Lecture 3: The Master Theorem; The Recursive Tree Method

1 Quick Review

- Recall, a divide-and-conquer algorithm recursively breaks up a problem of size n in smaller sub-problems such that:
    - There are exactly a sub-problems.
    - Each sub-problem has size at most $\frac{1}{b} \cdot \mathrm{n}$
    - Once solved, the solutions to the sub-problems can be <u>combined</u> to produce a solution to the original problem in time $O(n^d)$
- So the run-time of a divide and conquer algorithm satisfies the recurrence:

$$T(\mathrm{n}) = \mathrm{a} \cdot T(\tfrac{n}{b}) + O(n^d)$$

- Examples: MergeSort and Binary Search

2 The Master Theorem

- **The Master Theorem**: If $T(\mathrm{n}) = \mathrm{a} \cdot T(\frac{n}{b}) + O(n^d)$ for constants a $>$ 0, b $>$ 1, and d $\geq$ 0 then:

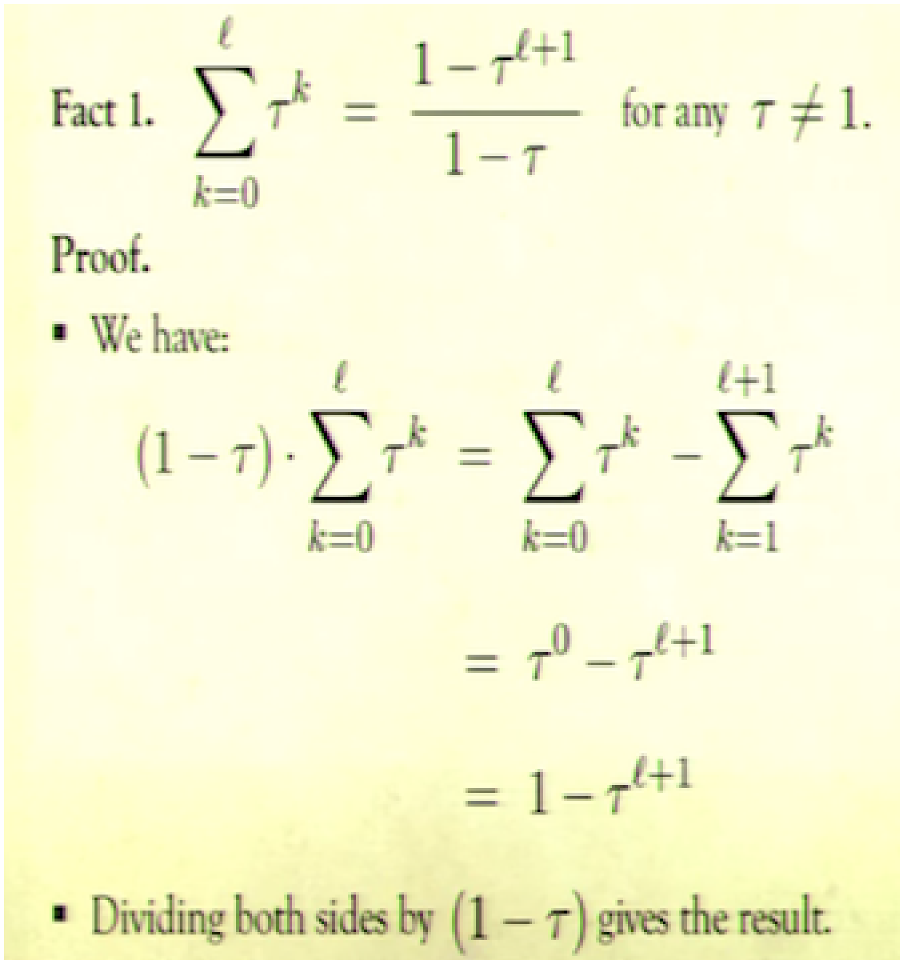
$$T(n) = \begin{cases} O(n^d) & \text{if } a < b^d \quad \text{[Case I]} \\ O(n^d \cdot \log n) & \text{if } a = b^d \quad \text{[Case II]} \\ O(n^{\log_b a}) & \text{if } a > b^d \quad \text{[Case III]} \end{cases}$$

- Sanity Check: What does this give for MergeSort and Binary Search?

	a	b	d	Case	Runtime
MergeSort	2	2	1	II	$O(n \cdot \log n)$
Binary Search	1	2	0	II	$O(\log n)$

3 Proof of The Master Theorem

- Fact One:



Fact 1. $\sum_{k=0}^{\ell} \tau^k = \frac{1-\tau^{\ell+1}}{1-\tau}$ for any $\tau \neq 1$.

