

# Algorithms and Datastructures

Divide and Conquer, Master theorem

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# Structure

## Divide and Conquer

- Concept

- Maximum Subtotal

## Recursion Equations

- Substitution Method

- Recursion Tree Method

- Master theorem

  - Master theorem (Simple Form)

  - Master theorem (General Form)

# Divide and Conquer

## Introduction

### Concept:

- ▶ **Divide** the problem into smaller subproblems
- ▶ **Conquer** the subproblems through recursive solving.  
If subproblems are small enough solve them directly
- ▶ **Connect** all subsolutions to solve the overall problem
- ▶ **Recursive** application of the algorithm on smaller subproblems
- ▶ **Direct** solving of small subproblems

# Divide and Conquer

## Maximum Subtotal

### Input:

- ▶ Sequence  $X$  of  $n$  integers

### Output:

- ▶ Maximum sum of an uninterrupted subsequence of  $X$  and its index boundary

Table: Input values

Index	0	1	2	3	4	5	6	7	8	9
Value	31	-41	59	26	-53	58	97	-93	-23	84

**Output:** Sum: 187, Start: 2, End: 6

# Divide and Conquer

## Maximum Subtotal

### Idea:



- ▶ Solve the left / right half of the problem **recursive**
- ▶ Combine both solutions into a overall solution
- ▶ The maximum is located in the **left half (A)** or the **right half (B)**
- ▶ The maximum interval can **overlap with the border (C)**

# Divide and Conquer

## Maximum Subtotal

### Principle:



- ▶ Small problems are solved directly:  $n = 1 \Rightarrow \max = X[0]$
- ▶ Big problems are decomposed into two subproblems and solved recursively. Subsolutions  $A$  and  $B$  are returned
- ▶ To solve  $C$  we have to calculate  $rmax$  and  $lmax$
- ▶ Overall solution is maximum of  $A$   $B$  and  $C$

# Divide and Conquer

## Maximum Subtotal - Python

```
def maxSubArray(X, i, j):  
    if i == j: # trivial case  
        return (X[i], i, i)  
  
    # recursive subolutions for A, B  
    m = (i + j) / 2  
    A = maxSubArray(X, i, m)  
    B = maxSubArray(X, m + 1, j)  
  
    # rmax and lmax for cornercase C  
    C1, C2 = rmax(X, i, m), lmax(X, m + 1, j)  
    C = (C1[0] + C2[0], C1[1], C2[1])  
  
    # compute solution from results A, B, C  
    return max([A, B, C], key=lambda i: i[0])
```

# Divide and Conquer

## Maximum Subtotal - Python

```
#Alternative trivial case
def maxSubArray(X, i, j):
    # trivial: only one element
    if i == j:
        return (X[i], i, i)

    # trivial: only two elements
    if i + 1 == j:
        return max([
            (X[i], i, i),
            (X[j], j, j),
            (X[i] + X[j], i, j)
        ], key=lambda item: item[0])

    ... # continue as before
```



# Divide and Conquer

## Maximum Subtotal - Python

```
#Implementation max
def max(a, b, c):
    if a > b:
        if a > c:
            return a
        else:
            return c
    else:
        if c > b:
            return c
        else:
            return b
```

# Divide and Conquer

## Maximum Subtotal - Python

```
#Alternative implementation max
```

```
def max(a, b):  
    if a > b:  
        return a  
    else:  
        return b
```

```
def maxTripel(a, b, c):  
    return max(max(a,b),c)
```

# Divide and Conquer

## Maximum Subtotal - Python

```
#Implementation left maximum
def lmax(X, i, j):
    maxSum = (X[i], i)
    s = X[i]

    # sum up from the lower index going up
    # (from left to right)
    for k in range(i+1, j+1):
        s += X[k]

        if s > maxSum[0]:
            maxSum = (s, k)

    return maxSum
```

# Divide and Conquer

## Maximum Subtotal - Python

```
#Implementation right maximum
def rmax(X, i, j):
    maxSum = (X[j], j)
    s = X[i]

    # sum up from the upper index going down
    # (from right to left)
    for k in range(j-1, i-1, -1):
        s += X[k]

        if s > maxSum[0]:
            maxSum = (s, k)

    return maxSum
```

