

# Master Method

<https://cs.pomona.edu/classes/cs140/>

# Notes on checkpoint

- The checkpoint will be administered through gradescope
- You may bring a single, two-sided 8" by 11" note sheet (no restrictions)
- You must come to class to complete it
- You have these options (maybe more?)
  - Write answers directly on gradescope (bring your laptop)
  - Write answers on paper and upload to gradescope
  - Write answers on a tablet, export to image or PDF, and upload to gradescope
- You will have plenty of time, so you might want to bring something to read during the down time
- We will have two stages to the exam
  - An individual stage
  - And a group stage

# Outline


## Topics and Learning Objectives

- Learn about the master method for solving recurrences
- Understand how to draw general recursion trees

## Exercise

- Applying the Master Method

# Extra Resources

- Chapter 4 (sections 4-6) in CLRS
- Algorithms Illuminated: Part 1: 4Chapter 4
-  • [Master Method](#)

# Master Method

- For “**solving**” recurrences

$63n$

$T(n)$  = the # of operations required to complete algorithm

$$T(n) = 2T(n/2) + 7n$$

**Base Case:**  $T(1) \leq$  base-case-work

**Recurrence:**  $T(n) \leq$  recursive-work + combine-work

Closest pair

$T(c)$

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

Closest Split Pair

Setup Recursive calls

# Recurrence Equation

- When an algorithm contains a recursive call to **itself**
- We usually specify its running time by a recurrence equation
- We also sometimes just call this a “**recurrence**”
- A recurrence equation describes the overall running time on a problem of size  $n$  in terms of the running time on smaller inputs (some fraction of  $n$ )

**T(n)** **FUNCTION** MergeSort(array)

**O(1)** = array.length

**O(1)** n == 1

**O(1)** **RETURN** array

Recurrence Equation

$$T(n) = 2 T(n/2) + O(n)$$

**T(n/2)** left\_sorted = MergeSort(array[0 ..< n//2])

**T(n/2)** right\_sorted = MergeSort(array[n//2 ..< n])

**O(n)** array\_sorted = Merge(left\_sorted, right\_sorted)

**O(1)** **RETURN** array\_sorted

# Master Method

$$T(n) = T\left(\frac{n}{5}\right) + T\left(\frac{n^2}{7}\right) + \dots$$

“Black Box” for solving recurrences

**Assumes** all subproblems are of **equal size** (most algorithms do this)

- The same amount of data is given to each recursive call

An algorithm that splits the subproblems into 1/3 and 2/3 (or an algorithm that splits data randomly) must be **solved** in a different manner. We'll look at other methods later

# Master Method Recurrence Equation

$$T(n) \leq a T\left(n/b\right) + O(n^d)$$

$O(n^0)$   
 $O(1)$   
constant

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

What does zero mean for  $d$ ?

# Master Method Cases

$$T(n) \leq a T\left(n/b\right) + O(n^d)$$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Master Method Cases

$$T(n) \leq a T\left(n/b\right) + O(n^d)$$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d & \text{Case 1} \\ O(n^d), & a < b^d & \text{Case 2} \\ O(n^{\log_b a}), & a > b^d & \text{Case 3} \end{cases}$$

# Exercise

## Merge sort

$$T(n) \leq 2T\left(\frac{n}{2}\right) + O(n)$$

$a = 2, b = 2, d = 1$

$2$  vs.  $2^1 \rightarrow \text{Case 1}$

$$O(n \lg n)$$

$$T(n) \leq a T\left(\frac{n}{b}\right) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

①  
②  
③

$\lg \rightarrow \log_2 n$



Sorted Array

## Exercise

Binary search

$$T(n) \leq 1 T\left(\frac{n}{2}\right) + O(n^0)$$

$$a = 1, b = 2, d = 0$$

$$a ? b^d$$

$$1 = 2^0 \rightarrow \text{case 1}$$

$$O(n^0 \lg n) \rightarrow O(\lg n)$$

$$T(n) \leq a T\left(\frac{n}{b}\right) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Exercise

Closest pair

(see  
Merge sort)

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Exercise

$$T(n) \leq 2 T(n/2) + O(n^2)$$

$$a = 2$$

$$b = 2$$

$$d = 2$$

case 2

$$T(n) = O(n^2)$$

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Integer Multiplication

**Input:** Two  $n$ -digit nonnegative integers,  $x$  and  $y$ .

**Output:** The product  $x \cdot y$

**Assumptions:**  $n$  is a power of 2

$O(n^2)$

What is the time complexity using the “grade-school” algorithm.

```
    123456789
x   987654321
-----
```

# Multiplication

(1) III (2) ~~IIII~~  
n-digit

What is the recurrence?

$$T(n) \leq 4T(n/2) + O(n')$$

$$a = 4$$

$$b = 2$$

$$d = 1$$

**FUNCTION** RecursiveIntMult(x, y)

n = NumDigits(x)

**IF** n == 1, **RETURN** x \* y

a, b = SplitIntIntoHalves(x)

c, d = SplitIntIntoHalves(y)

ac = RecursiveIntMult(a, c)

ad = RecursiveIntMult(a, d)

bc = RecursiveIntMult(b, c)

bd = RecursiveIntMult(b, d)