Proof.

- We have:

$$(1-\tau)\cdot\sum_{k=0}^{\ell}\tau^k = \sum_{k=0}^{\ell}\tau^k - \sum_{k=1}^{\ell+1}\tau^k$$

$$= \tau^0 - \tau^{\ell+1}$$

$$= 1 - \tau^{\ell+1}$$

- Dividing both sides by $(1-\tau)$ gives the result.

- Fact Two:

Fact 2. $x^{\log_b y} = y^{\log_b x}$ for any base b.

Proof.

$\boxed{\log_b z^p = p \cdot \log_b z}$

- Observe that, by the *power rule of logarithms*, we have:

$$\log_b x \cdot \log_b y = \log_b(y^{\log_b x})$$

- Similarly:

$$\log_b x \cdot \log_b y = \log_b(x^{\log_b y})$$

- Putting this together gives

$$\log_b(y^{\log_b x}) = \log_b(x^{\log_b y})$$

$$\implies \quad x^{\log_b y} = y^{\log_b x}$$

- Proof of the Master Theorem

Proof.

- We may assume n is a power of b: $n = b^\ell$
- So we have:

$$\begin{aligned} T(n) &= n^d + a \cdot \left(\frac{n}{b}\right)^d + a^2 \cdot \left(\frac{n}{b^2}\right)^d + \cdots + a^\ell \cdot \left(\frac{n}{b^\ell}\right)^d \\ &= n^d \cdot \left(1 + a \cdot \left(\frac{1}{b}\right)^d + a^2 \cdot \left(\frac{1}{b^2}\right)^d + \cdots + a^\ell \cdot \left(\frac{1}{b^\ell}\right)^d\right) \\ &= n^d \cdot \left(1 + \frac{a}{b^d} + \left(\frac{a}{b^d}\right)^2 + \cdots + \left(\frac{a}{b^d}\right)^\ell\right) \end{aligned}$$

Proof [cont.] $T(n) = n^d \cdot \left(1 + \frac{a}{b^d} + \left(\frac{a}{b^d}\right)^2 + \cdots + \left(\frac{a}{b^d}\right)^\ell\right)$

Case I: $\frac{a}{b^d} < 1$

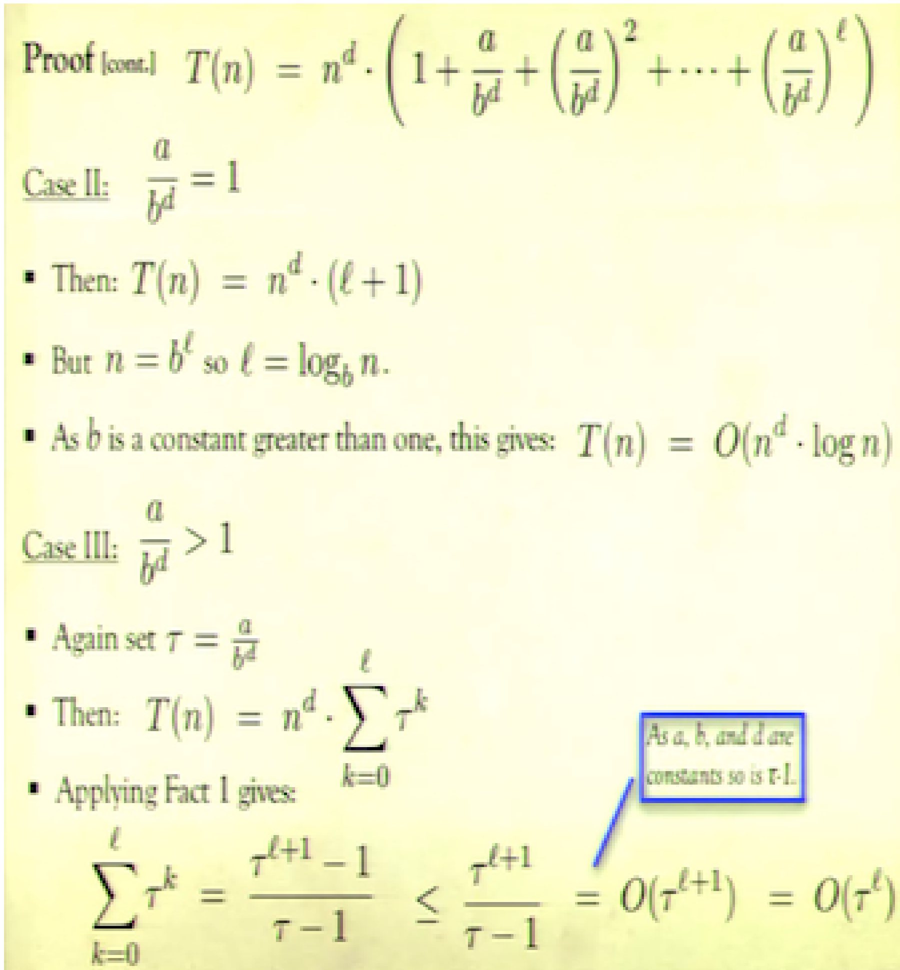
- Set $\tau = \frac{a}{b^d}$
- Then: $T(n) = n^d \cdot \sum_{k=0}^{\ell} \tau^k$
- Applying Fact 1, we know that:

$$\sum_{k=0}^{\ell} \tau^k = \frac{1 - \tau^{\ell+1}}{1 - \tau} \leq \frac{1}{1 - \tau} = O(1)$$

As a, b, and d are constants so is 1-τ.

- Therefore:

$$T(n) \leq n^d \cdot \frac{1}{1 - \frac{a}{b^d}} = n^d \cdot \frac{b^d}{b^d - a} = O(n^d)$$



Proof [cont.] $T(n) = n^d \cdot \left(1 + \frac{a}{b^d} + \left(\frac{a}{b^d}\right)^2 + \cdots + \left(\frac{a}{b^d}\right)^\ell\right)$

Case II: $\frac{a}{b^d} = 1$

- Then: $T(n) = n^d \cdot (\ell + 1)$
- But $n = b^\ell$ so $\ell = \log_b n$.
- As b is a constant greater than one, this gives: $T(n) = O(n^d \cdot \log n)$

Case III: $\frac{a}{b^d} > 1$

- Again set $\tau = \frac{a}{b^d}$
- Then: $T(n) = n^d \cdot \sum_{k=0}^{\ell} \tau^k$
- Applying Fact 1 gives:

As a, b, and d are constants so is τ-1.

$$\sum_{k=0}^{\ell} \tau^k = \frac{\tau^{\ell+1} - 1}{\tau - 1} \leq \frac{\tau^{\ell+1}}{\tau - 1} = O(\tau^{\ell+1}) = O(\tau^\ell)$$

Proof [cont.]

- Thus: $T(n) = O(n^d \cdot \tau^\ell)$

- Observe that:

$$
\begin{aligned}
n^d \cdot \tau^\ell &= n^d \cdot \left(\frac{a}{b^d}\right)^\ell \\
&= \left(\frac{n}{b^\ell}\right)^d \cdot a^\ell \\
&= 1 \cdot a^\ell && \boxed{\text{As } n = b^\ell.} \\
&= a^{\log_b n} \\
&= n^{\log_b a} && \boxed{\text{By Fact 2.}}
\end{aligned}
$$

- This gives the final case:

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

- Specifically, what matters is **not** the statement of the Master Theorem but the **ideas** underlying its proof.
  - First, if we understand the proof then we can easily reconstruct the theorem.
  - Second, if we understand the proof then we can easily apply the method to a much broader class of problems. For example:
    - → The sub-problems have different sizes.

e.g. The Deterministic Selection Algorithm.

$$T(n) \leq T(\frac{7n}{10}) + T(\frac{n}{5}) + O(n)$$

$\rightarrow$ The combination function is not of the form $f(\text{n}) = n^d$.

e.g. Euclid's Greatest Common Divisor Algorithm.

$$T(n) = T(\frac{n}{2}) + O(\log n)$$

$\rightarrow$ The parameters a, b, and d are <u>not</u> constants.

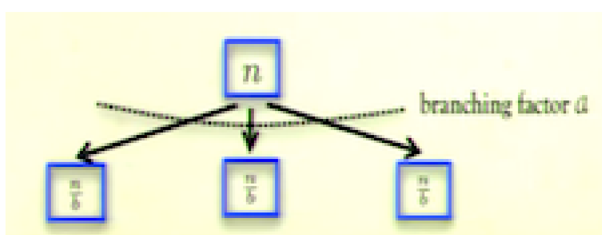
e.g. $T(n) = \sqrt{n} \cdot T(\sqrt{n}) + O(n^{\frac{1}{\log \log n}})$

