

Master method

- Idea: solve *class* of recurrences of form

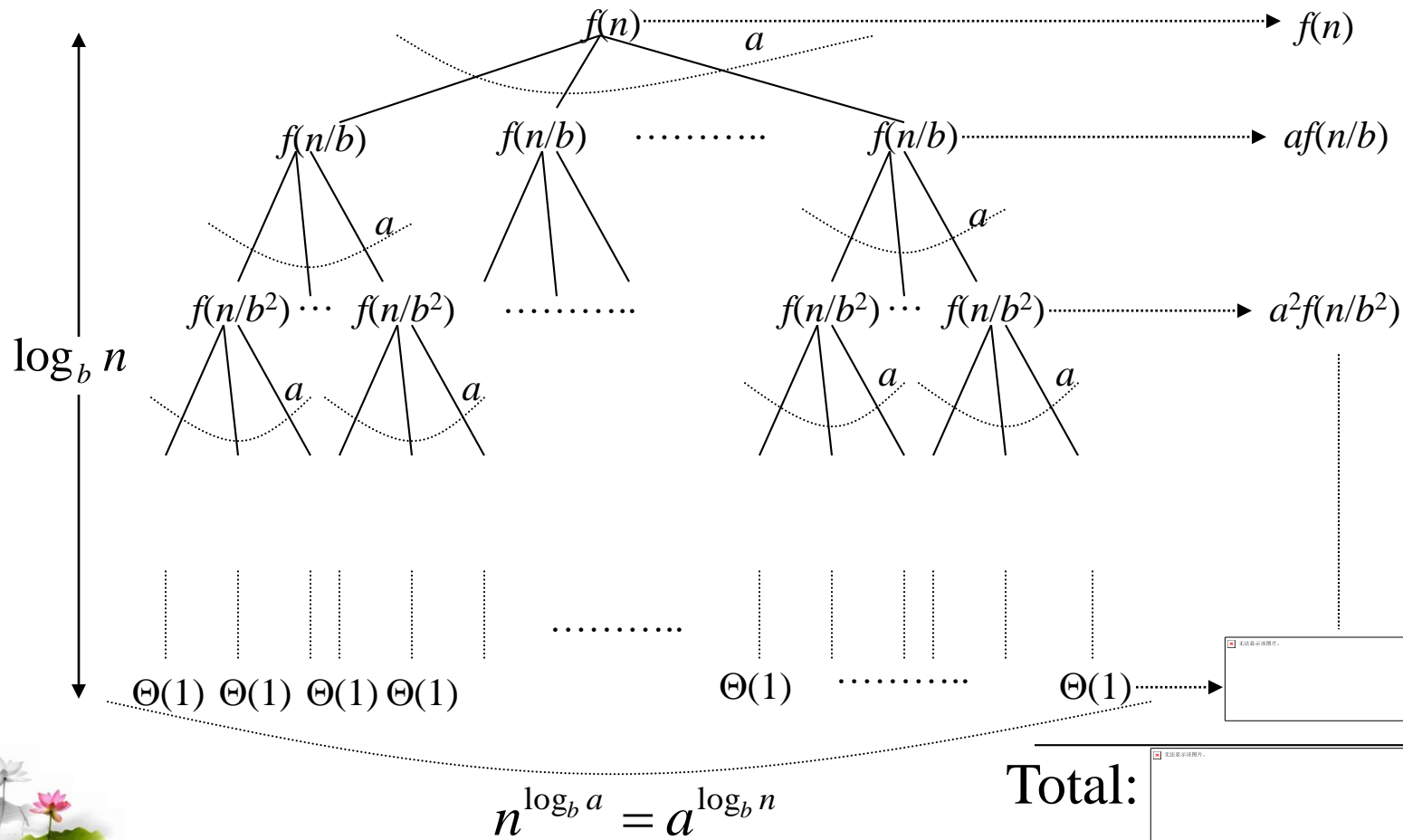
$$T(n) = aT(n/b) + f(n)$$

$a \geq 0$ and $b > 0$, and f asymptotically positive.

- Abstractly: $T(n)$ is runtime for an algorithm; it's unknown, but we do know that:
 - a subproblems of size n/b are solved recursively, each in time $T(n/b)$.
 - $f(n)$ is the cost of **dividing** problem (beforehand) and **combining** the results (afterward).



Recursion tree



Analysis

- #of leaves = $n^{\log_b a} = a^{\log_b n}$
- Iterating the recurrence (expanding the tree) yields

$$\begin{aligned} T(n) &= f(n) + aT(n/b) \\ &= f(n) + af(n/b) + a^2T(n/b^2) \\ &= f(n) + af(n/b) + a^2f(n/b^2) + \dots \\ &\quad + a^{\log_b n - 1} f(n/b^{\log_b n - 1}) + a^{\log_b n} T(1) \end{aligned}$$



Intuition

- Three common cases:
 - Running time dominated by cost at leaves.
 - Running time evenly distributed throughout tree
 - Running time dominated by cost at root
- Thus, to solve recurrence we need only characterize the **dominant** term in each case!



In each case, compare $f(n)$ and $n^{\log_b a}$

- Case 1:

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

- $f(n)$ grows polynomially **slower** than $n^{\log_b a}$
- Weight of each level increases geometrically from root to leaves ($1, a^1, a^2, \dots$)
- Leaves contain **constant fraction** of total weight; i.e., total is constant \times #of leaves.

- the work at leaves dominates.



