over Θ

$$(1) \Rightarrow 0 \leq c_1 g(n) \leq f(n) \leq c_2 g(n)$$

$$\Rightarrow 0 \leq f(n) \leq c_2 g(n) \Rightarrow 0 \leq (1/c_2) f(n) \leq g(n) \quad (6)$$

$$(2) \Rightarrow 0 \leq c_3 h(n) \leq g(n) \leq c_4 h(n)$$

$$\Rightarrow 0 \leq g(n) \leq c_4 h(n) \quad (7)$$

$$\text{From (6) and (7), } 0 \leq (1/c_2) f(n) \leq g(n) \leq (c_4) h(n)$$

$$\Rightarrow 0 \leq (1/c_2) f(n) \leq (c_4) h(n)$$

$$\Rightarrow 0 \leq f(n) \leq c_2 c_4 h(n) \quad (8)$$

$$\text{From (5), (8), } 0 \leq c_1 c_3 h(n) \leq f(n) \wedge 0 \leq f(n) \leq c_2 c_4 h(n)$$

$$0 \leq c_1 c_3 h(n) \leq f(n) \leq c_2 c_4 h(n)$$

$$0 \leq c_5 h(n) \leq f(n) \leq c_6 h(n)$$

$$\text{And hence } f(n) = \Theta(h(n)) \quad \forall n \geq n_0$$

Transitivity Relation over Big O

Property 2

$$f(n) = O(g(n)) \ \& \ g(n) = O(h(n)) \Rightarrow f(n) = O(h(n))$$

Proof

- Since $f(n) = O(g(n))$ i.e. $f(n) \in O(g(n)) \Rightarrow$
 \exists constants $c_1 > 0$ and $n_{01} \in \mathbb{N}$ such that
$$0 \leq f(n) \leq c_1 g(n) \quad \forall n \geq n_{01} \quad (1)$$
- 2. Now since $g(n) = O(h(n))$ i.e. $g(n) \in O(h(n)) \Rightarrow$
 \exists constants $c_2 > 0$ and $n_{02} \in \mathbb{N}$ such that
$$0 \leq g(n) \leq c_2 h(n) \quad \forall n \geq n_{02} \quad (2)$$
- 3. Now let us suppose that $n_0 = \max (n_{01}, n_{02})$

Transitivity Relation over Big O

Now we have to two equations

$$0 \leq f(n) \leq c_1 g(n) \quad \forall n \geq n_{01} \quad (1)$$

$$0 \leq g(n) \leq c_2 h(n) \quad \forall n \geq n_{02} \quad (2)$$

$$(2) \Rightarrow 0 \leq c_1 g(n) \leq c_1 c_2 h(n) \quad \forall n \geq n_{02} \quad (3)$$

From (1) and (3)

$$0 \leq f(n) \leq c_1 g(n) \leq c_1 c_2 h(n)$$

Now suppose that $c_3 = c_1 c_2$

$$0 \leq f(n) \leq c_1 c_2 h(n)$$

And hence $f(n) = O(h(n)) \quad \forall n \geq n_0$

Transitivity Relation over Big Ω

Property 3

$$f(n) = \Omega(g(n)) \ \& \ g(n) = \Omega(h(n)) \Rightarrow f(n) = \Omega(h(n))$$

Proof

- Since $f(n) = \Omega(g(n)) \Rightarrow$
 \exists constants $c_1 > 0$ and $n_{01} \in \mathbb{N}$ such that
$$0 \leq c_1 g(n) \leq f(n) \qquad \forall \ n \geq n_{01} \qquad (1)$$
- 2. Now since $g(n) = \Omega(h(n)) \Rightarrow$
 \exists constants $c_2 > 0$ and $n_{02} \in \mathbb{N}$ such that
$$0 \leq c_2 h(n) \leq g(n) \qquad \forall \ n \geq n_{02} \qquad (2)$$
- 3. Suppose that $n_0 = \max (n_{01}, n_{02})$

Transitivity Relation over Big Ω

4. We have to show that $f(n) = \Omega(h(n))$ i.e. we have to prove that

\exists constants $c_3 > 0$ and $n_0 \in \mathbb{N}$ such that

$$0 \leq c_3 h(n) \leq f(n) \quad \forall n \geq n_0 \quad ?$$

$$(2) \Rightarrow 0 \leq c_2 h(n) \leq g(n)$$

$$(1) \Rightarrow 0 \leq c_1 g(n) \leq f(n)$$

$$\Rightarrow 0 \leq g(n) \leq (1/c_1)f(n) \quad (3)$$

From (2) and (3), $0 \leq c_2 h(n) \leq g(n) \leq (1/c_1)f(n)$

$$\Rightarrow 0 \leq c_1 c_2 h(n) \leq f(n) \text{ hence } f(n) = \Omega(h(n)), \forall n \geq n_0$$

Transitivity Relation over *little o*

Property 4

$$f(n) = o(g(n)) \ \& \ g(n) = o(h(n)) \Rightarrow f(n) = o(h(n))$$

Proof

- Since $f(n) = o(g(n))$ i.e. $f(n) \in o(g(n)) \Rightarrow$
 \exists constants $c_1 > 0$ and $n_{01} \in \mathbb{N}$ such that
$$0 \leq f(n) < c_1 g(n) \quad \forall n \geq n_{01} \quad (1)$$
- 2. Now since $g(n) = o(h(n))$ i.e. $g(n) \in o(h(n)) \Rightarrow$
 \exists constants $c_2 > 0$ and $n_{02} \in \mathbb{N}$ such that
$$0 \leq g(n) < c_2 h(n) \quad \forall n \geq n_{02} \quad (2)$$
- 3. Now let us suppose that $n_0 = \max (n_{01}, n_{02})$