4 The Recursion Tree Method

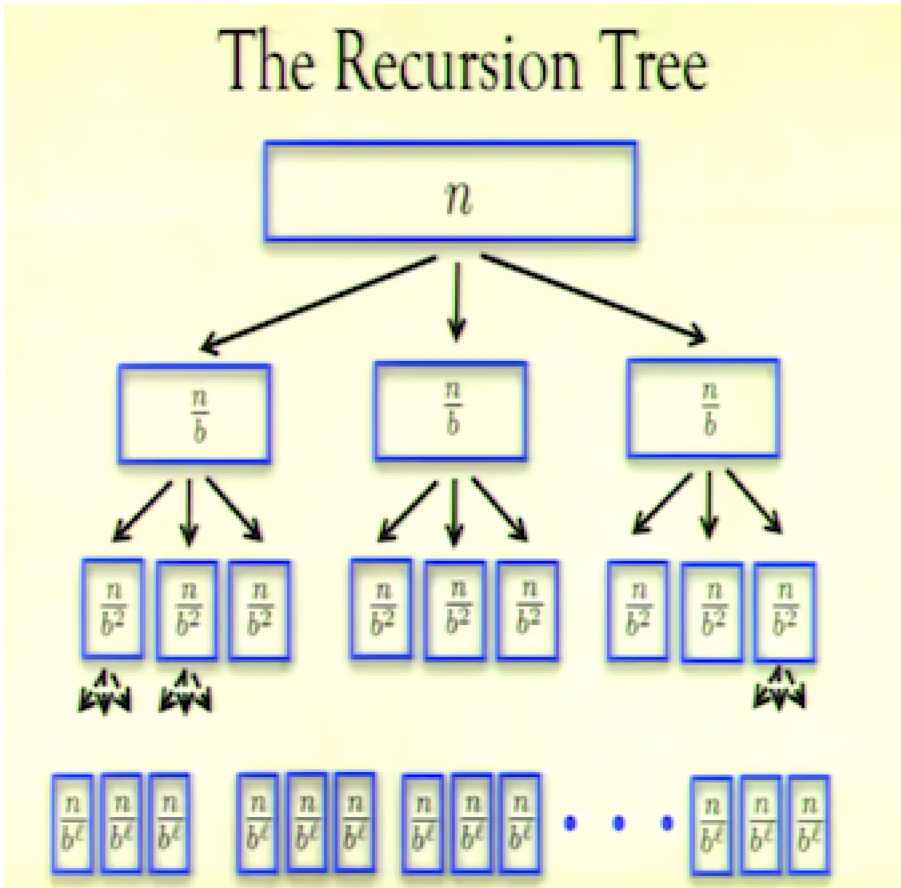
- The Master Theorem is a special case the the **recursion tree method**.
- Specifically, we model the *divide and conquer* recursive formula by a tree:

$$T(\text{n}) = \text{a} \cdot T(\frac{n}{b}) + O(n^d)$$

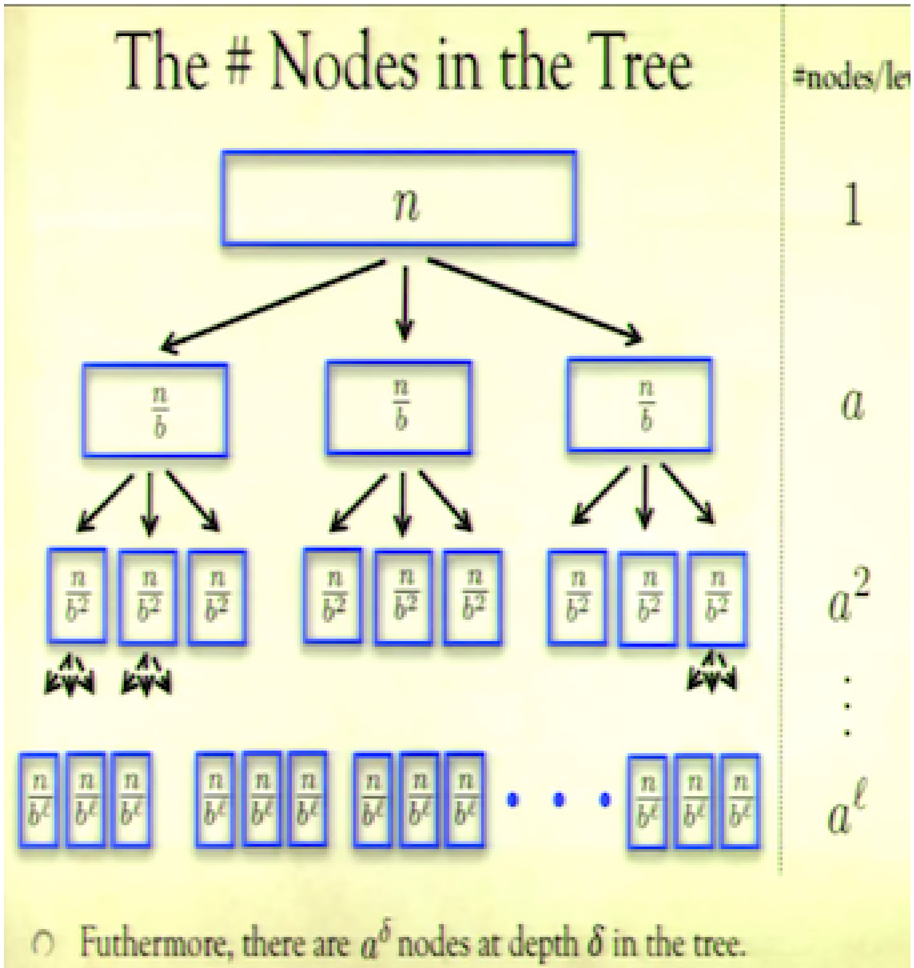
  - The **root** node of the trees has a label n.
  - The root has a children each with label $\frac{n}{b}$.



