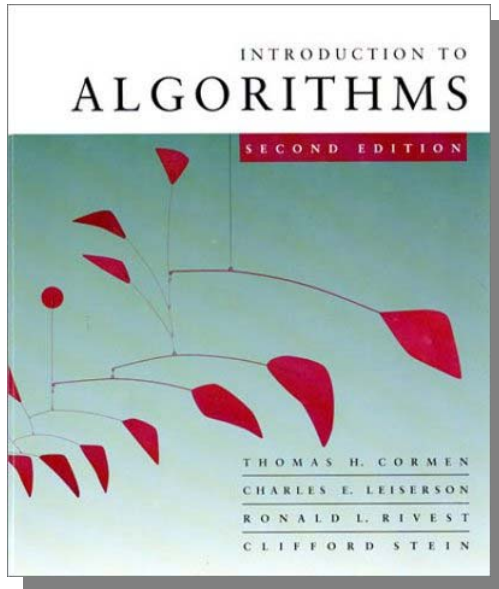


Introduction to Algorithms

6.046J/18.401J



LECTURE 2

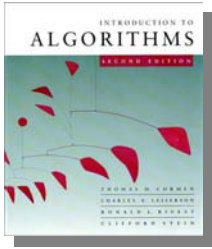
Asymptotic Notation

- O -, Ω -, and Θ -notation

Recurrences

- Substitution method
- Iterating the recurrence
- Recursion tree
- Master method

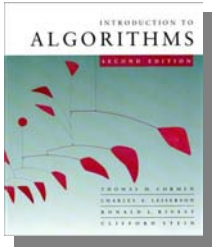
Prof. Charles E. Leiserson



Asymptotic notation

O -notation (upper bounds):

We write $f(n) = O(g(n))$ if there exist constants $c > 0$, $n_0 > 0$ such that $0 \leq f(n) \leq cg(n)$ for all $n \geq n_0$.

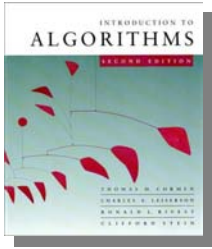


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EXAMPLE: $2n^2 = O(n^3)$ ($c = 1$, $n_0 = 2$)



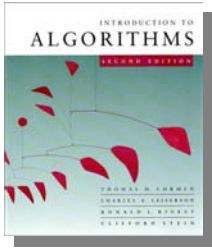
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*functions,
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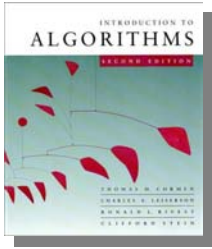
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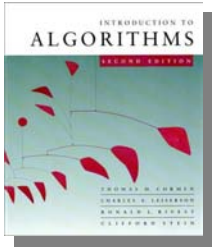
*functions,
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*funny, “one-way”
equality*



Set definition of O -notation

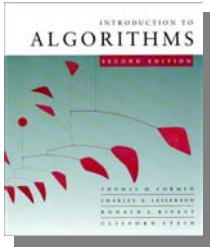
$O(g(n)) = \{ f(n) : \text{there exist constants } c > 0, n_0 > 0 \text{ such that } 0 \leq f(n) \leq cg(n) \text{ for all } n \geq n_0 \}$



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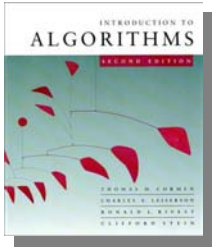


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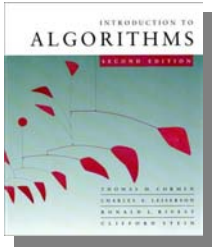
EXAMPLE: $2n^2 \in O(n^3)$

(*Logicians:* $\lambda n. 2n^2 \in O(\lambda n. n^3)$, but it's convenient to be sloppy, as long as we understand what's *really* going on.)



Macro substitution

Convention: A set in a formula represents an anonymous function in the set.



Macro substitution

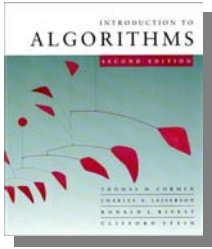
Convention: A set in a formula represents an anonymous function in the set.

EXAMPLE: $f(n) = n^3 + O(n^2)$

means

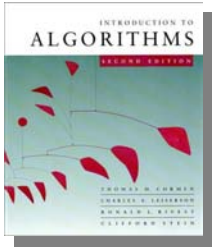
$$f(n) = n^3 + h(n)$$

for some $h(n) \in O(n^2)$.



Ω -notation (lower bounds)

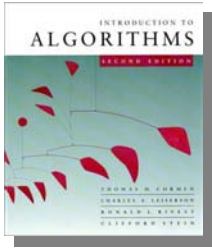
O -notation is an *upper-bound* notation. It makes no sense to say $f(n)$ is at least $O(n^2)$.



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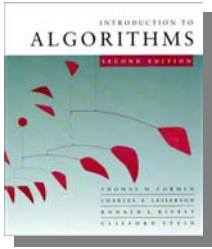
$\Omega(g(n)) = \{ f(n) : \text{there exist constants } c > 0, n_0 > 0 \text{ such that } 0 \leq cg(n) \leq f(n) \text{ for all } n \geq n_0 \}$



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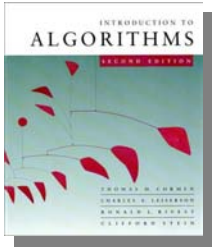
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EXAMPLE: $\sqrt{n} = \Omega(\lg n)$



Θ -notation (tight bounds)

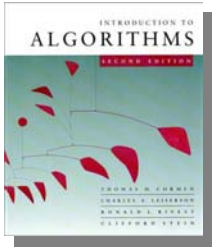
$$\Theta(g(n)) = O(g(n)) \cap \Omega(g(n))$$



Θ -notation (tight bounds)

$$\Theta(g(n)) = O(g(n)) \cap \Omega(g(n))$$

EXAMPLE: $\frac{1}{2}n^2 - 2n = \Theta(n^2)$

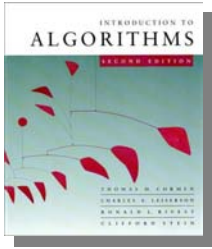


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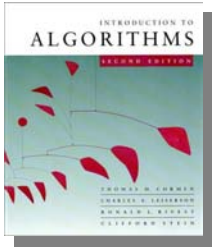
EXAMPLE: $\frac{1}{2}n^2 - 2n = \Theta(n^2)$

Theorem. The leading constant and low-order terms don't matter. \square



Solving recurrences

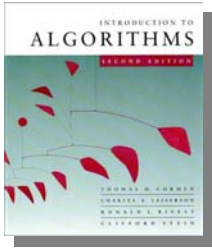
- The analysis of merge sort from *Lecture 1* required us to solve a recurrence.
- Recurrences are like solving integrals, differential equations, etc.
 - Learn a few tricks.
- *Lecture 3*: Applications of recurrences to divide-and-conquer algorithms.



Substitution method

The most general method:

- 1. *Guess*** the form of the solution.
- 2. *Verify*** by induction.
- 3. *Solve*** for constants.



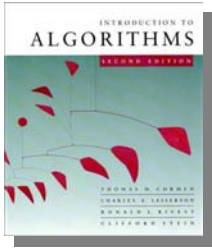
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EXAMPLE: $T(n) = 4T(n/2) + n$

- [Assume that $T(1) = \Theta(1)$.]
- Guess $O(n^3)$. (Prove O and Ω separately.)
- Assume that $T(k) \leq ck^3$ for $k < n$.
- Prove $T(n) \leq cn^3$ by induction.