**RETURN** 10<sup>n</sup> \* ac  
+ 10<sup>(n/2)</sup> \* (ad + bc)  
+ bd

# Multiplication

$$T(n) \leq 4 T(n/2) + O(n)$$

$$a=4, b=2, d=1$$

4 ? 2<sup>1</sup> → case 3

$$O(n^{\log_2 4})$$

$$O(n^2)$$

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Karatsuba (guess the year) 1960!

```
FUNCTION RecursiveIntMult(x, y)
  n = NumDigits(x)
  IF n == 1, RETURN x * y

  a, b = SplitIntIntoHalves(x)
  c, d = SplitIntIntoHalves(y)

  ac = RecursiveIntMult(a, c)
  ad = RecursiveIntMult(a, d)
  bc = RecursiveIntMult(b, c)
  bd = RecursiveIntMult(b, d)

  RETURN 10^n * ac
        + 10^(n/2) * (ad + bc)
        + bd
```

```
FUNCTION Karatsuba(x, y)
  n = NumDigits(x)
  IF n == 1, RETURN x * y

  a, b = SplitIntIntoHalves(x)
  c, d = SplitIntIntoHalves(y)

  p = a + b
  q = c + d

  ac = Karatsuba(a, c)
  bd = Karatsuba(b, d)

  pq = Karatsuba(p, q)

  adbc = pq - ac - bd

  RETURN 10^n * ac
        + 10^(n/2) * adbc
        + bd
```

# Karatsuba

```
FUNCTION RecursiveIntMult(x, y)
    n = NumDigits(x)
    IF n == 1, RETURN x * y

    a, b = SplitIntIntoHalves(x)
    c, d = SplitIntIntoHalves(y)

    ac = RecursiveIntMult(a, c)
    ad = RecursiveIntMult(a, d)
    bc = RecursiveIntMult(b, c)
    bd = RecursiveIntMult(b, d)

    RETURN 10^n * ac
           + 10^(n/2) * (ad + bc)
           + bd
```

```
FUNCTION Karatsuba(x, y)
    n = NumDigits(x)
    IF n == 1, RETURN x * y

    a, b = SplitIntIntoHalves(x)
    c, d = SplitIntIntoHalves(y)

    p = a + b
    q = c + d

    ac = Karatsuba(a, c)
    bd = Karatsuba(b, d)

    pq = Karatsuba(p, q)

    adbc = pq - ac - bd

    RETURN 10^n * ac
           + 10^(n/2) * adbc
           + bd
```

# Karatsuba

What is the recurrence?

$a=3$  ,  $b=2$  ,  $d=1$

$3 ? 2^1 \rightarrow \text{case 3}$

$O(n)$

```
FUNCTION Karatsuba(x, y)
```

```
  n = NumDigits(x)
```

```
  IF n == 1, RETURN x * y
```

Constant

```
  a, b = SplitIntIntoHalves(x)
```

```
  c, d = SplitIntIntoHalves(y)
```

Constant

```
  p = a + b
```

```
  q = c + d
```

Linear

```
  ac = Karatsuba(a, c)
```

```
  bd = Karatsuba(b, d)
```

```
  pq = Karatsuba(p, q)
```

```
  adbc = pq - ac - bd
```

Linear

```
  RETURN 10^n * ac
```

```
          + 10^(n/2) * adbc
```

```
          + bd
```

Linear

# Karatsuba

$$T(n) \leq 3 T(n/\overset{2}{\cancel{3}}) + O(n)$$

$$a = 3, \quad b = 2, \quad d = 1$$

$$3 ? 2^1 \Rightarrow \text{case 3}$$

$$O(n^{\log_2 3})$$
$$O(n^{1.58})$$

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

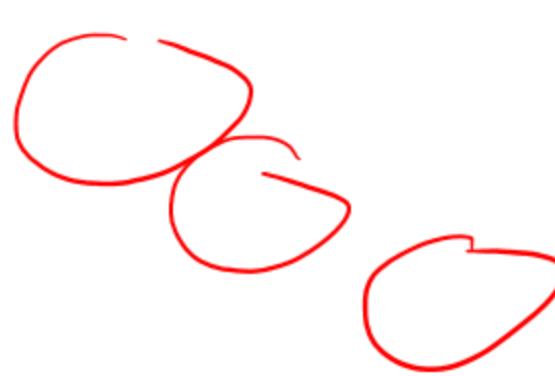
$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Iterative Matrix Multiplication

$$z_{ij} = \sum_{k=1}^n x_{ik} y_{kj}$$

```
1. FUNCTION IMM(X, Y)
2.   Z = create_new_matrix(X.size, X.size)
3.
4.   FOR i IN [0 ..< X.size]
5.     FOR j IN [0 ..< X.size]
6.       FOR k IN [0 .. < X.size]
7.         Z[i][j] += X[i][k] * Y[k][j]
8.
9.   RETURN Z
```



$O(n^3)$

What are “a”, “b”, and “d”?

# Recursive Matrix Multiplication

1. **FUNCTION** RMM(X, Y)

2.     **IF** X.size == 1

3.         **RETURN** X \* Y

4.

5.     Z = create\_new\_matrix(X.size, X.size)

6.

7.     Z(1,1) = RMM(X(1,1), Y(1,1)) + RMM(X(1,2), Y(2,1)) # Upper left

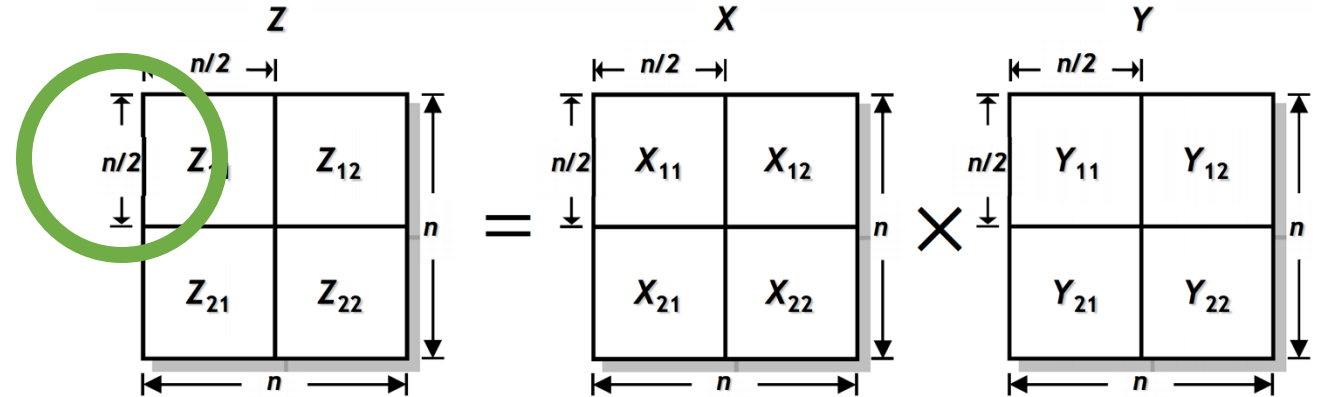
8.     Z(1,2) = RMM(X(1,1), Y(1,2)) + RMM(X(1,2), Y(2,2)) # Upper right