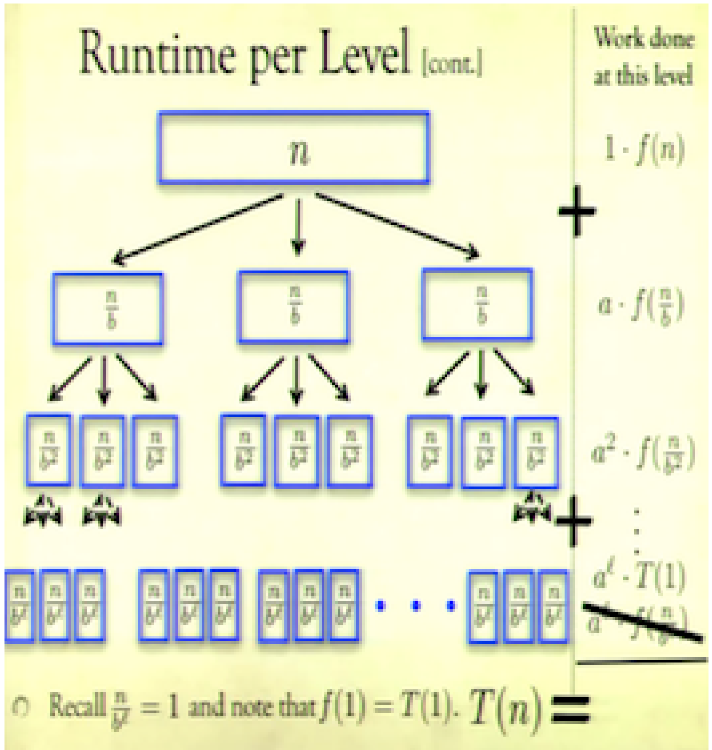
- This pattern then repeats at the children, then grandchildren, etc.



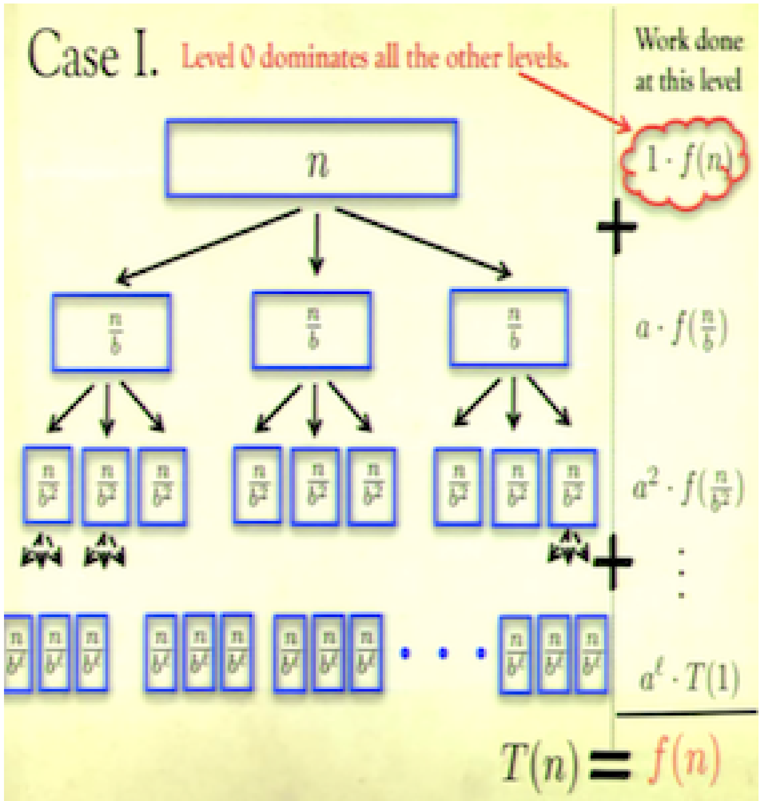
- This process stops at the **leaves** (base cases) which have label $\frac{n}{b^l} = 1$. (As n $= b^l$)