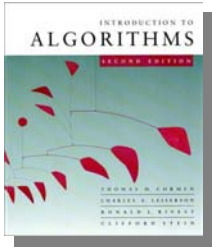


Example of substitution

$$\begin{aligned}T(n) &= 4T(n/2) + n \\ &\leq 4c(n/2)^3 + n \\ &= (c/2)n^3 + n \\ &= cn^3 - ((c/2)n^3 - n) \leftarrow \textit{desired} - \textit{residual} \\ &\leq cn^3 \leftarrow \textit{desired}\end{aligned}$$

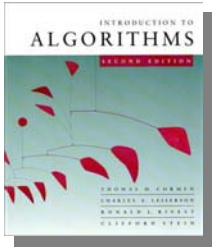
whenever $(c/2)n^3 - n \geq 0$, for example,
if $c \geq 2$ and $n \geq 1$.

residual



Example (continued)

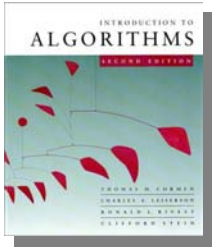
- We must also handle the initial conditions, that is, ground the induction with base cases.
- **Base:** $T(n) = \Theta(1)$ for all $n < n_0$, where n_0 is a suitable constant.
- For $1 \leq n < n_0$, we have “ $\Theta(1)$ ” $\leq cn^3$, if we pick c big enough.



Example (continued)

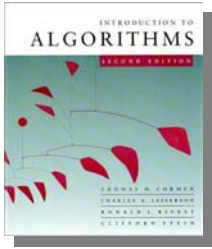
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This bound is not tight!



A tighter upper bound?

We shall prove that $T(n) = O(n^2)$.

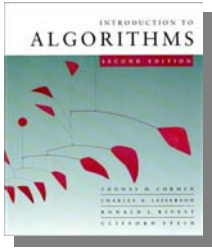


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We shall prove that $T(n) = O(n^2)$.

Assume that $T(k) \leq ck^2$ for $k < n$:

$$\begin{aligned}T(n) &= 4T(n/2) + n \\ &\leq 4c(n/2)^2 + n \\ &= cn^2 + n \\ &= O(n^2)\end{aligned}$$



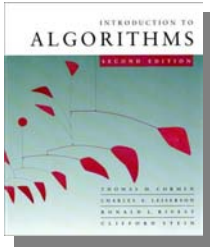
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~~$= O(n^2)$~~ **Wrong!** We must prove the I.H.



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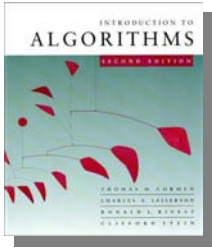
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$$= cn^2 - (-n) \quad [\text{desired} - \text{residual}]$$

$\leq cn^2$ for **no** choice of $c > 0$. Lose!

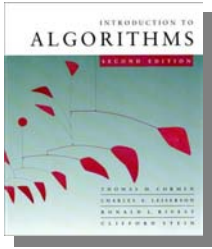


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IDEA: Strengthen the inductive hypothesis.

- *Subtract* a low-order term.

Inductive hypothesis: $T(k) \leq c_1k^2 - c_2k$ for $k < n$.



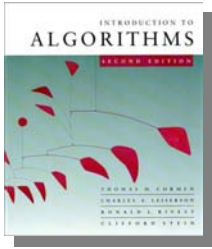
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$$\begin{aligned}T(n) &= 4T(n/2) + n \\&= 4(c_1(n/2)^2 - c_2(n/2)) + n \\&= c_1n^2 - 2c_2n + n \\&= c_1n^2 - c_2n - (c_2n - n) \\&\leq c_1n^2 - c_2n \quad \text{if } c_2 \geq 1.\end{aligned}$$



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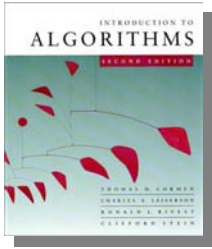
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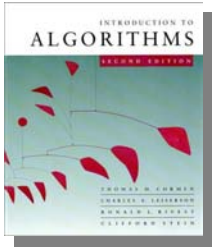
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Pick c_1 big enough to handle the initial conditions.



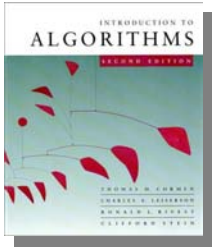
Recursion-tree method

- A recursion tree models the costs (time) of a recursive execution of an algorithm.
- The recursion-tree method can be unreliable, just like any method that uses ellipses (...).
- The recursion-tree method promotes intuition, however.
- The recursion tree method is good for generating guesses for the substitution method.



Example of recursion tree

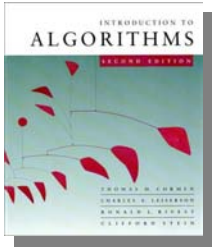
Solve $T(n) = T(n/4) + T(n/2) + n^2$:



Example of recursion tree

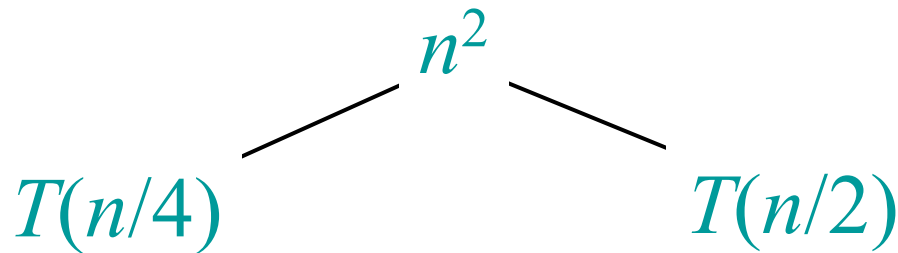
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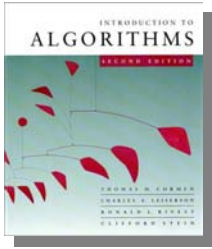
$$T(n)$$



Example of recursion tree

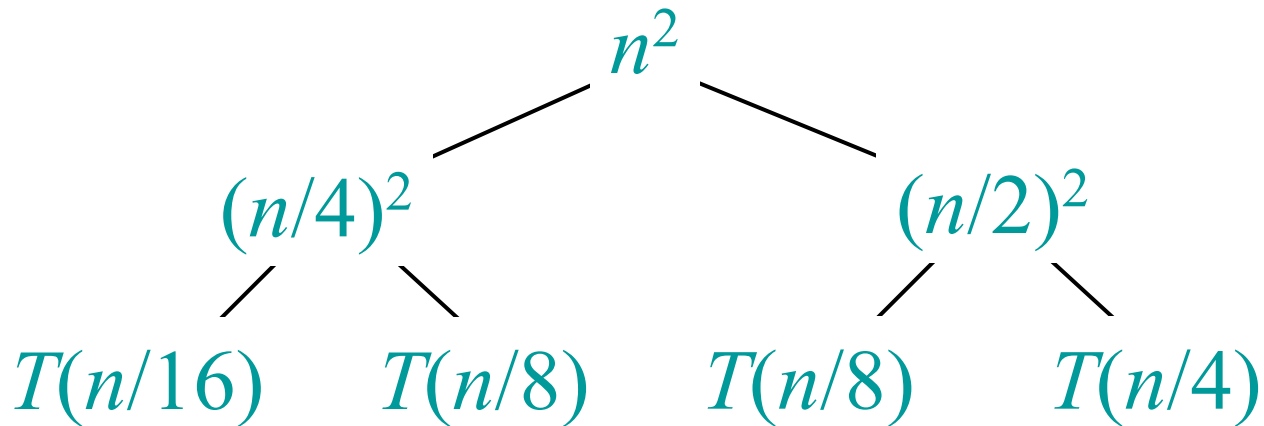
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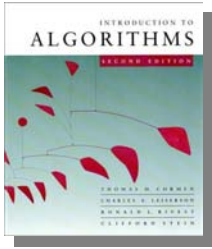