9.     Z(2,1) = RMM(X(2,1), Y(1,1)) + RMM(X(2,2), Y(2,1)) # Lower left

10.    Z(2,2) = RMM(X(2,1), Y(1,2)) + RMM(X(2,2), Y(2,2)) # Lower right

11.

12.    **RETURN** Z



Quadratic

Element-wise addition of matrices

What are “a”, “b”, and “d”?

a=8, b=2, d=2

# Matrix Multiplication

## Recursive matrix multiplication

$$O(n^3)$$

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Strassen's Matrix Multiplication

```
1. FUNCTION SMM(X, Y)
2.   IF X.size == 1
3.     RETURN X * Y
4.
5.   PA = SMM(X(1,1), Y(1,2) - Y(2,2))
6.   PB = SMM(X(1,1) + X(1,2), Y(2,2))
7.   PC = SMM(X(2,1) + X(2,2), Y(1,1))
8.   PD = SMM(X(2,2), Y(2,1) - Y(1,1))
9.   PE = SMM(X(1,1) + X(2,2), Y(1,1) + Y(2,2))
10.  PF = SMM(X(1,2) - X(2,2), Y(2,1) + Y(2,2))
11.  PG = SMM(X(1,1) - X(2,1), Y(1,1) + Y(1,2))
```

Quadratic

```
12.  Z(1,1) = PE + PD - PB + PF
13.  Z(1,2) = PA + PB
14.  Z(2,1) = PC + PD
15.  Z(2,2) = PA + PE - PC - PG
16.
17.  RETURN Z
```

What are “a”, “b”, and “d”?

$$a = 7$$

$$b = 2$$

$$d = 2$$

# Exercise

Strassen's matrix multiplication

$$T(n) \leq 7 T(n/2) + O(n^2)$$

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Master Method Proof

Does the Master Method actually work?

## Assume

- $T(1) = O(1)$  (this is our base-case)
  - $T(n) \leq a T(n/b) + cn^d$
  - $n$  is a power of  $b$  (not necessary, but makes the math easier)
- How did we analyze the running time of merge sort?

$$\left\lfloor \frac{n}{2} \right\rfloor$$

Drew a pretty picture : recursion tree

# Generalizing the Recursion Tree Analysis

For merge sort

- What was the # number of subproblems for a given level  $L$ ?
- What was the size of each of the subproblems at level  $L$ ?
- How many total levels were there?

# Merge Sort Exercise

1. How many sub-problems are there at level 'L'? (Note: the top level is 'Level 0', the second level is 'Level 1', and the bottom level is 'Level  $\log_2(n)$ ')

Answer:  $2^L$

2. How many elements are there for a given sub-problem found in level 'L'?

Answer:  $n/2^L$

3. How many computations are performed at a given level? (Note the cost of a 'merge' operation was  $21m$ )

Answer:  $2^L 21(n/2^L) \rightarrow 21n$

4. What is the total computational cost of merge sort?

Answer:  $21n (\log_2(n) + 1)$

# Generalizing the Recursion Tree Analysis

For merge sort

- What was the # number of subproblems for a given level  $L$ ?
- What was the size of each of the subproblems at level  $L$ ?
- How many total levels were there?