Transitivity Relation over *little o*

Now we have to two equations

$$0 \leq f(n) < c_1 g(n) \quad \forall n \geq n_{01} \quad (1)$$

$$0 \leq g(n) < c_2 h(n) \quad \forall n \geq n_{01} \quad (2)$$

$$(2) \Rightarrow 0 \leq c_1 g(n) < c_1 c_2 h(n) \quad \forall n \geq n_{02} \quad (3)$$

From (1) and (3)

$$0 \leq f(n) \leq c_1 g(n) < c_1 c_2 h(n)$$

Now suppose that $c_3 = c_1 c_2$

$$0 \leq f(n) < c_1 c_2 h(n)$$

And hence $f(n) = o(h(n)) \quad \forall n \geq n_{01}$

Transitivity Relation over little ω

Property 5

$$f(n) = \omega(g(n)) \ \& \ g(n) = \omega(h(n)) \Rightarrow f(n) = \omega(h(n))$$

Proof

- Since $f(n) = \omega(g(n)) \Rightarrow$

\exists constants $c_1 > 0$ and $n_{01} \in \mathbb{N}$ such that

$$0 \leq c_1 g(n) < f(n) \qquad \forall n \geq n_{01} \qquad (1)$$

2. Now since $g(n) = \omega(h(n)) \Rightarrow$

\exists constants $c_2 > 0$ and $n_{02} \in \mathbb{N}$ such that

$$0 \leq c_2 h(n) < g(n) \qquad \forall n \geq n_{02} \qquad (2)$$

3. Suppose that $n_0 = \max (n_{01}, n_{02})$

Transitivity Relation over little ω

4. We have to show that $f(n) = \omega(h(n))$ i.e. we have to prove that

\exists constants $c_3 > 0$ and $n_0 \in \mathbb{N}$ such that

$$0 \leq c_3 h(n) \leq f(n) \quad \forall n \geq n_0 \quad ?$$

$$(2) \Rightarrow 0 \leq c_2 h(n) < g(n)$$

$$(1) \Rightarrow 0 \leq c_1 g(n) < f(n)$$

$$\Rightarrow 0 \leq g(n) < (1/c_1)f(n) \quad (3)$$

$$\text{From (2) and (3), } 0 \leq c_2 h(n) \leq g(n) < (1/c_1)f(n)$$

$$\Rightarrow 0 \leq c_1 c_2 h(n) < f(n) \text{ hence } f(n) = \omega(h(n)), \forall n \geq n_0$$

Transpose Symmetry

Property 1

Prove that $f(n) = O(g(n)) \Leftrightarrow g(n) = \Omega(f(n))$

Proof

Since $f(n) = O(g(n)) \Rightarrow$

\exists constants $c > 0$ and $n_0 \in \mathbb{N}$ such that

$$0 \leq f(n) \leq cg(n) \quad \forall n \geq n_0$$

Dividing both side by c

$$0 \leq (1/c)f(n) \leq g(n) \quad \forall n \geq n_0$$

Put $1/c = c'$

$$0 \leq c'f(n) \leq g(n) \quad \forall n \geq n_0$$

Hence, $g(n) = \Omega(f(n))$

Transpose Symmetry

Property 2

Prove that $f(n) = o(g(n)) \Leftrightarrow g(n) = \omega(f(n))$

Proof

Since $f(n) = o(g(n)) \Rightarrow$

\exists constants $c > 0$ and $n_0 \in \mathbb{N}$ such that

$$0 \leq f(n) < cg(n) \quad \forall n \geq n_0$$

Dividing both side by c

$$0 \leq (1/c)f(n) < g(n) \quad \forall n \geq n_0$$

Put $1/c = c'$

$$0 \leq c'f(n) < g(n) \quad \forall n \geq n_0$$

Hence, $g(n) = \omega(f(n))$

Relation between Q, W, O

Trichotomy property over real numbers

- For any two real numbers a and b , exactly one of the following must hold: $a < b$, $a = b$, or $a > b$.
- The asymptotic comparison of two functions f and g and the comparison of two real numbers a and b .

Trichotomy property over Θ , Ω and O

1. $f(n) = O(g(n)) \approx a \leq b$
2. $f(n) = \Omega(g(n)) \approx a \geq b$
3. $f(n) = \Theta(g(n)) \approx a = b$
4. $f(n) = o(g(n)) \approx a < b$
5. $f(n) = \omega(g(n)) \approx a > b$

Some Other Standard Notations

Monotonicity

- monotonically increasing if $m \leq n \Rightarrow f(m) \leq f(n)$.
- monotonically decreasing if $m \geq n \Rightarrow f(m) \geq f(n)$.
- strictly increasing if $m < n \Rightarrow f(m) < f(n)$.
- strictly decreasing if $m > n \Rightarrow f(m) > f(n)$.

Polynomials

- Given a positive integer d , a polynomial in n of degree d is a function of the form given below, a_i are coefficient of polynomial.

$$p(n) = \sum_{i=0}^d a_i n^i$$

Standard Logarithms Notations

Some Definitions

Exponent

- $x = \log_b a$ is the exponent for $a = b^x$.

Natural log

- $\ln a = \log_e a$

Binary log

- $\lg a = \log_2 a$

Square of log

- $\lg^2 a = (\lg a)^2$

Log of Log

- $\lg \lg a = \lg (\lg a)$

Standard Logarithms Notations

$$a = b^{\log_b a}$$

$$\log_c (ab) = \log_c a + \log_c b$$

$$\log_b a^n = n \log_b a$$

$$\log_b a = \frac{\log_c a}{\log_c b}$$

$$\log_b (1/a) = -\log_b a$$

$$\log_b a = \frac{1}{\log_a b}$$

$$a^{\log_b c} = c^{\log_b a}$$