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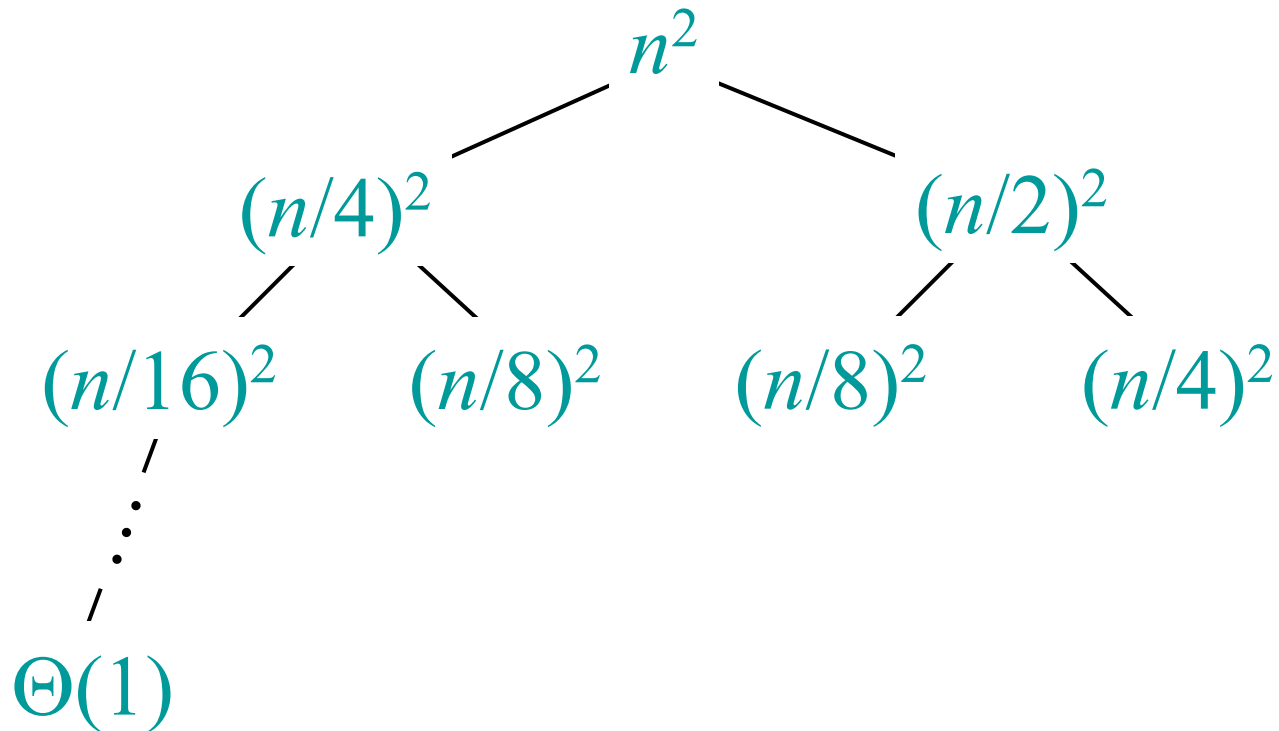
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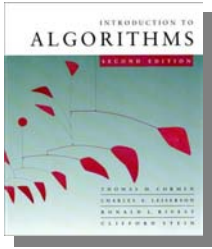




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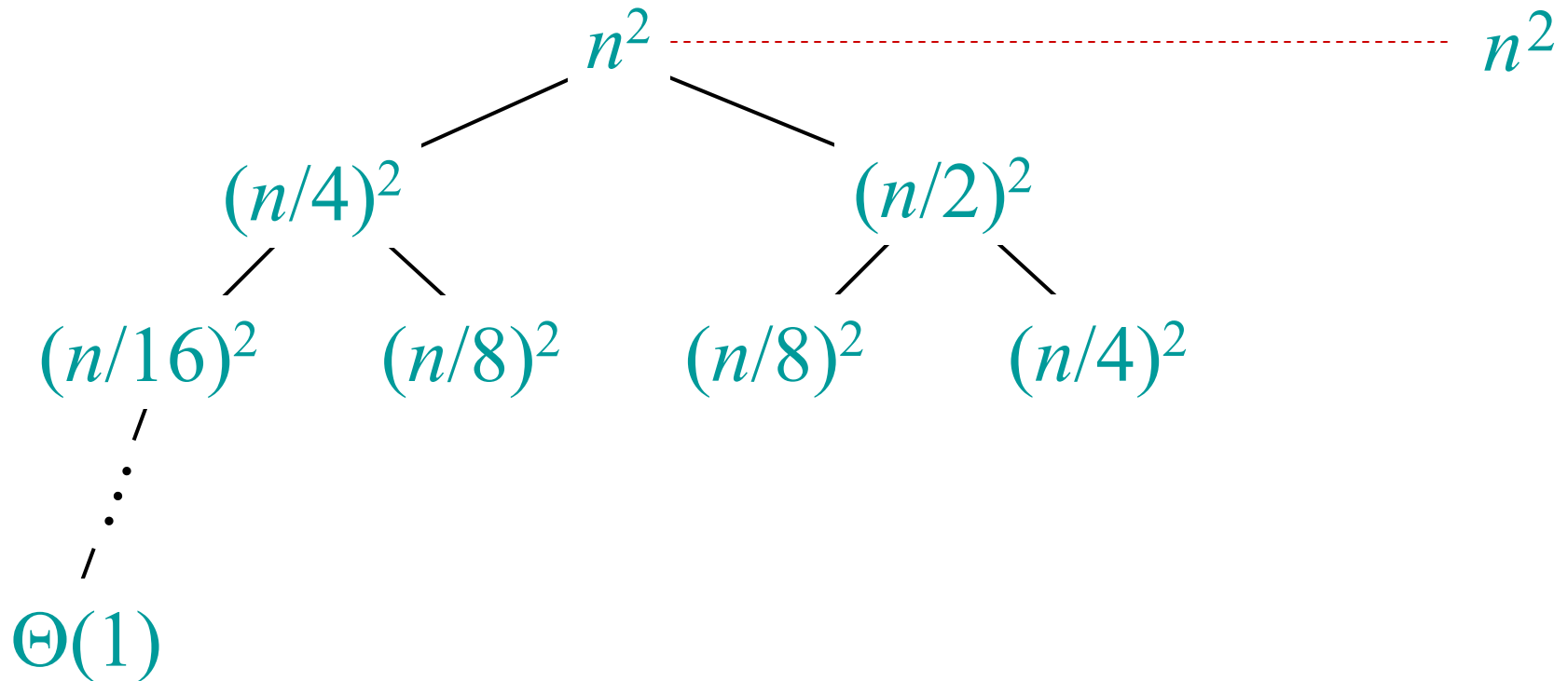
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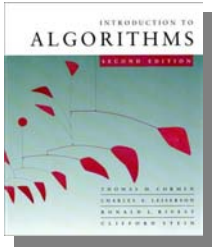




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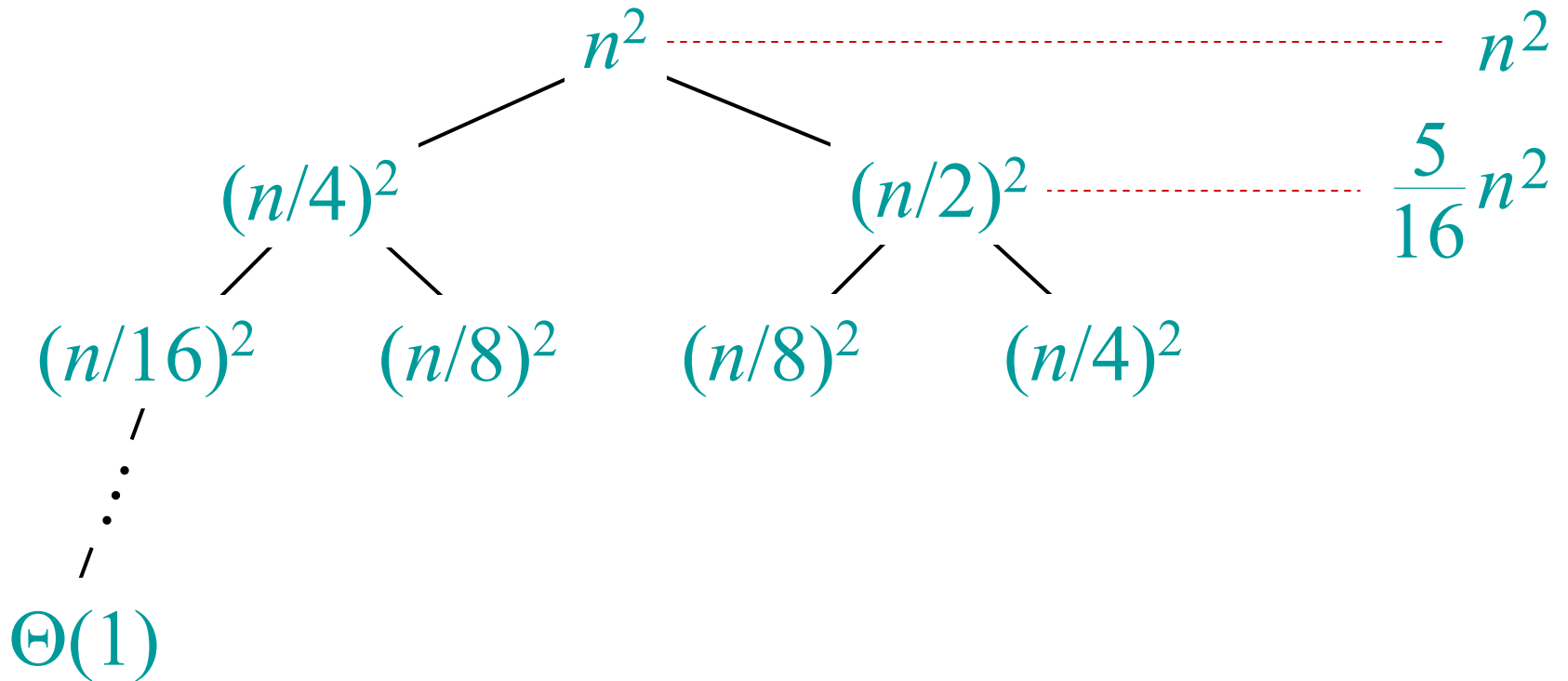
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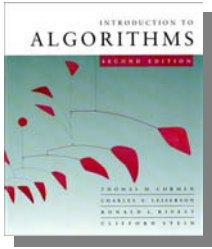




