

Lecture: Analysis of Algorithms (CS583 - 002)

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Fall 2017

- 1 Outline of Today's Class
- 2 Techniques for Bounding Recurrences
 - Iteration Method
 - Recursion-tree Method
 - Substitution Method
 - Master Theorem

Techniques for Bounding Recurrences

What is a Recurrence?

- A recurrence is an equation of inequality that describes a function in terms of its value on smaller inputs
 - Example: $T(n)$ of Mergesort is described in terms of $T(n/2)$
- Recurrences have boundary conditions (bottom out)
 - Example: $T(n) = c$ when $n = 1$

Techniques for Bounding Recurrences

- 1 Iteration or expansion method
- 2 Recursion-tree method
- 3 Substitution method
- 4 Master Theorem
- 5 Generating Functions* (beyond scope of this course)

Iteration Method

Expand $T(n) = 2T(n/2) + cn$ – iterate down to boundary condition

$$\begin{aligned}
 T(n) &= 2T(n/2) + cn \\
 &= 2 \cdot [2T(n/4) + c\frac{n}{2}] + cn \\
 &= 4 \cdot [2T(n/8) + c\frac{n}{4}] + 2cn \\
 &= 8 \cdot T(n/8) + 3cn \\
 &= 2^3 \cdot T(n/2^3) + 3cn \\
 &= \dots \text{ do you see the pattern?} \\
 &= 2^k \cdot T(n/2^k) + kcn
 \end{aligned}$$

Since the recursion bottoms out at $n = 1$, $k = \lg(n)$. So:

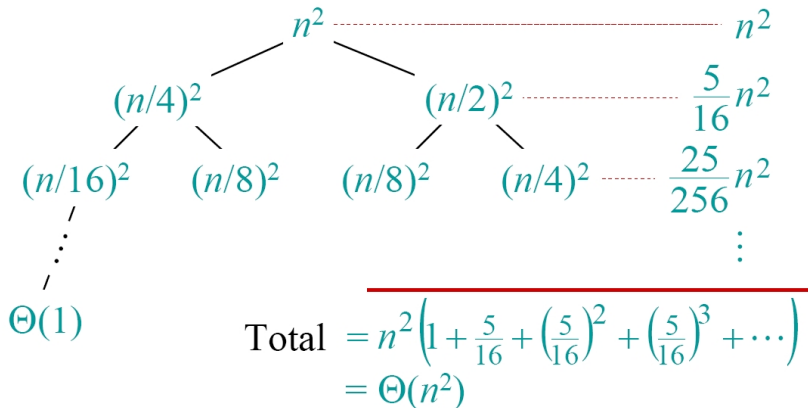
$$\begin{aligned}
 T(n) &= n \cdot T(1) + \lg(n) \cdot cn \\
 &= cn + cn \cdot \lg(n) \in \theta(n \cdot \lg n)
 \end{aligned}$$

Try to solve $T(n) = T(n-1) + n$, where $T(1) = 1$.

Try to solve $T(n) = 2T(n/2) + n$, where $T(1) = 1$.

Example of Recursion-tree Method

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



Substitution (Induction) Method

Guess that $T(n) = 2T(\frac{n}{2}) + n \in O(n + n \cdot \lg n)$, where $T(1) = 1$.
 Then use induction to prove that the guess is correct.

- 1 Base Case:** The boundary condition states that $T(1) = 1$.
 The guess states that $T(1) \in O(1 + 1 \cdot \lg 1)$. Since,
 $1 + 1 \cdot \lg 1 = 1$ and $1 \in O(1)$, the guess is correct.
- 2 Inductive Step:** Assuming that $T(\frac{n}{2}) \in O(\frac{n}{2} + \frac{n}{2} \cdot \lg(\frac{n}{2}))$, we
 have to show that the guess holds for $T(n)$:

$$\begin{aligned}
 T(n) &= 2T(\frac{n}{2}) + n \\
 &\leq 2[c \cdot (\frac{n}{2} + \frac{n}{2} \cdot \lg(\frac{n}{2}))] + n, \text{ where } c > 0 \\
 &= c \cdot n + c \cdot n \cdot \lg n - cn + n \\
 &= c \cdot n \cdot \lg n + n
 \end{aligned}$$