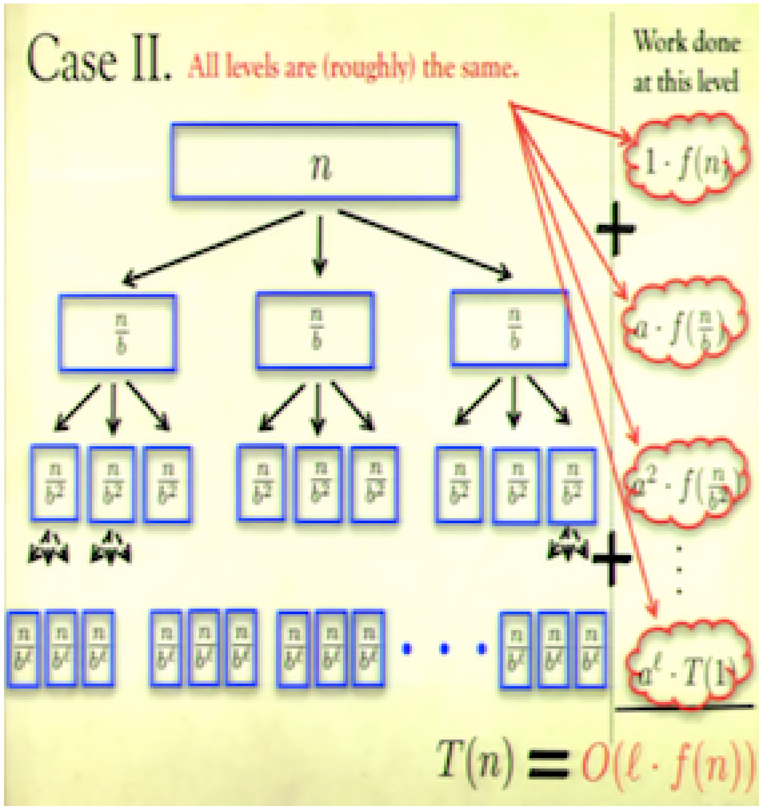


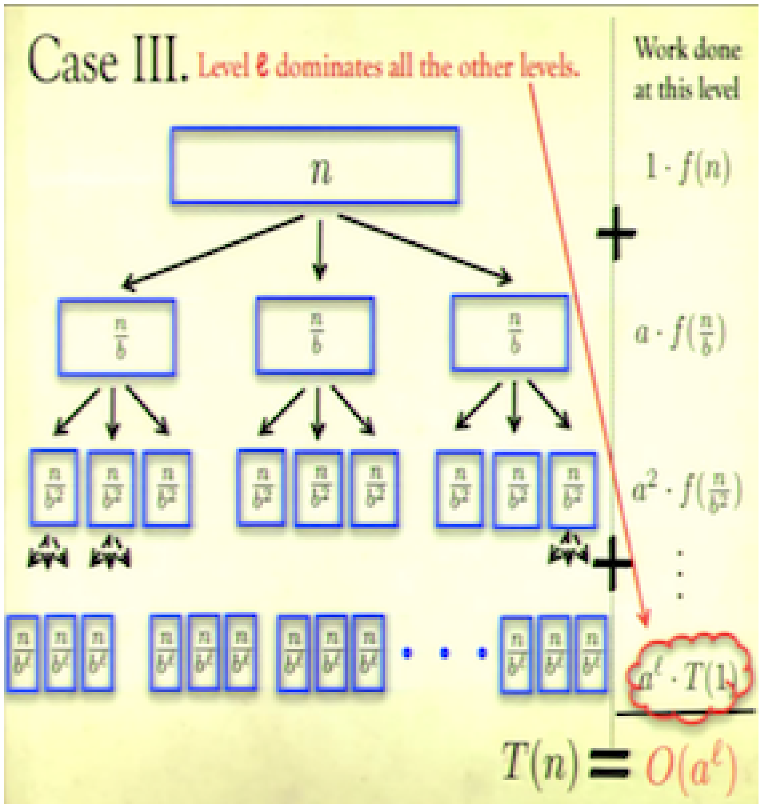
- How much time do we spend at each level?