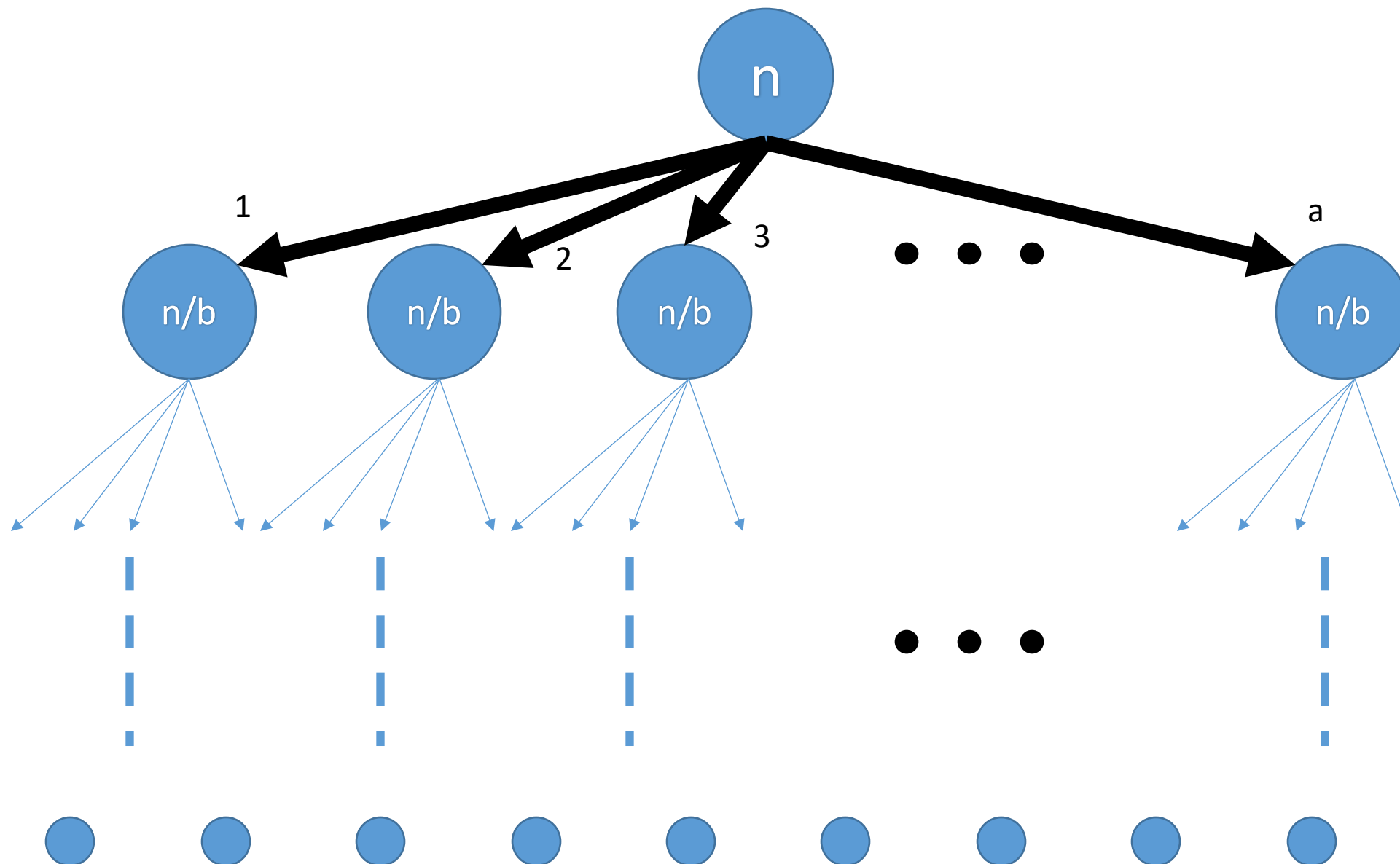
In the general case

- What is the # number of subproblems for a given level  $L$ ?
- What is the size of each of the subproblems at level  $L$ ?
- How many total levels are there?