# Divide and Conquer

## Maximum Subtotal

Table:  $lmax$  example

index	$i$	$i + 1$	$\dots$	$\dots$	$j - 1$	$j$
$X$	58	-53	26	59	-41	31
$sum$	58	5	31	90	49	80
$lmax$	58	58	58	90	90	90

- ▶ The  $sum$  and  $lmax$  are initialized with  $X[i]$
- ▶ We iterate over  $X$  from  $i + 1$  to  $j$  and update  $sum$
- ▶ If  $sum > lmax$  then  $lmax$  gets updated

# Divide and Conquer

## Maximum Subtotal

Call with array of four elements



# Divide and Conquer

## Maximum Subtotal - Python

```
def maxSubArray(X, i, j):  
    if i == j:                                     # O(1)  
        return (X[i], i, i)                       # O(1)  
  
    m = (i + j) / 2                                # O(1)  
    A = maxSubArray(X, i, m)                       # T(n/2)  
    B = maxSubArray(X, m + 1, j)                   # T(n/2)  
  
    C1 = rmax(X, i, m)                             # O(n)  
    C2 = lmax(X, m + 1, j)                         # O(n)  
    C = (C1[0] + C2[0], C1[1], C2[1])              # O(1)  
  
    return max([A, B, C], \                        # O(1)  
               key=lambda item: item[0])
```

# Divide and Conquer

Maximum Subtotal - Number of steps  $T(n)$

**Recursion equation:**

$$T(n) = \begin{cases} \Theta(1) & n = 1 \\ \underbrace{2 \cdot T\left(\frac{n}{2}\right)}_{\text{solving of subproblems}} + \underbrace{\Theta(n)}_{\text{combination of solutions}} & n > 1 \end{cases}$$

$\underbrace{\Theta(1)}_{\text{trivial case}}$

- There exist two constants  $a$  and  $b$  with:

$$T(n) \leq \begin{cases} a & n = 1 \\ 2 \cdot T\left(\frac{n}{2}\right) + b \cdot n & n > 1 \end{cases}$$

- We define  $c := \max(a, b)$ :

$$T(n) \leq \begin{cases} c & n = 1 \\ 2 \cdot T\left(\frac{n}{2}\right) + c \cdot n & n > 1 \end{cases}$$



# Divide and Conquer

Maximum Subtotal - Illustration of  $T(n)$



Figure: Illustration of the runtime

# Divide and Conquer

## Maximum Subtotal - Illustration of $T(n)$



1 node processing  $n$  elements  
 $\Rightarrow c \cdot n$

2 nodes processing  $\frac{n}{2}$  elements  
 $\Rightarrow 2 c \cdot \frac{n}{2} = c \cdot n$

4 nodes processing  $\frac{n}{4}$  elements  
 $\Rightarrow 4 c \cdot \frac{n}{4} = c \cdot n$

$2^i$  nodes processing  $\frac{n}{2^i}$  elements  
 $\Rightarrow 2^i c \cdot \frac{n}{2^i} = c \cdot n$

$n$  nodes processing 1 element  
 $\Rightarrow c \cdot n$

Figure: Recursion tree method

# Divide and Conquer

Maximum Subtotal - Illustration of  $T(n)$

## Depth:

- ▶ Top level with depth  $i = 0$
- ▶ Lowest level with  $2^i = n$  elements

$$\Rightarrow i = \log_2 n$$

## Runtime:

- ▶ A total of  $\log_2 n + 1$  levels with each cost of  $c \cdot n$   
The costs of merging the solutions and solving of the trivial problems are the same here

$$T(n) = c \cdot n \log_2 n + c \cdot n \in \Theta(n \log n)$$

# Divide and Conquer

## Maximum Subtotal - Summary

### Summary:

- ▶ Direct solution is slow with  $\mathcal{O}(n^3)$
- ▶ Better solution with incremental update of sum was  $\mathcal{O}(n^2)$
- ▶ Divide and conquer approach results in  $\mathcal{O}(n \log n)$
- ▶ There is an approach running in  $\mathcal{O}(n)$  if you assume that all subtotals are positive