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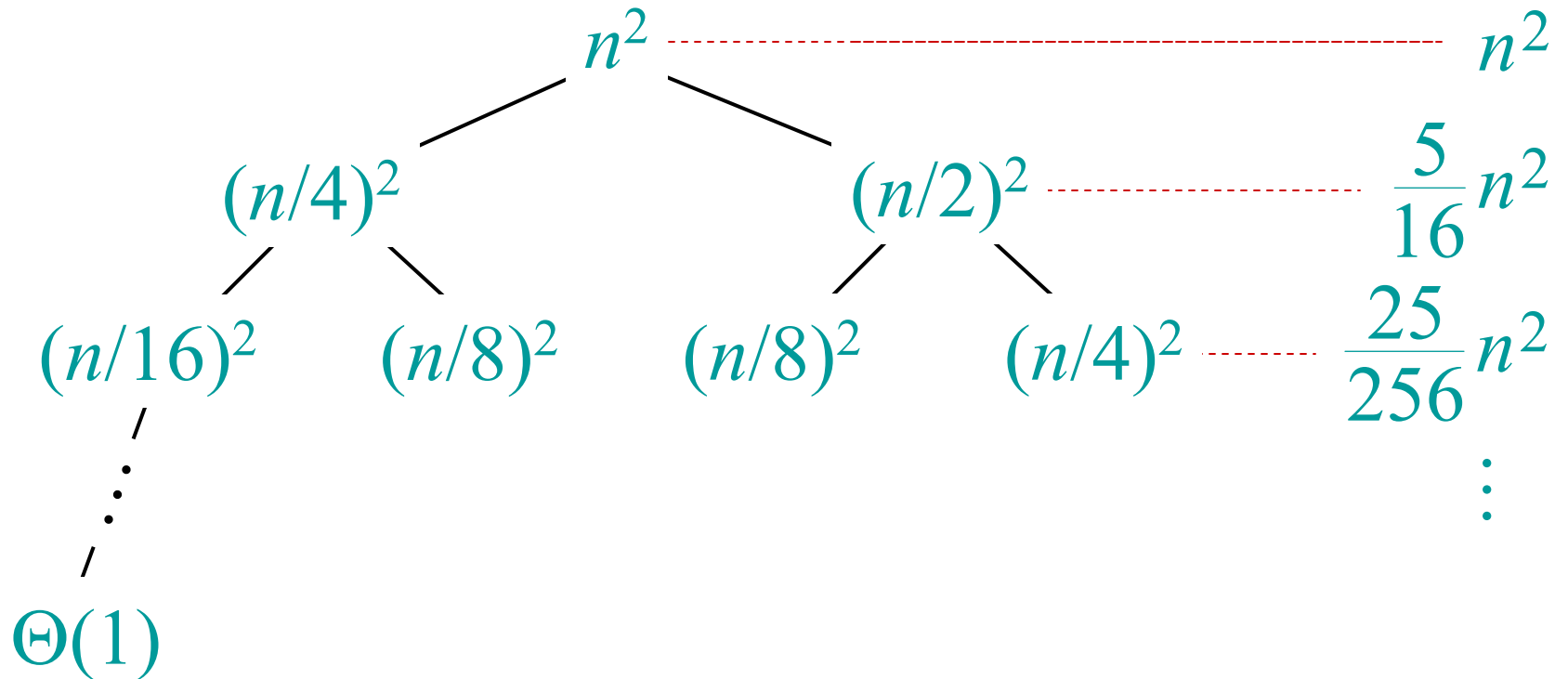
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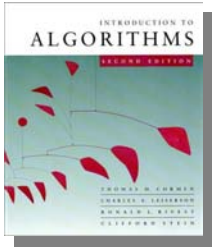




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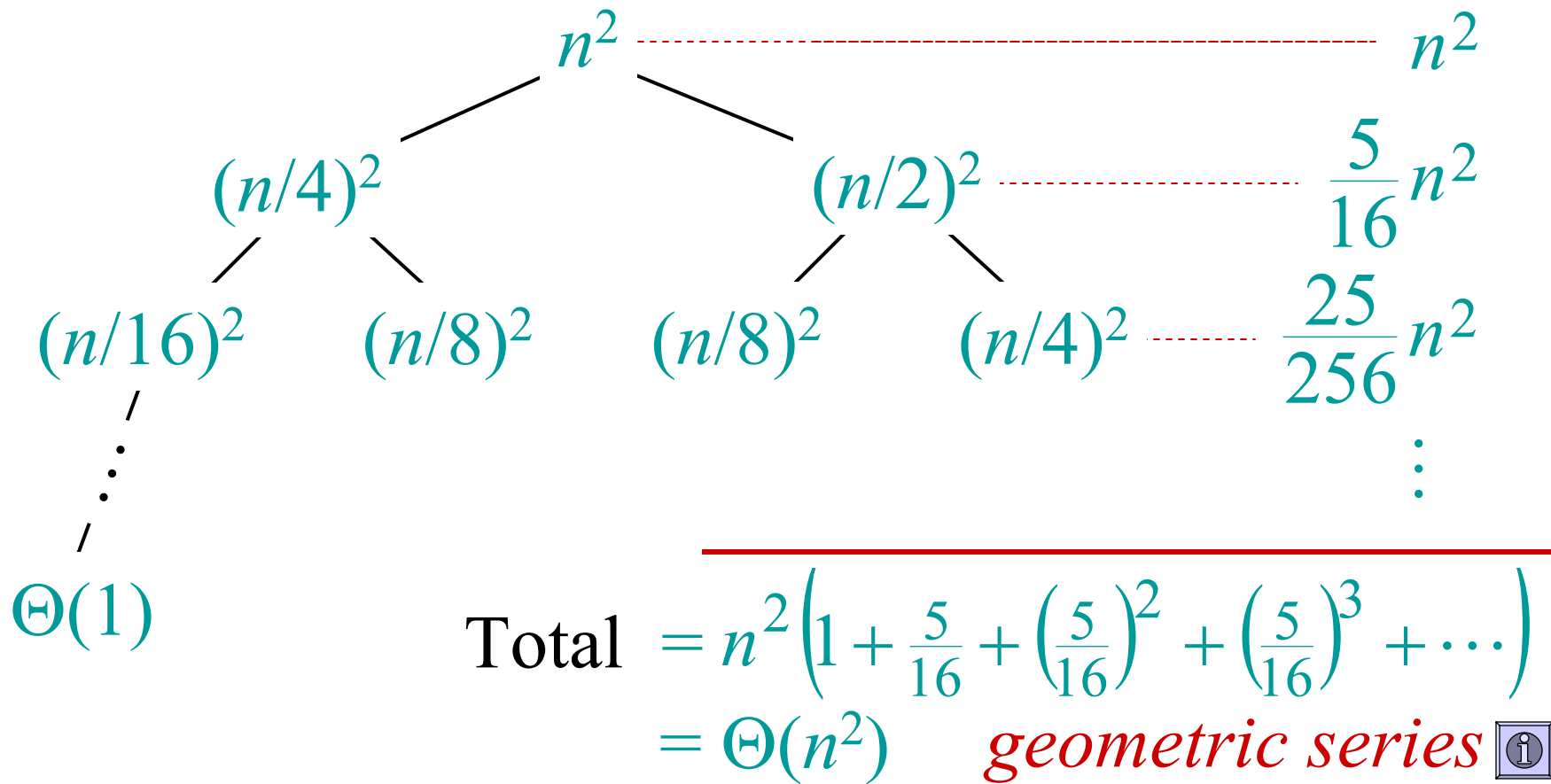
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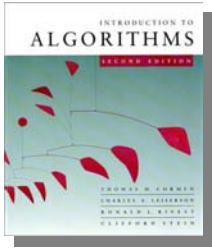