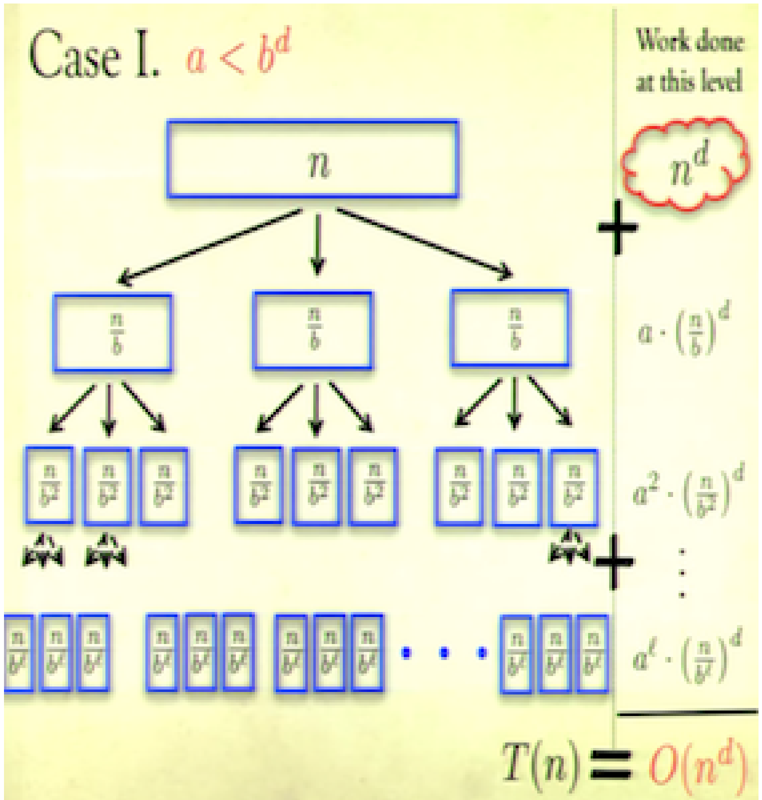
Runtime per Level [cont.]
Work done at this level
n
$1 \cdot f(n)$
$\frac{n}{b}$
$a \cdot f(\frac{n}{b})$
$\frac{n}{b^2}$
$a^2 \cdot f(\frac{n}{b^2})$
$\frac{n}{b^\ell}$
$a^\ell \cdot T(1)$
Recall $\frac{n}{b^\ell} = 1$ and note that $f(1) = T(1)$. $T(n) =$