Analysis of Case 1

$$\begin{aligned}\sum_{j=0}^{\log_b n-1} a^j f(n/b^j) &= O\left(\sum_{j=0}^{\log_b n-1} a^j \left(\frac{n}{b^j}\right)^{\log_b a - \varepsilon}\right) \\&= O\left(n^{\log_b a - \varepsilon} \sum_{j=0}^{\log_b n-1} \left(\frac{ab^\varepsilon}{b^{\log_b a}}\right)^j\right) \\&= O\left(n^{\log_b a - \varepsilon} \sum_{j=0}^{\log_b n-1} (b^\varepsilon)^j\right) \\&= O\left(n^{\log_b a - \varepsilon} \frac{b^{\varepsilon \log_b n} - 1}{b^\varepsilon - 1}\right) \\&= O(n^{\log_b a})\end{aligned}$$

Thus $T(n) = \Theta(n^{\log_b a})$



Case 2

- $f(n) = \Theta(n^{\log_b a} \lg^k n)$ for some constant $k \geq 0$
- $f(n)$ and $n^{\log_b a}$ same to within a polylogarithmic factor (log to a power)
- Weight decreases from root to leaves

- Thus $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$

Work is distributed evenly throughout tree



Case 3

- $f(n) = \Omega(n^{\log_b a + \varepsilon})$ for some constant $\varepsilon > 0$
- Also, need “regularity condition”:
 $\exists c < 1$ and $n_0 > 0$ such that
$$af(n/b) \leq cf(n) \quad \forall n > n_0$$
- $f(n)$ grows polynomially faster than $n^{\log_b a}$
- Weight is geometrically decreasing from root to leaves
- Root contains constant fraction of total weight
- Thus, $\boxed{T(n) = \Theta(f(n))}$ Cost at root dominates.



Master Theorem, Summarized

Master Theorem: $T(n) = aT(n/b) + f(n)$

1. $f(n) = O(n^{\log_b a - \varepsilon}) \Rightarrow T(n) = O(n^{\log_b a})$

2. $f(n) = \Theta(n^{\log_b a} \lg^k n) \Rightarrow T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$

3. $f(n) = \Omega(n^{\log_b a + \varepsilon})$ and $af(n/b) \leq cf(n)$
 $\Rightarrow T(n) = \Theta(f(n))$



MT Strategy

Basic strategy:

1. Extract a , b , and $f(n)$ from given recurrence
2. Determine $n^{\log_b a}$
3. Compare $f(n)$ and $n^{\log_b a}$ asymptotically
4. Determine appropriate MT case (if any), and apply it.



MT examples (cont.)

$$T(n) = 7T(n/2) + \Theta(n^2)$$

$$n^{\log_b a} = n^{\log_2 7} = n^{\lg 7}$$

$$f(n) / n^{\log_b a} = \Theta(n^2) / n^{\lg 7} = \Theta(n^{2-\lg 7}) = O(n^{-0.8})$$

\Rightarrow Case 1, applies

$$T(n) = \Theta(n^{\lg 7})$$



MT examples (cont.)

- Binary **search** (not sort!):

$$T(n) = T(n/2) + \Theta(1); (a=1, b=2)$$

$$n^{\lg 1} = n^0 = 1$$

$$\Theta(1)/1 = \Theta(\lg^0 n) = 1$$

\Rightarrow Case 2,

$$T(n) = \Theta(\lg n)$$



MT examples (cont.)

$$T(n) = 4T(n/2) + n^3; (a=4, b=2)$$

$$n^3 / n^{\lg 4} = n \quad \Rightarrow \text{Case 3}$$

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

Are we done?

No... Need to check regularity condition:

$$4f(n/2) \leq cf(n)$$

$$4n^3/8 \leq cn^3$$

$$n^3/2 \leq cn^3$$

$$c=3/4 < 1$$



MT examples (cont.)

One more recurrence:

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

$$\frac{n^2 / \lg n}{n^2} = 1 / \lg n = \begin{cases} O(n^{-\varepsilon}) & \varepsilon > 0? \lg n = \Omega(n^\varepsilon)? \\ \Theta(\lg^k n) & k \geq 0? \text{No} \\ \Omega(n^\varepsilon) & \varepsilon > 0? \text{No} \end{cases}$$

No MT case applies!

Solution: $T(n) = \Theta(n^2 \lg \lg n)$ – substitution.



Merge sort analysis

For merge sort:

$$T(n) = 2T(n/2) + \Theta(n); a=2, b=2$$

$$n^{\log_b a} = n^{\log_2 2} = n$$

$$f(n) / n^{\log_b a} = \Theta(n) / n = \Theta(1) = \Theta(\lg^0 n)$$

\Rightarrow Case 2, with $k=0$

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



Binary search

Search for a key in a *sorted* array

Example: Given array:

3 5 7 8 9 12 15

Find key 9



Binary search

Binary search as Divide-and-conquer algorithm:

1. *Divide*: Check middle element.
2. *Conquer*: Search one subarray.
3. *Combine*: Trivial.



Recurrence for binary search

$$T(n) = \begin{array}{c} \text{subproblem size} \\ 1 \quad T(n/2) \\ \text{\#subproblems} \end{array} + \begin{array}{c} \Theta(1) \\ \text{work dividing \& combining} \end{array}$$

$$T(n) = T(n/2) + \Theta(1)$$



Binary search analysis

Solve using MT:

Characterize $O(n^{\log_b a})$

$$a=1 \text{ and } b=2 \Rightarrow O(n^{\log_b a}) = n^{\log_2 1} = 1$$

$$\Rightarrow f(n) / O(n^{\log_b a}) = \Theta(1)$$

$$\Rightarrow \text{Case 2 of MT} \Rightarrow T(n) = \Theta(\lg n)$$