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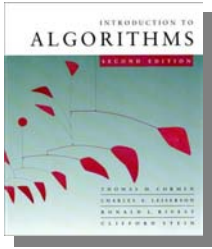


The master method

The master method applies to recurrences of the form

$$T(n) = aT(n/b) + f(n),$$

where $a \geq 1$, $b > 1$, and f is asymptotically positive.



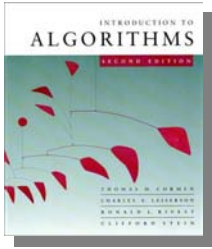
Three common cases

Compare $f(n)$ with $n^{\log_b a}$:

1. $f(n) = O(n^{\log_b a - \varepsilon})$ for some constant $\varepsilon > 0$.

- $f(n)$ grows polynomially slower than $n^{\log_b a}$ (by an n^ε factor).

Solution: $T(n) = \Theta(n^{\log_b a})$.



Three common cases

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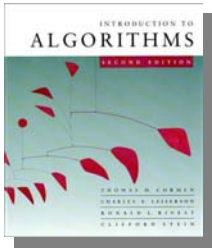
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Solution: $T(n) = \Theta(n^{\log_b a})$.

2. $f(n) = \Theta(n^{\log_b a} \lg^k n)$ for some constant $k \geq 0$.

- $f(n)$ and $n^{\log_b a}$ grow at similar rates.

Solution: $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$.



Three common cases (cont.)

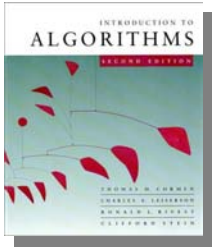
Compare $f(n)$ with $n^{\log_b a}$:

3. $f(n) = \Omega(n^{\log_b a + \varepsilon})$ for some constant $\varepsilon > 0$.

- $f(n)$ grows polynomially faster than $n^{\log_b a}$ (by an n^ε factor),

and $f(n)$ satisfies the **regularity condition** that $af(n/b) \leq cf(n)$ for some constant $c < 1$.

Solution: $T(n) = \Theta(f(n))$.



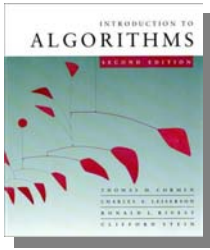
Examples

Ex. $T(n) = 4T(n/2) + n$

$$a = 4, b = 2 \Rightarrow n^{\log_b a} = n^2; f(n) = n.$$

CASE 1: $f(n) = O(n^{2-\epsilon})$ for $\epsilon = 1$.

$$\therefore T(n) = \Theta(n^2).$$



Examples

Ex. $T(n) = 4T(n/2) + n$

$$a = 4, b = 2 \Rightarrow n^{\log_b a} = n^2; f(n) = n.$$

CASE 1: $f(n) = O(n^{2-\epsilon})$ for $\epsilon = 1$.

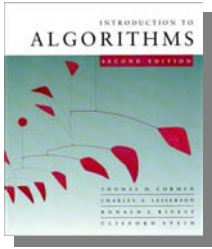
$$\therefore T(n) = \Theta(n^2).$$

Ex. $T(n) = 4T(n/2) + n^2$

$$a = 4, b = 2 \Rightarrow n^{\log_b a} = n^2; f(n) = n^2.$$

CASE 2: $f(n) = \Theta(n^2 \lg^0 n)$, that is, $k = 0$.

$$\therefore T(n) = \Theta(n^2 \lg n).$$



Examples

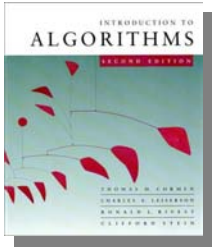
Ex. $T(n) = 4T(n/2) + n^3$

$a = 4, b = 2 \Rightarrow n^{\log_b a} = n^2; f(n) = n^3.$

CASE 3: $f(n) = \Omega(n^{2 + \epsilon})$ for $\epsilon = 1$

and $4(n/2)^3 \leq cn^3$ (reg. cond.) for $c = 1/2.$

$\therefore T(n) = \Theta(n^3).$



Examples

Ex. $T(n) = 4T(n/2) + n^3$

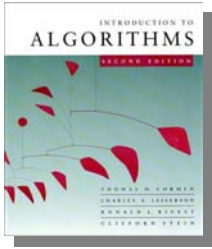
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Ex. $T(n) = 4T(n/2) + n^2/\lg n$

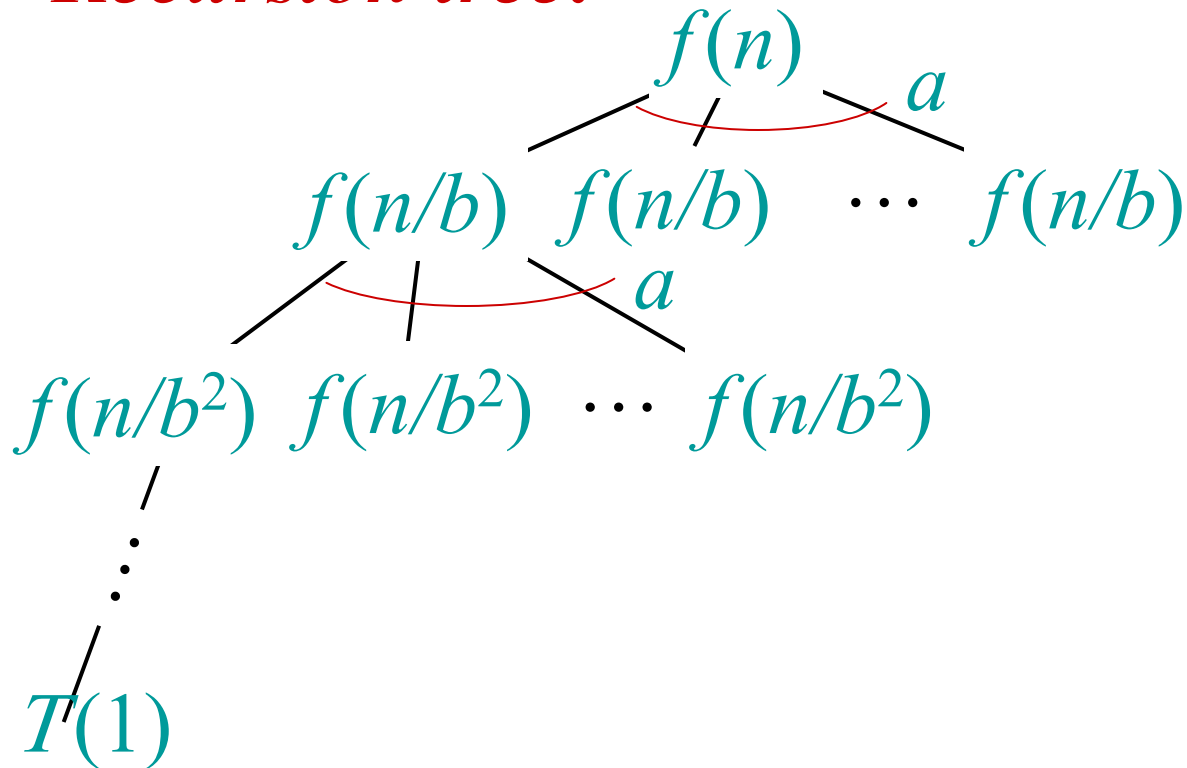
$$a = 4, b = 2 \Rightarrow n^{\log_b a} = n^2; f(n) = n^2/\lg n.$$

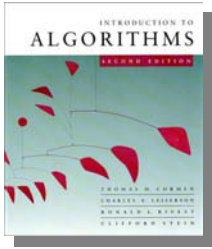
Master method does not apply. In particular, for every constant $\varepsilon > 0$, we have $n^\varepsilon = \omega(\lg n)$.