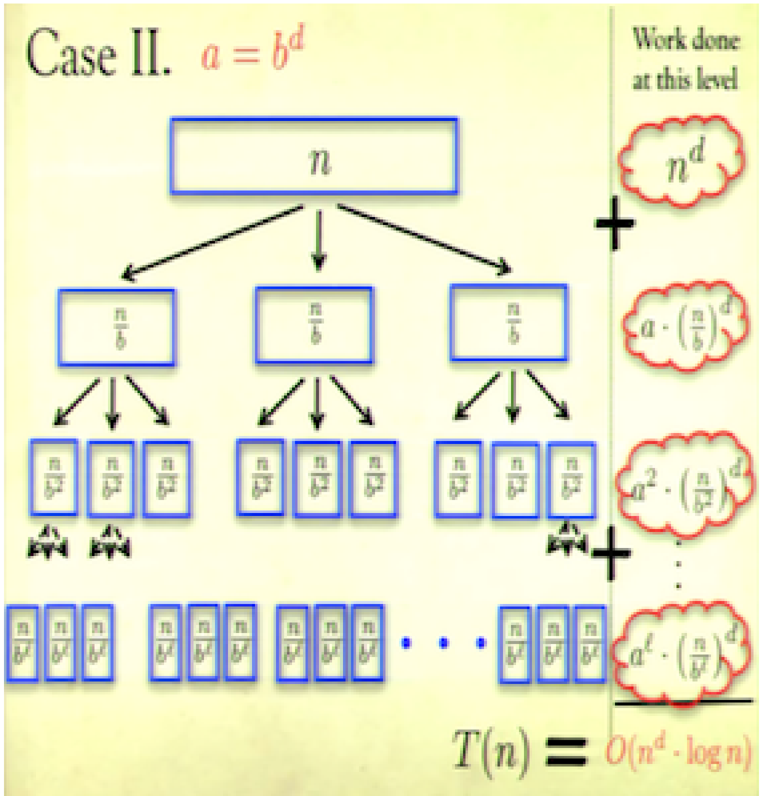

Case I. Level 0 dominates all the other levels.
Work done at this level
n
$1 \cdot f(n)$
$\frac{n}{b}$
$a \cdot f(\frac{n}{b})$
$\frac{n}{b^2}$
$a^2 \cdot f(\frac{n}{b^2})$
$a^\ell \cdot T(1)$
$T(n) = f(n)$

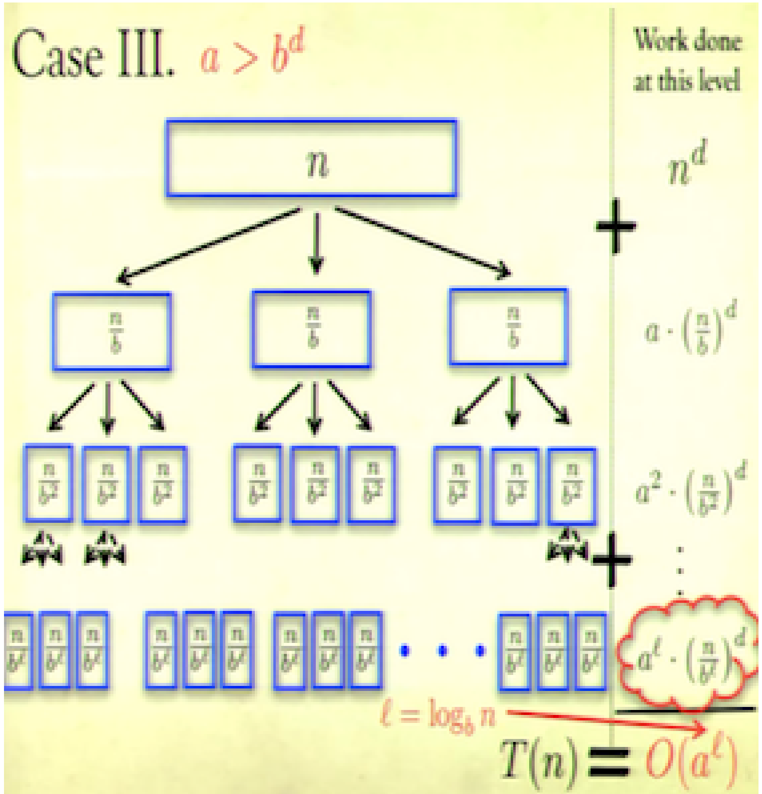

Case II. All levels are (roughly) the same.
Work done at this level
n
$\frac{n}{b}$
$\frac{n}{b^2}$
$\frac{n}{b^\ell}$
$1 \cdot f(n)$
$a \cdot f(\frac{n}{b})$
$a^2 \cdot f(\frac{n}{b^2})$
$a^\ell \cdot T(1)$
$T(n) = O(\ell \cdot f(n))$



- This gives us the proof of the Master Theorem:


Case I. $a < b^d$
Work done at this level
n
n^d
$\frac{n}{b}$
$a \cdot \left(\frac{n}{b}\right)^d$
$\frac{n}{b^2}$
$a^2 \cdot \left(\frac{n}{b^2}\right)^d$
$\frac{n}{b^\ell}$
$a^\ell \cdot \left(\frac{n}{b^\ell}\right)^d$
$T(n) = O(n^d)$


Case II. $a = b^d$
Work done at this level
n
$\frac{n}{b}$
n^d
$a \cdot \left(\frac{n}{b}\right)^d$
$a^2 \cdot \left(\frac{n}{b^2}\right)^d$
$a^\ell \cdot \left(\frac{n}{b^\ell}\right)^d$
$T(n) = O(n^d \cdot \log n)$


Case III. $a > b^d$
Work done at this level
n
$\frac{n}{b}$
$\frac{n}{b^2}$
$\frac{n}{b^\ell}$
n^d
$a \cdot \left(\frac{n}{b}\right)^d$
$a^2 \cdot \left(\frac{n}{b^2}\right)^d$
$a^\ell \cdot \left(\frac{n}{b^\ell}\right)^d$
$\ell = \log_b n$
$T(n) = O(a^\ell)$