Level 0

Level 1

Level  $\log_b n$

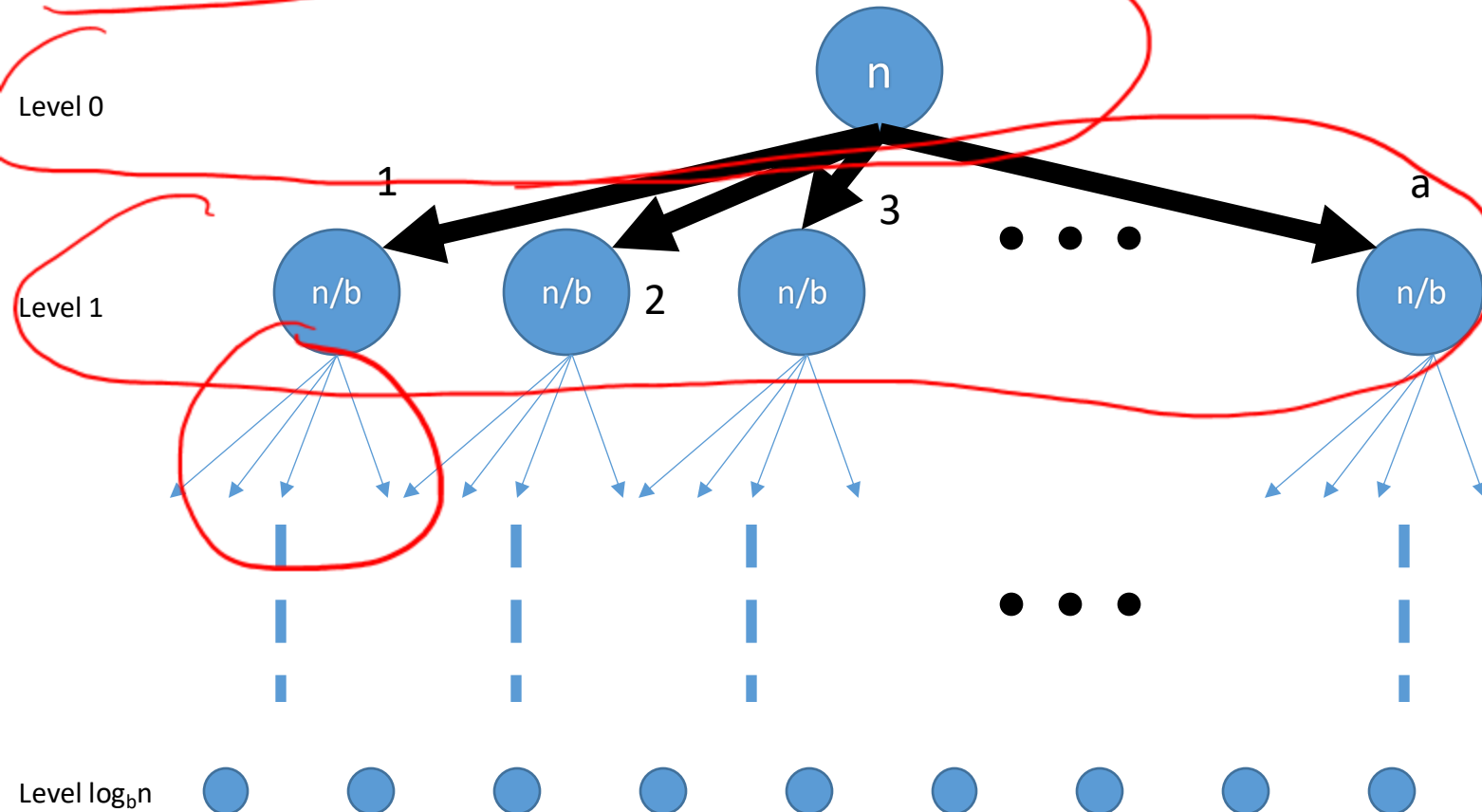


# How many sub-problems at level L?

$L = 432$

$SP(L) =$

$a^L$



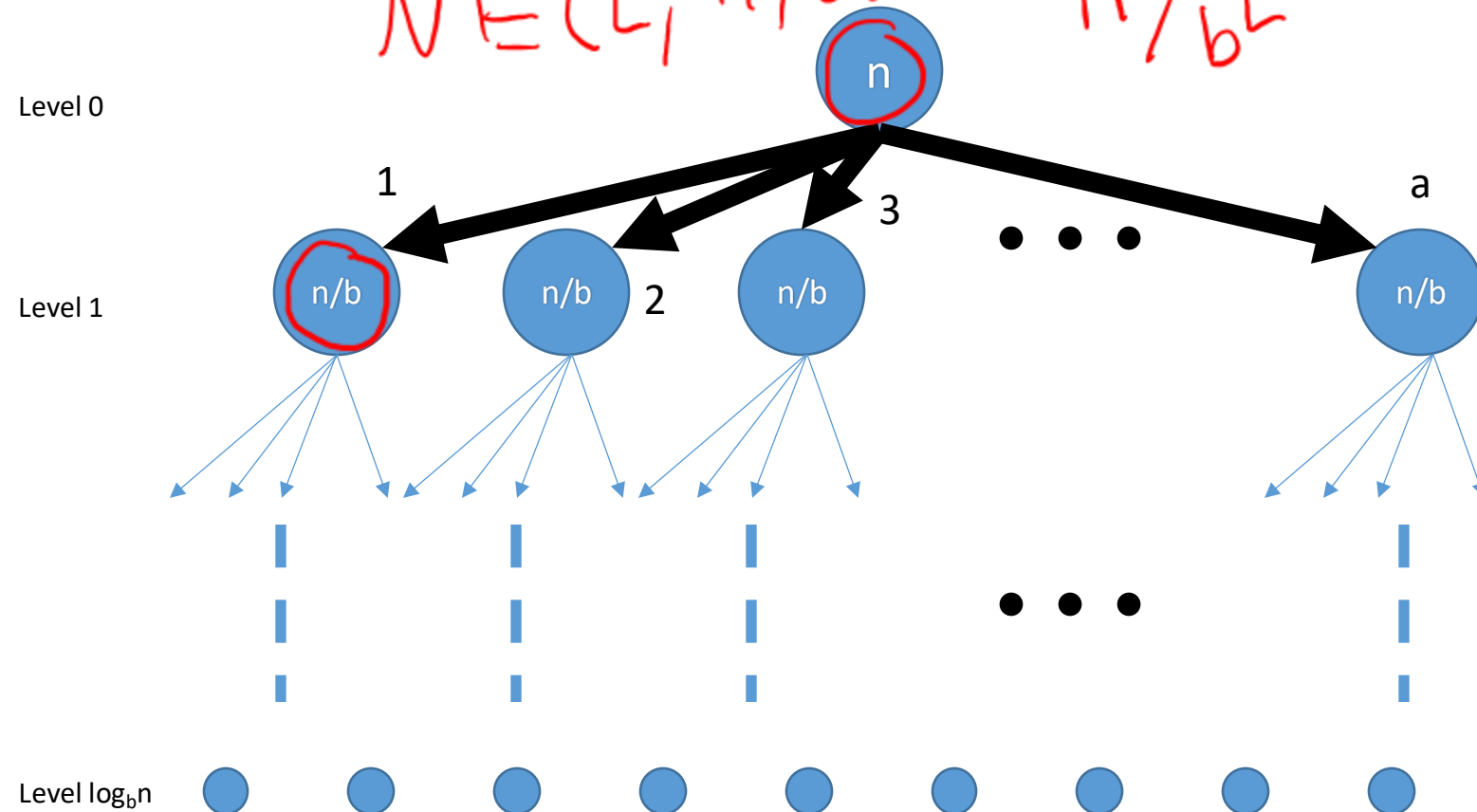
L	# Sub-Problems
0	1
1	a
2	a · a
⋮	
<del>1</del>	