# Divide and Conquer

## Maximum Subtotal



Figure: Scanning the array in linear time

# Divide and Conquer

## Maximum Subtotal - Python

```
#Implementation - linear runtime
def maxSubArray(X):
    # sum, start index
    rMax, irMax = 0, 0 # current maximum
    tMax, itMax = 0, 0 # total maximum

    for i in range(len(X)):
        if rMax == 0:
            irMax = i
            rMax = max(0, rMax + X[i])

        if rMax > tMax:
            tMax, itMax = rMax, irMax

    return (tMax, itMax)
```

# Recursion Equations

## Recursion Equation

### Recursion equation:

- Describes the runtime for recursive functions:

$$T(n) = \begin{cases} \overbrace{f_0(n)}^{\text{trivial case for } n_0} & n = n_0 \\ \underbrace{a \cdot T\left(\frac{n}{b}\right)}_{\substack{\text{solving of } a \\ \text{subproblems} \\ \text{with reduced} \\ \text{input size } \frac{n}{b}}} + \underbrace{f(n)}_{\substack{\text{slicing and} \\ \text{splicing of} \\ \text{subsolutions}}} & n > n_0 \end{cases}$$

# Recursion Equations

## Recursion Equation

### Recursion equation:

- ▶ Describes the runtime for recursive functions:

$$T(n) = \begin{cases} f_0(n) & n = n_0 \\ a \cdot T\left(\frac{n}{b}\right) + f(n) & n > n_0 \end{cases}$$

- ▶  $n_0$  is normally small,  $f_0(n_0) \in \Theta(1)$
- ▶ Normally  $a > 1$  and  $b > 1$
- ▶ Dependent on the strategy of solving  $T(n)$   $f_0$  is ignored
- ▶  $T(n)$  is only defined for integers of  $\frac{n}{b}$  which is often ignored in benefit of a simpler solution



# Recursion Equations

## Substitution Method

### Substitution Method:

- ▶ Guess the solution and prove it with induction
- ▶ Example:

$$T(n) = \begin{cases} 1 & n = 1 \\ 2 \cdot T\left(\frac{n}{2}\right) + n & n > 1 \end{cases}$$

- ▶ Assumption:  $T(n) = n + n \cdot \log_2 n$

# Recursion Equations

## Substitution Method

### Induction:

- ▶ Induction basis (for  $n = 1$ ):  $T(1) = 1 + 1 \cdot \log_2 1 = 1$
- ▶ Induction step (from  $\frac{n}{2}$  to  $n$ ):

$$\begin{aligned}T(n) &= 2 \cdot T\left(\frac{n}{2}\right) + n \\&\stackrel{IA}{=} 2 \cdot \left(\frac{n}{2} + \frac{n}{2} \cdot \log_2 \frac{n}{2}\right) + n \\&= 2 \cdot \left(\frac{n}{2} + \frac{n}{2} \cdot (\log_2 n - 1)\right) + n \\&= n + n \log_2 n - n + n \\&= n + n \log_2 n\end{aligned}$$

# Recursion Equations

## Substitution Method

### Substitution Method:

- ▶ Alternative assumption
- ▶ Example:

$$T(n) = \begin{cases} 1 & n = 1 \\ 2 \cdot T\left(\frac{n}{2}\right) + n & n > 0 \end{cases}$$

- ▶ Assumption:  $T(n) \in O(n \log n)$
- ▶ Solution: Find  $c > 0$  with  $T(n) \leq c \cdot n \log_2 n$

# Recursion Equations

## Substitution Method

### Induction:

- ▶ Solution: Find  $c > 0$  with  $T(n) \leq c \cdot n \log_2 n$
- ▶ Induction step (from  $\frac{n}{2}$  to  $n$ ):

$$\begin{aligned}T(n) &= 2 \cdot T\left(\frac{n}{2}\right) + n \\&\leq 2 \cdot \left(c \cdot \frac{n}{2} \log_2 \frac{n}{2}\right) + n \\&= c \cdot n \log_2 n - c \cdot n \log_2 2 + n \\&= c \cdot n \log_2 n - c \cdot n + n \\&\leq c \cdot n \log_2 n, \quad c \geq 1\end{aligned}$$