Idea of master theorem

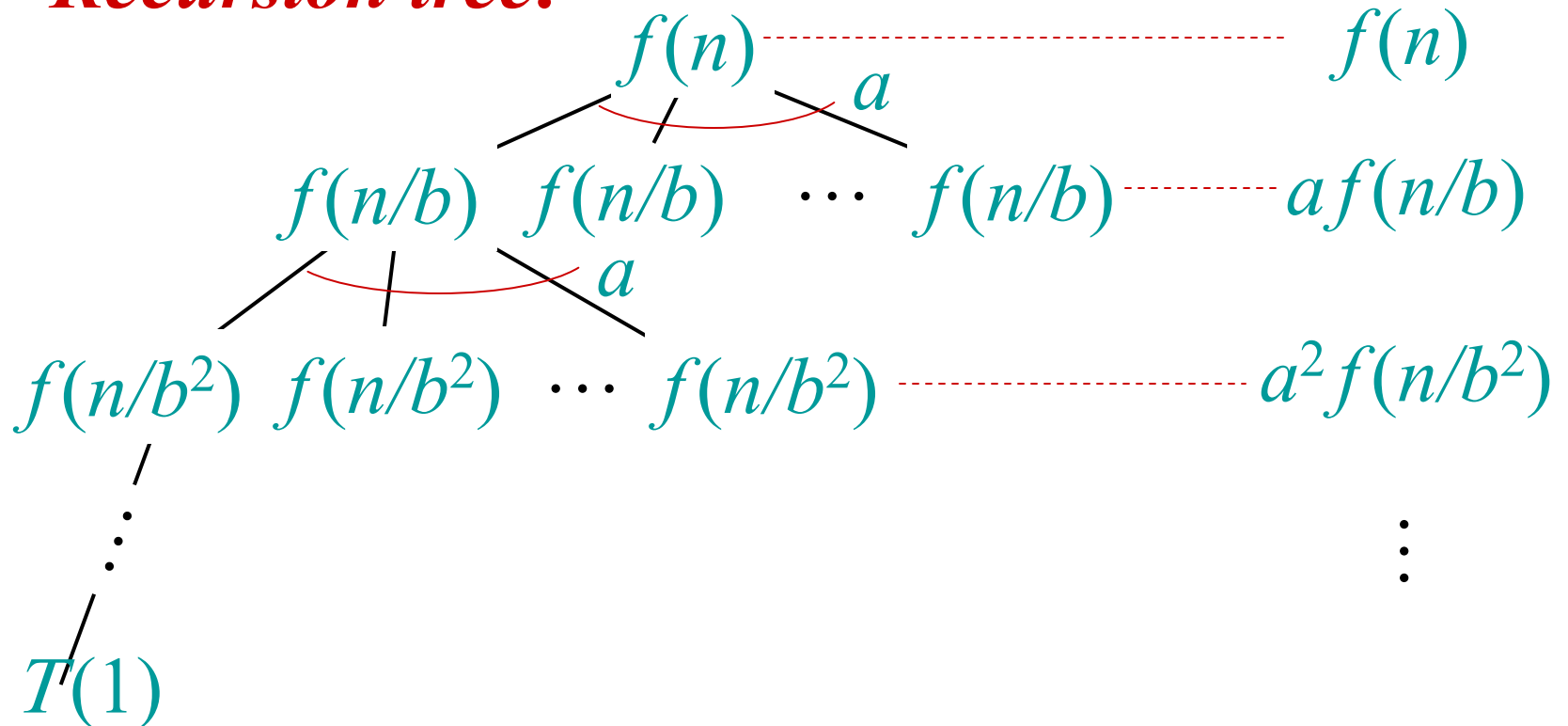
Recursion tree:

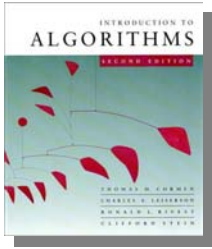




Idea of master theorem

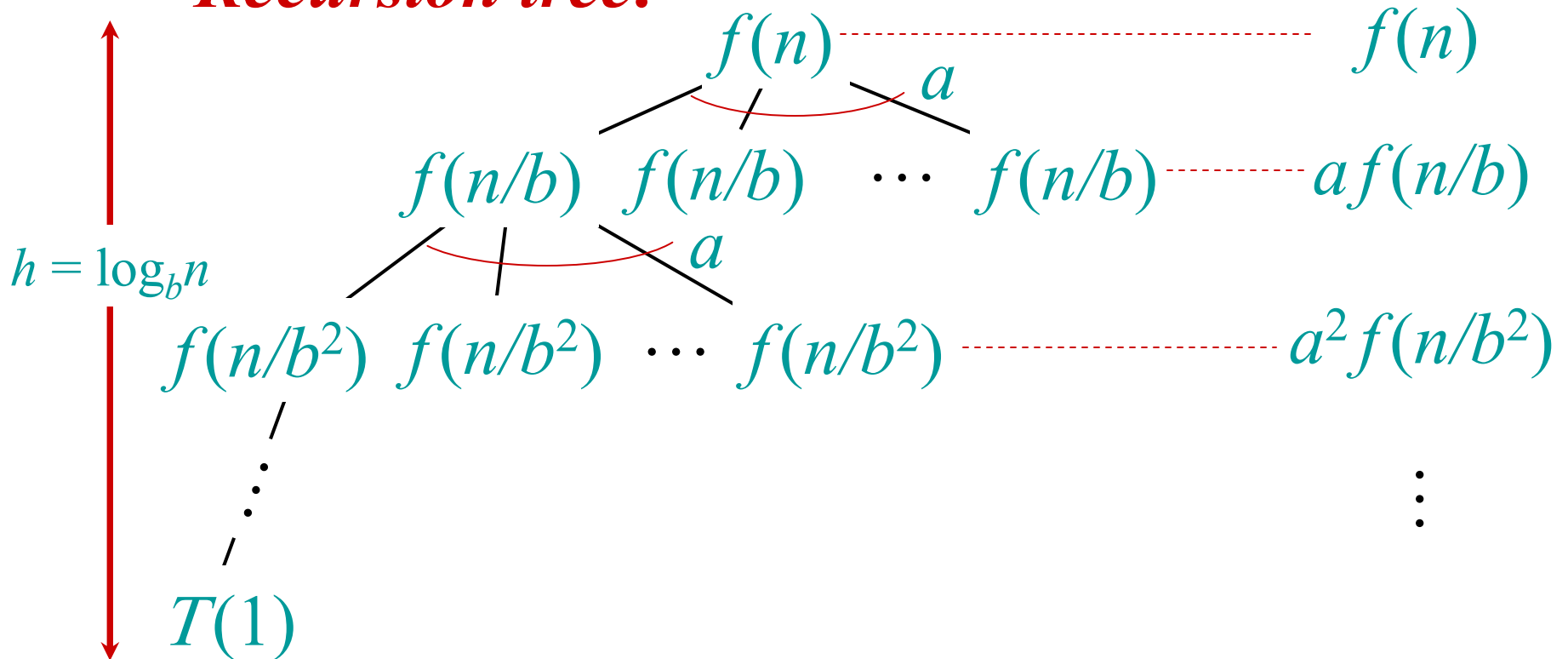
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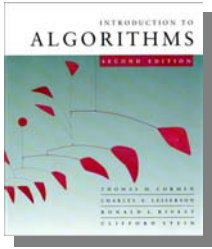