# How many elements for each problem at level L?

$a, b, d$

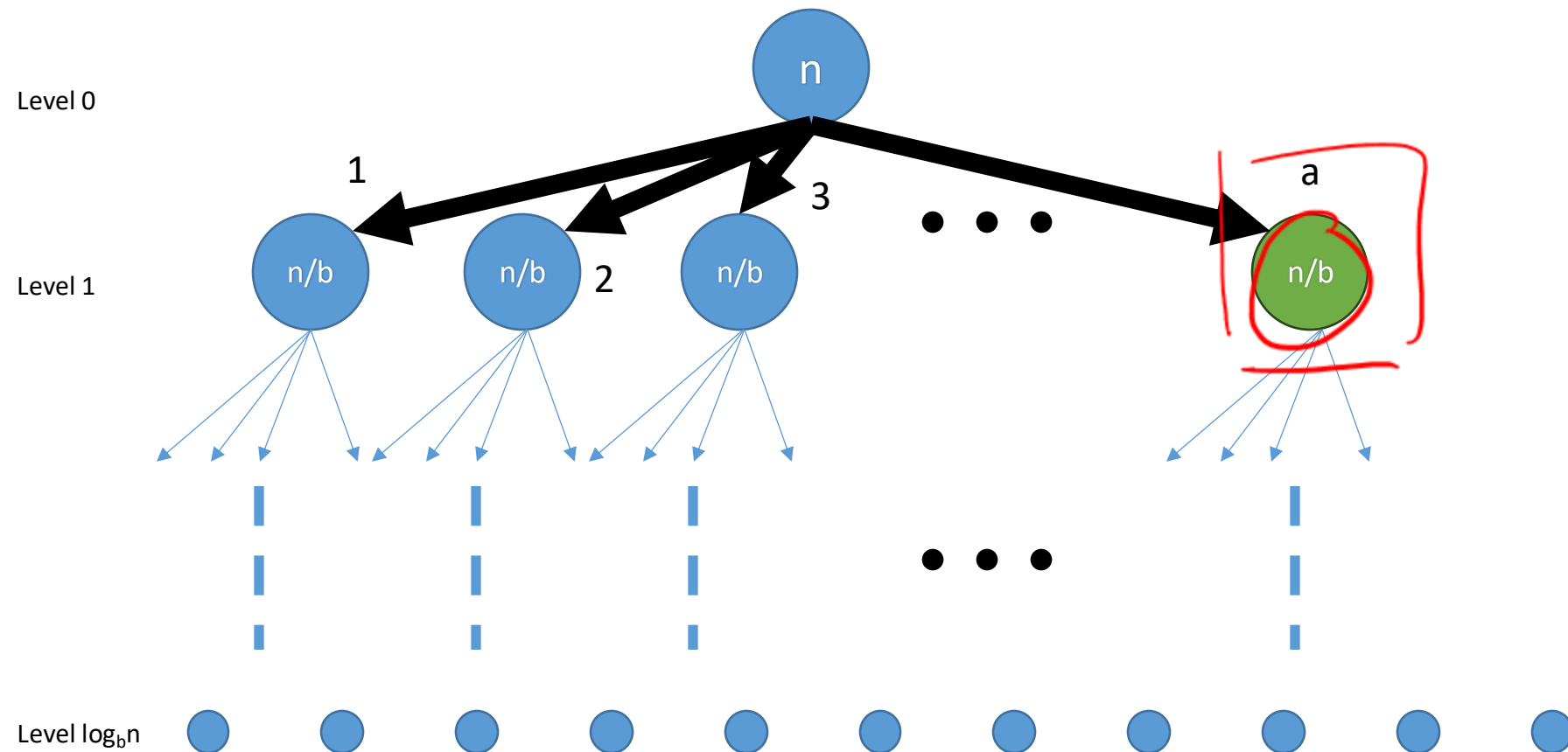
$$NE(L) = \frac{n}{b^L}$$

$$NE(L, n, b) = n/b^L$$



L	# Elements
0	$n$
1	$n/b$
2	$n/b/b$
$\vdots$	
$\log_b n$	$n/b^{\log_b n}$

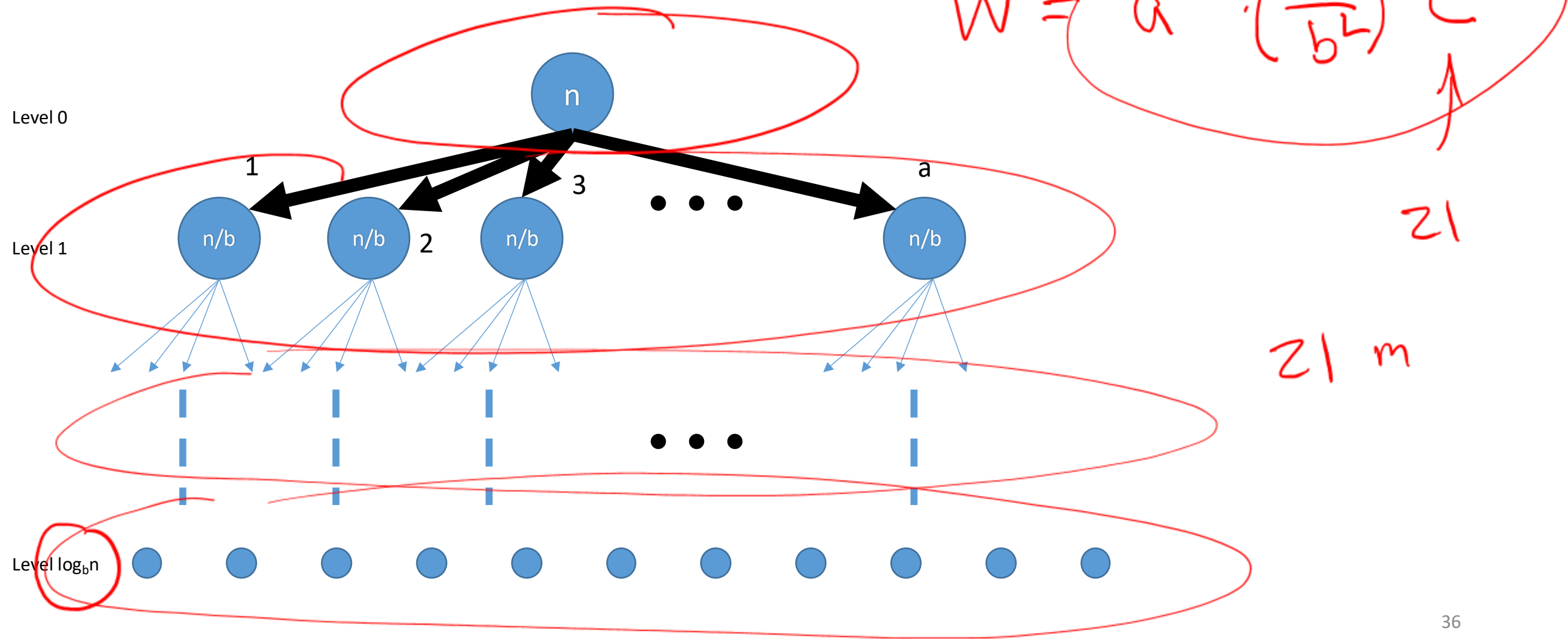
# How much work is done outside of recursion?