# Recursion Equations

## Recursion Tree Method

### Recursion tree method:

- ▶ Can be used to make assumptions about the runtime
- ▶ Example:

$$T(n) = 3 \cdot T\left(\frac{n}{4}\right) + \Theta(n^2) \leq 3 \cdot T\left(\frac{n}{4}\right) + c \cdot n^2$$

# Recursion Equations

## Recursion Tree Method

$$T(n) = 3 \cdot T\left(\frac{n}{4}\right) + c \cdot n^2$$

$$T(n) = 3 \cdot T\left(\frac{n}{4}\right) + c \cdot n^2$$

$$T(n) = 3 \cdot T\left(\frac{n}{4}\right) + c \cdot n^2$$

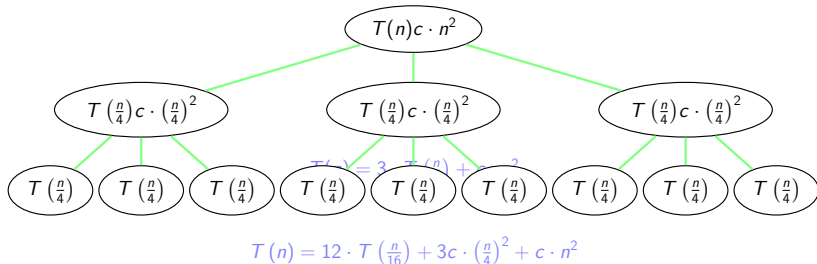


Figure: Recursion tree of example

# Recursion Equations

## Recursion Tree Method



Figure: Levels of the recursion tree

# Recursion Equations

## Recursion Tree Method Costs

### Costs of connecting the partial solutions:

(excludes the last layer)

- ▶ Size of partial problems on level  $i$ :  $s_i(n) = \left(\frac{1}{4}\right)^i \cdot n$
- ▶ Costs of partial problem on level  $i$ :

$$T_{i_p}(n) = c \cdot \left(\left(\frac{1}{4}\right)^i \cdot n\right)^2$$

- ▶ Number of partial problems on level  $i$ :  $n_i = 3^i$
- ▶ Costs on level  $i$ :

$$T_i(n) = 3^i \cdot c \cdot \left(\left(\frac{1}{4}\right)^i \cdot n\right)^2 = \left(\frac{3}{16}\right)^i \cdot c \cdot n^2$$



# Recursion Equations

## Recursion Tree Method Costs

**Costs of solving partial solutions:** (only the last layer)

- ▶ Size of partial problems on the last level:  $s_{i+1}(n) = 1$
- ▶ Costs of partial problem on the last level:  $T_{i+1_p}(n) = d$
- ▶ With this the depth of the tree is:

$$\left(\frac{1}{4}\right)^i \cdot n = 1 \quad \Rightarrow \quad n = 4^i \quad \Rightarrow \quad i = \log_4 n$$

- ▶ Number of partial problems on the last level:

$$n_{i+1} = 3^{\log_4 n} = n^{\log_4 3} \quad \leftarrow \text{next slide}$$

- ▶ Costs on the last level:  $T_{i+1}(n) = d \cdot n^{\log_4 3}$

# Fun with logarithm

## Logarithm

- ▶ Transforming  $3^{\log_4 n}$  uses general log rules

$$\begin{aligned}\log_4 n &= \log_4 \left( 3^{\log_3 n} \right) \\ &= \log_3 n \cdot \log_4 3\end{aligned}$$

$$\text{uses } n = 3^{\log_3 n}$$

$$\text{uses } \log a^b = b \cdot \log a$$

- ▶ This proves the general log rule  $\log_b c = \log_a c \cdot \log_b a$
- ▶ Now the whole expression:

$$\begin{aligned}3^{\log_4 n} &= 3^{\log_3 n \cdot \log_4 3} \\ &= \left( 3^{\log_3 n} \right)^{\log_4 3} \\ &= n^{\log_4 3}\end{aligned}$$