Idea of master theorem

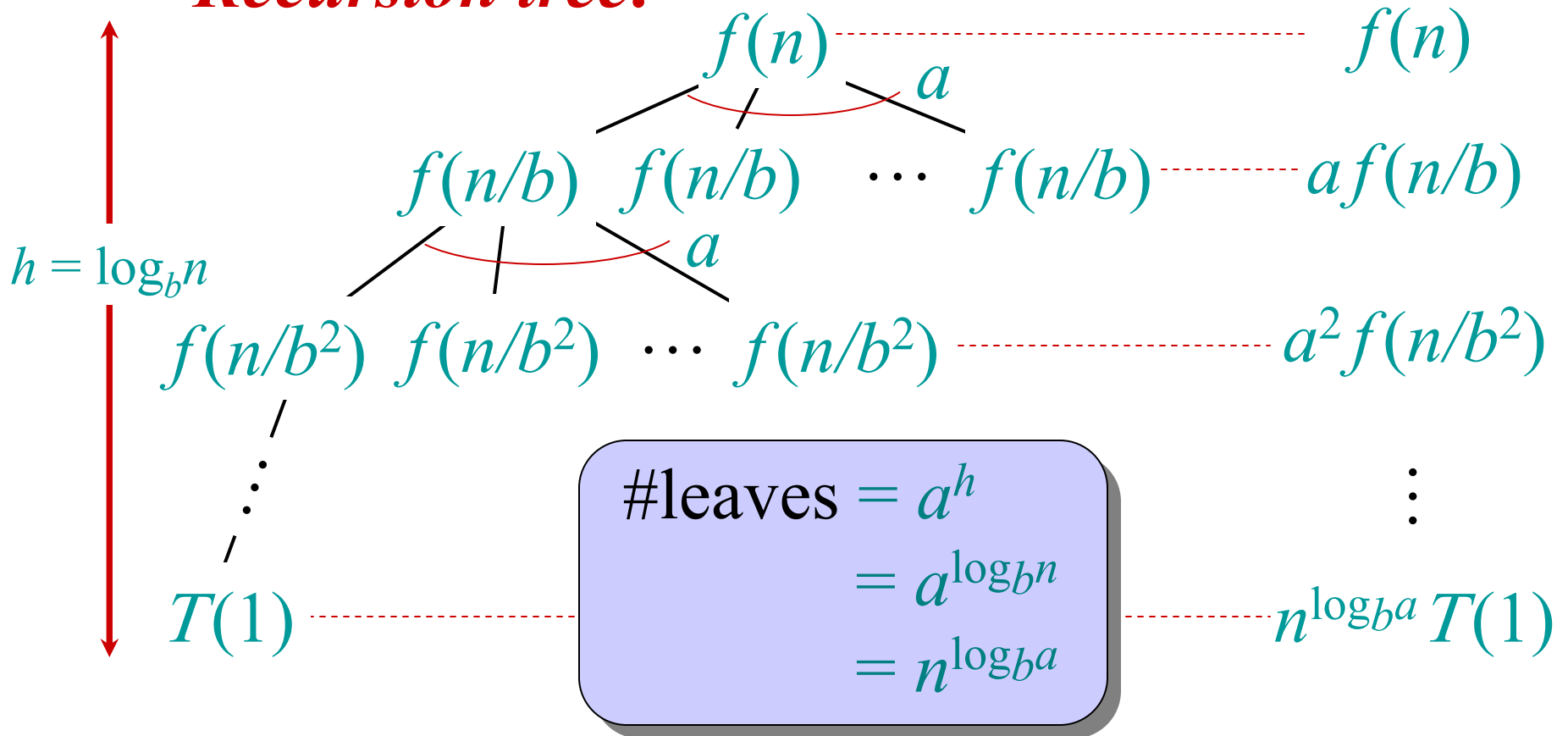
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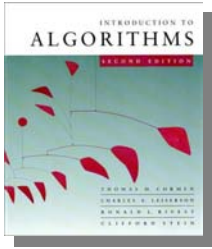




Idea of master theorem

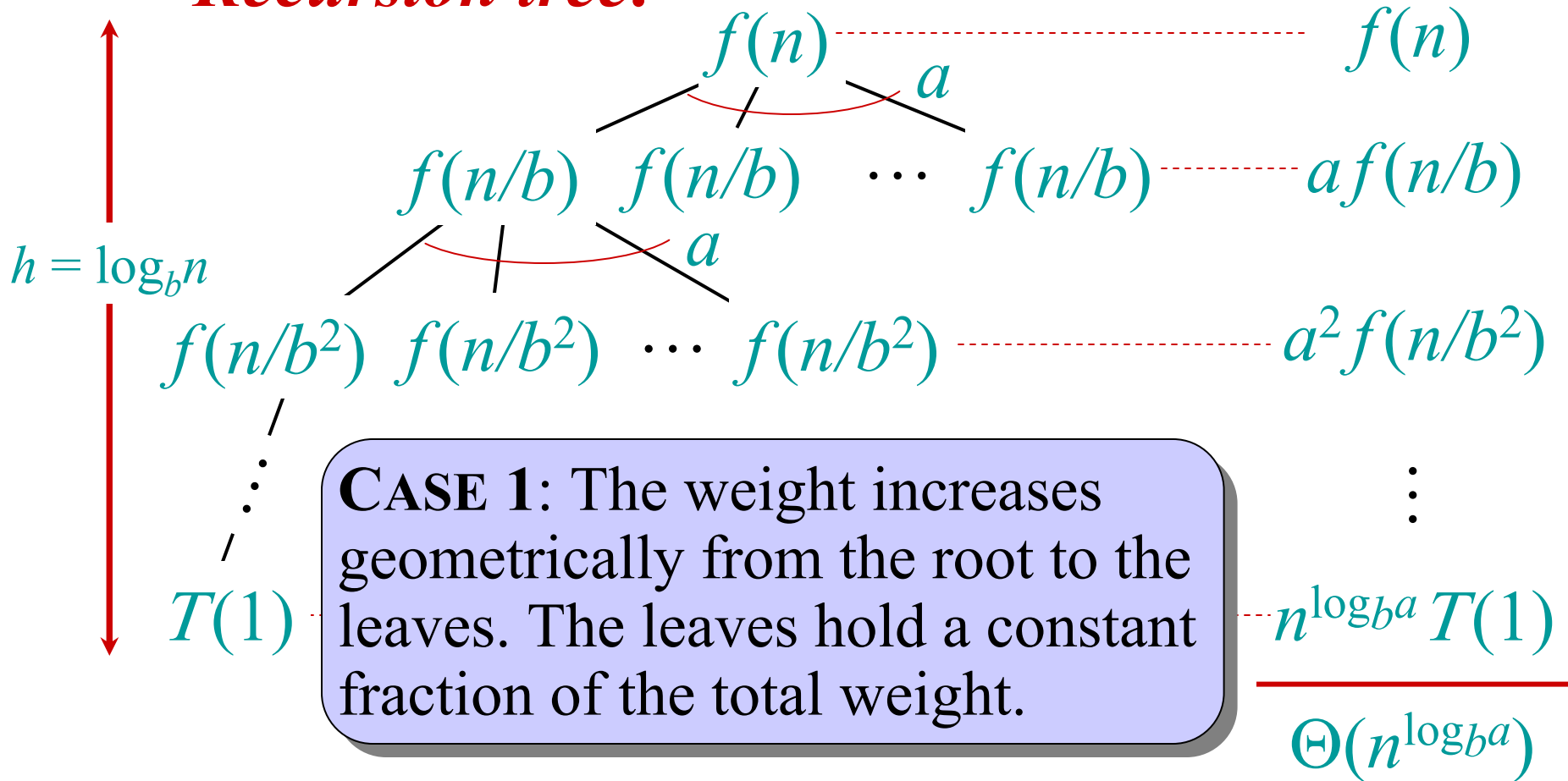
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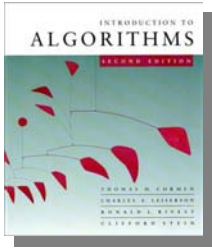