Easy to show that $c \cdot n \cdot \lg n + n \in O(n + n \cdot \lg n)$

Master Theorem

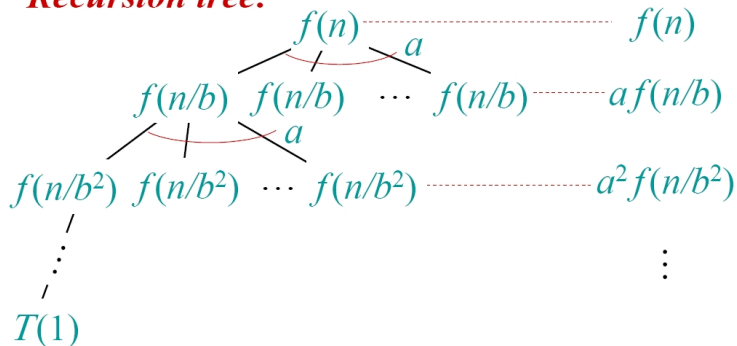
Theorem: Let $a \geq 1$ and $b > 1$ be constants, let $f(n)$ be a function, and let $T(n)$ be defined on the nonnegative integers by the recurrence $T(n) = a \cdot T(n/b) + f(n)$, where n/b can mean $\lfloor n/b \rfloor$ or $\lceil n/b \rceil$.

- 1 If $f(n) \in O(n^{\log_b a - \epsilon})$ for some constant $\epsilon > 0$, then $T(n) \in \theta(n^{\log_b a})$
- 2 If $f(n) \in \theta(n^{\log_b a})$, then $T(n) \in \theta(n^{\log_b a} \cdot \lg n)$
- 3 If $f(n) \in \Omega(n^{\log_b a + \epsilon})$ for some constant $\epsilon > 0$, and if $a \cdot f(n/b) \leq c f(n)$ for some constant $c < 1$ and all sufficiently large n , then $T(n) \in \theta(f(n))$

Examples: $T(n) = 9T(n/3) + n$, $T(n) = T(\frac{2n}{3}) + 1$,
 $T(n) = 3T(\frac{n}{4}) + n \lg n$, $T(n) = 2T(\frac{n}{2}) + n \lg n$, $T(n) = n \cdot T^2(\frac{n}{2})$.

Idea Behind Master Theorem: Case 1.

Recursion tree:



Idea Behind Master Theorem: Case 1.

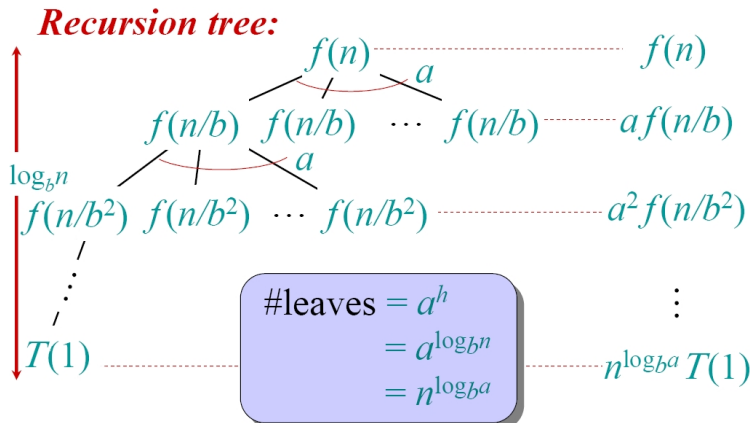
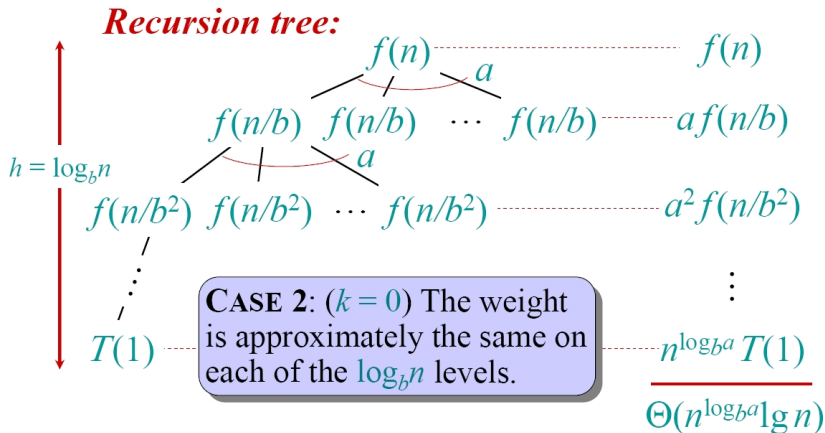


Figure: The weight increases geometrically from the root to the leaves. The leaves hold a constant fraction of the total weight. $T(n) \in \theta(n^{\log_b a})$.

Idea Behind Master Theorem: Case 2.



Idea Behind Master Theorem: Case 3.