Related  
to d

$n^d$   
 $(n/b^d)^d$

# What is the total work done at level L?



$a =$  ,  $b =$  ,  $d =$

What is the total work done at level  $L$ ?

Work at (any) Level  $L$

$$a^L c \left( \frac{n}{b^L} \right)^d$$

$$\cancel{a^L c} \cancel{n^d} \frac{1}{b^L d}$$
$$c n^d \left( \frac{a}{b^d} \right)^L$$

What is the total work done at level L?

Work at (any) Level L

$$a^L c (n/b^L)^d$$

Rewrite to group together terms dependent on level

$$c n^d (a/b^d)^L$$

# What is the total work done at level L?

Work at (any) Level L

$$a^L c (n/b^L)^d$$

Rewrite to group together terms dependent on level

$$c n^d (a/b^d)^L$$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

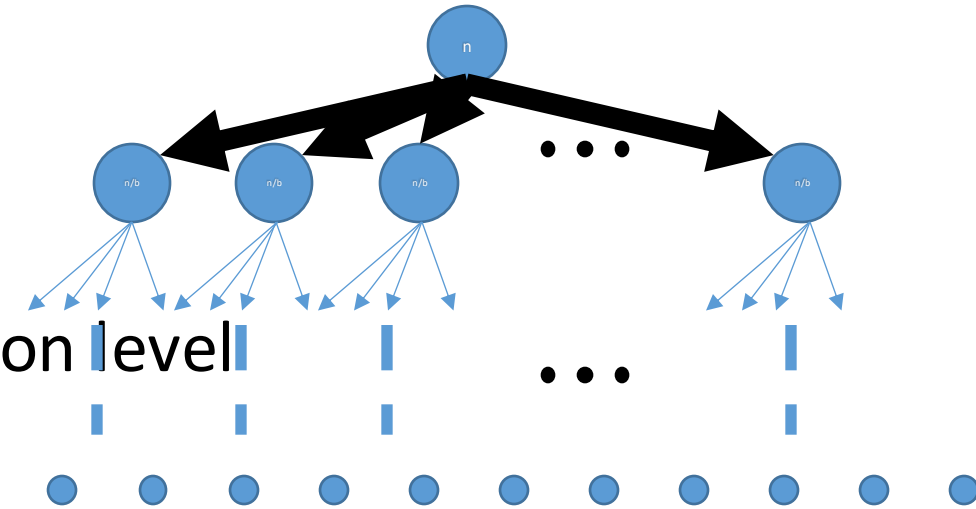
# What is the total work done for the tree?

Work at (any) Level **L**

$$a^L c (n/b^L)^d$$

Rewrite to group together terms dependent on level

$$cn^d (a/b^d)^L$$



Work done for the entire tree

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

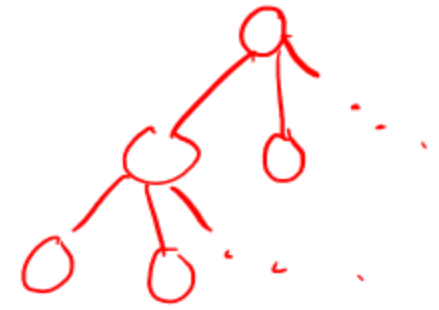
# Work done by a recursive algorithm\*

\*With an equal number of elements in each subproblem.

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

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} \left( \frac{a}{b^d} \right)^L$$

# Let's look at the cases again



What happens when

$a = b^d$  : work stays roughly the same at each level

$O(\text{work at each level} * \text{number of levels})$

$O(n^d \lg n)$

$a < b^d$  : work goes down at each level

$O(\text{work done at the root})$

$O(n^d)$

$a > b^d$  : work goes up at each level

$O(\text{work done at the leaves})$

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

# Review

From where do we get the cases?

- We have three different cases of trees
  1. Work is similar at each level
  2. Work decreases at each level
  3. Work increases at each level
- These trees lead to our three cases for the Master Method
- What really matters is the ratio between  $a$  and  $b^d$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d & \text{Case 1} \\ O(n^d), & a < b^d & \text{Case 2} \\ O(n^{\log_b a}), & a > b^d & \text{Case 3} \end{cases}$$

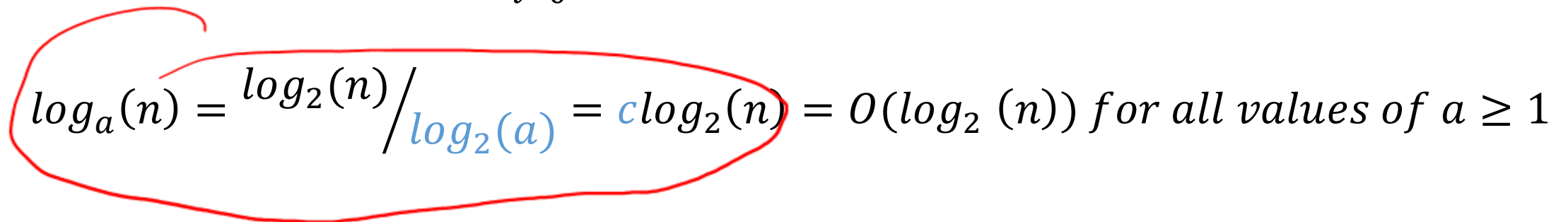
a vs b<sup>d</sup>?