Idea of master theorem

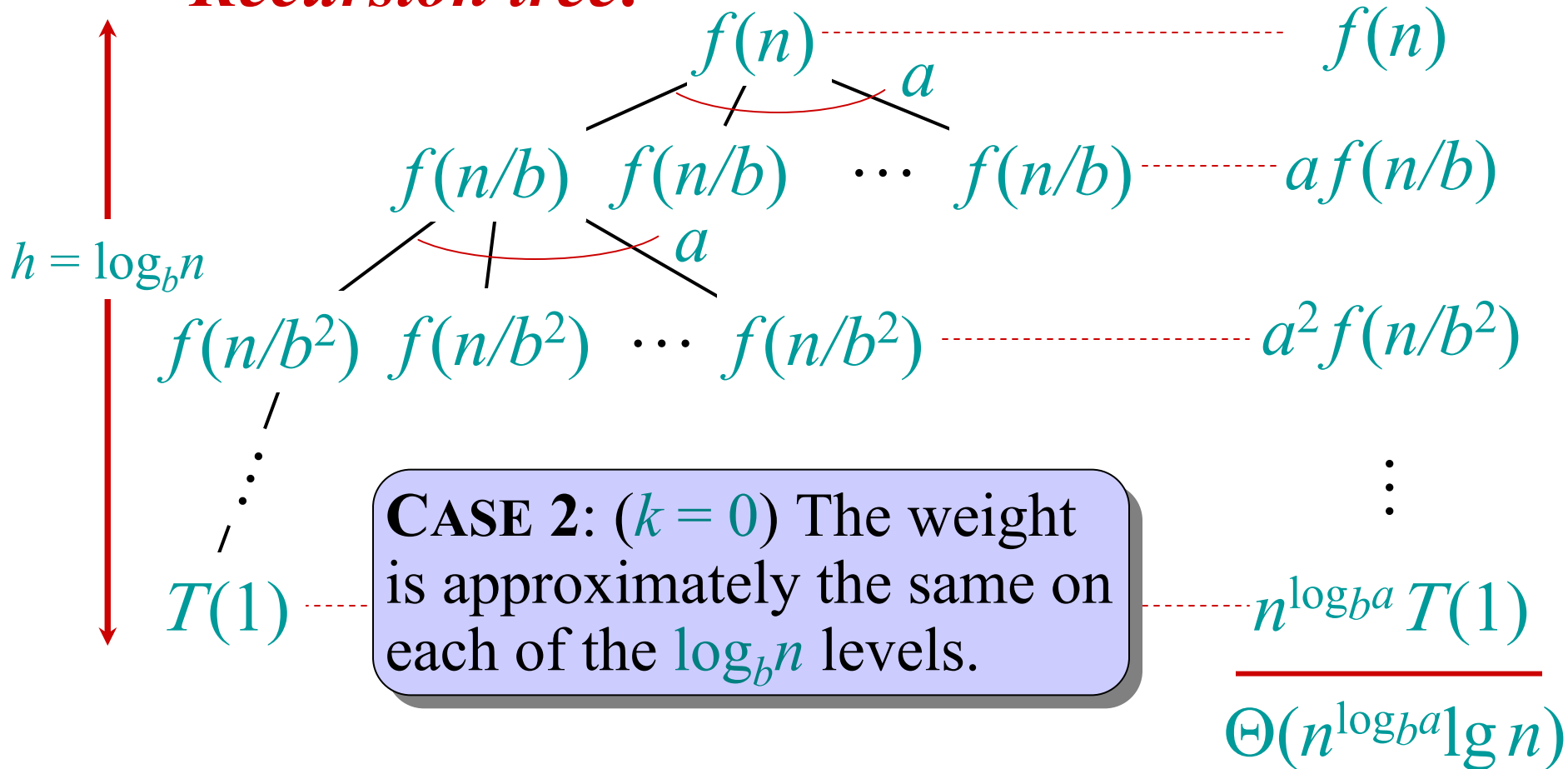
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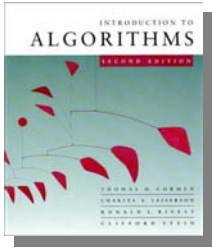




Idea of master theorem

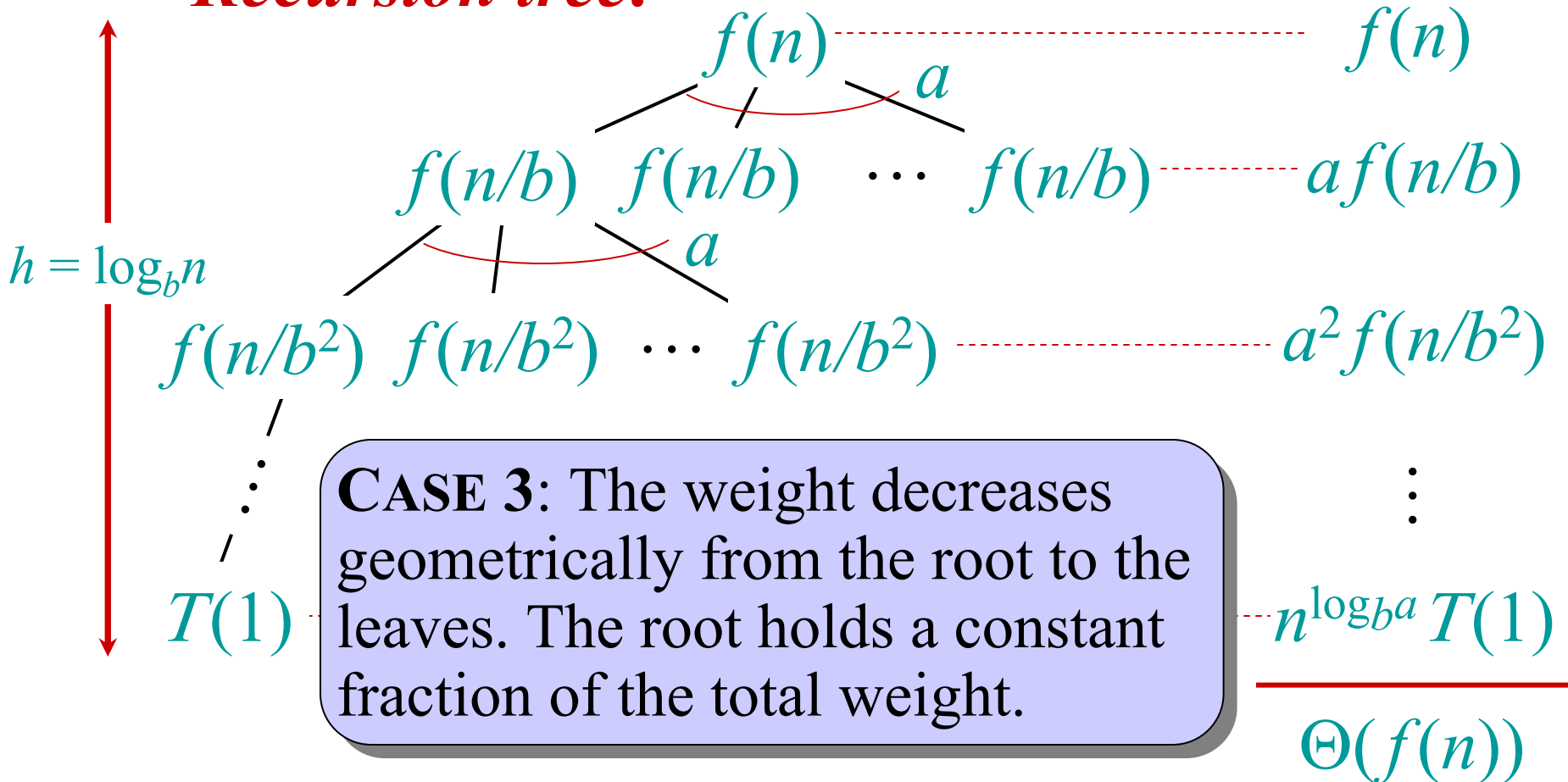
Recursion tree:

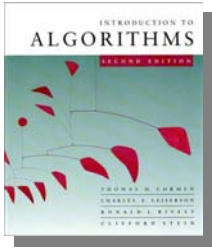




Idea of master theorem

Recursion tree:





Appendix: geometric series

$$1 + x + x^2 + \dots + x^n = \frac{1 - x^{n+1}}{1 - x} \quad \text{for } x \neq 1$$

$$1 + x + x^2 + \dots = \frac{1}{1 - x} \quad \text{for } |x| < 1$$

Return to last
slide viewed.