A few helpers

$$\sum_{i=0}^k 1 = k + 1$$

$$\sum_{i=0}^{\infty} r^i = \frac{1}{1-r} \text{ when } r < 1$$

$$\sum_{i=0}^k r^i = \frac{r^{k+1} - 1}{r - 1} \text{ when } r > 1$$


$$\log_a(n) = \log_2(n) / \log_2(a) = c \log_2(n) = O(\log_2(n)) \text{ for all values of } a \geq 1$$

# Proving the Master Method: Case 1: $a = b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} \left( \frac{a}{b^d} \right)^L$$

$$cn^d \sum_{L=0}^{\log_b n} (1)^L$$

$$cn^d (\log_b n + 1)$$

1.  $a = b^d$

2.  $\sum_{i=0}^k 1 = k + 1$

$cn^d \log_b n$  +  ~~$cn^d$~~

**Claim:**  $T(n) = O(n^d \lg n)$

$$cn^d(\log_b n + 1) = O(n^d \lg n)$$

On your own.

# Master Method

$$T(n) \leq a T(n/b) + O(n^d)$$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

# Proving the Master Method: Case 2: $a < b^d$

$$\begin{aligned} T(n) &\leq cn^d \sum_{L=0}^{\log_b n} \left(\frac{a}{b^d}\right)^L \\ &= cn^d \sum_{L=0}^{\log_b n} \left(\frac{a}{b^d}\right)^L \\ &= cn^d \frac{\left(\frac{a}{b^d}\right)^{\log_b n+1} - 1}{\left(\frac{a}{b^d}\right) - 1} \\ &= cn^d \frac{1 - \left(\frac{a}{b^d}\right)^{\log_b n+1}}{1 - \left(\frac{a}{b^d}\right)} \end{aligned}$$

1.  $a < b^d$

2.  $\sum_{i=0}^k r^i = \frac{r^{k+1} - 1}{r - 1}$

3. Multiply top and bottom by -1

$$< cn^d \frac{1}{1 - \left(\frac{a}{b^d}\right)}$$

# Proving the Master Method: Case 2: $a < b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$cn^d \frac{(a/b^d)^{\log_b n+1} - 1}{(a/b^d) - 1}$$

$$cn^d \frac{1 - (a/b^d)^{\log_b n+1}}{1 - (a/b^d)}$$

1.  $a < b^d$

2.  $\sum_{i=0}^k r^i = \frac{r^{k+1} - 1}{r - 1}$

3. Multiply top and bottom by -1

4. We can remove the complex term from the numerator and keep the original inequality

# Proving the Master Method: Case 2: $a < b^d$

What can we say about this term?

$$T(n) \leq cn^d \frac{1}{1 - (a/b^d)}$$

$$cn^d c_2$$

$a/b^d$  is constant with respect to  $n$

Claim:  $T(n) = O(n^d)$

$$cn^d c_2 = O(n^d)$$

On your own

# Master Method

$$T(n) \leq a T(n/b) + O(n^d)$$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$

$$C_1 + C_2 \lg(n) + C_3 n + C_4 n^2 + C_5 n^7 = O(n^7)$$

Proving the Master Method: Case 3:  $a > b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} \left(\frac{a}{b^d}\right)^L$$

$$cn^d \sum_{L=0}^{\log_b n} \left(\frac{a}{b^d}\right)^L$$

1.  $a > b^d$

2. Last term of summation is asymptotically largest:



$$cn^d \left( \left(\frac{a}{b^d}\right)^0 + \left(\frac{a}{b^d}\right)^1 + \left(\frac{a}{b^d}\right)^2 + \dots + \left(\frac{a}{b^d}\right)^{\log_b n} \right)$$

$$cn^d + cn^d \left(\frac{a}{b^d}\right) + \dots + cn^d \left(\frac{a}{b^d}\right)^{\log_b n}$$

# Proving the Master Method: Case 3: $a > b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$c_1 n^d (a/b^d)^{\log_b n}$$

$$= O(n^d (a/b^d)^{\log_b n})$$

1.  $a > b^d$

2. Last term of summation is asymptotically largest:

$$(a/b^d)^{\log_b n}$$

~~$\times \log_b n$~~

## Proving the Master Method: Case 3: $a > b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$c_1 n^d (a/b^d)^{\log_b n}$$

$$\begin{aligned} & c_1 n^d a^{\log_b n} \cancel{b^{-d \log_b n}} \\ & \cancel{c_1 n^d} \cancel{a^{\log_b n}} \cancel{b^{\log_b n}} \cancel{n^{-d}} = c_1 a^{\log_b n} \end{aligned}$$

1.  $a > b^d$

2. Last term of summation is asymptotically largest:

$$(a/b^d)^{\log_b n}$$

3. Distribute the exponent and simplify


$$= c_1 a^{\log_b n}$$

# Proving the Master Method: Case 3: $a > b^d$

$$T(n) \leq cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$cn^d \sum_{L=0}^{\log_b n} (a/b^d)^L$$

$$c_1 n^d (a/b^d)^{\log_b n}$$

$$c_1 a^{\log_b n}$$


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

1.  $a > b^d$

2. Last term of summation is asymptotically largest:

$$(a/b^d)^{\log_b n}$$

3. Distribute the exponent and simplify

$$\log_b \text{ ———}$$

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

On your own.

# Master Method Summary

1. We analyzed a generalized recursion tree
2. Counted the amount of work done at each level
3. Counted the amount of work done by the tree
4. Found that we have three different types of trees
  1. Same rate throughout (case 1:  $a = b^d$ )
  2. Root dominates (case 2:  $a < b^d$ )
  3. Leaves dominate (case 3:  $a > b^d$ )
5. Saw that these trees relate to the difference master method cases

$$T(n) \leq a T(n/b) + O(n^d)$$

$T(n)$  : total amount of operations

$a$  : recursive calls (# of subproblems), always  $\geq 1$

$b$  : fraction of input size (shrinkage), always  $> 1$

$d$  : extra work needed to combine, always  $\geq 0$

$$T(n) = \begin{cases} O(n^d \lg n), & a = b^d \\ O(n^d), & a < b^d \\ O(n^{\log_b a}), & a > b^d \end{cases}$$