uses reformulation above

$$\text{uses } x^{a \cdot b} = (x^a)^b$$

- ▶ This term will recur in the master theorem

# Recursion Equations

## Total costs

### Total costs:

- ▶ Costs of **level i**:  $T_i(n) = \left(\frac{3}{16}\right)^i \cdot c \cdot n^2$
- ▶ Costs of **last level**:  $T_{i+1}(n) = d \cdot n^{\log_4 3}$

$$T(n) = \underbrace{\sum_{i=0}^{(\log_4 n)-1} \left(\frac{3}{16}\right)^i \cdot c \cdot n^2}_{\substack{\text{geometric series,} \\ \text{constant} \\ \left( \begin{array}{c} \text{even with} \\ \text{infinite elements} \end{array} \right)}} + \underbrace{d \cdot n^{\log_4 3}}_{\substack{\log_4 3 < 1, \\ \text{grows a lot} \\ \text{slower than } n^2}} \in \mathcal{O}(n^2)$$

- ▶ Here: The costs of connecting the partial problems dominate

# Recursion Equations

## Geometric Series

- ▶ **Geometric progression:**

Quotient of two neighboring sequence parts is constant

$$2^0, 2^1, 2^2, \dots, 2^k$$

- ▶ **Geometric series:**

The series (cumulative sum) of a geometric sequence

- ▶ For  $|q| < 1$ :

$$\sum_{k=0}^{\infty} a_0 \cdot q^k = \frac{a_0}{1 - q} \Rightarrow \text{constant}$$

# Recursion Equations

Proof of  $O(n^2)$

**Proof of  $O(n^2)$ :**

► We know:

$$\begin{aligned}T(n) &= 3T\left(\frac{n}{4}\right) + \Theta(n^2) \\&\leq 3T\left(\frac{n}{4}\right) + c \cdot n^2\end{aligned}$$

► Assumption:  $T(n) \in O(n^2)$ , so there exists a  $k > 0$  with

$$T(n) \leq k \cdot n^2$$

# Recursion Equations

Proof of  $O(n^2)$

**Proof of  $O(n^2)$ :**

- Presumption:  $T(n) \in O(n^2)$ , so there exists a  $k > 0$  with

$$T(n) < k \cdot n^2$$

- Substitution method:

$$\begin{aligned} T(n) &\leq 3 \cdot T\left(\frac{n}{4}\right) + c \cdot n^2 \\ &\leq 3k \cdot \left(\frac{n}{4}\right)^2 + c \cdot n^2 \\ &= \frac{3}{16} k \cdot n^2 + c \cdot n^2 \\ &\leq k \cdot n^2 \qquad \text{for } k \geq \frac{16}{13} c \end{aligned}$$

# Recursion Equations

## Master theorem

### Master theorem:

- ▶ Approach to solve for a recursion equation of the form:

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + f(n), \quad a \geq 1, b > 1$$

- ▶  $T(n)$  is the runtime of an algorithm ...
  - ▶ ... which divides a **problem of size  $n$**  in  **$a$  partial problems**
  - ▶ ... which solves each partial problem recursively with a **runtime of  $T\left(\frac{n}{b}\right)$**
  - ▶ ... which takes  **$f(n)$**  steps to merge all partial solutions

# Recursion Equations

## Master theorem (Simple Form)

### Master theorem:

- ▶ In the examples we have seen that ...
  - ▶ Either the runtime of **connecting the solutions** dominates
  - ▶ Or the runtime of **solving the problems** dominates
  - ▶ Or both have **equal influence on runtime**
- ▶ **Simple form:** Special case with runtime of connecting the solutions  $f(n) \in O(n)$



# Recursion Equations

## Master theorem (Simple Form)

### Simple form:

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + \underbrace{c \cdot n}_{\substack{\text{Is any } f(n) \\ \text{in general form}}}, \quad a \geq 1, b > 1, c > 0$$

- This yields a runtime of:

$$T(n) = \begin{cases} \Theta(\overbrace{n^{\log_b a}}^{\text{Number of leaves}}) & \text{if } a > b \\ \Theta(n \log n) & \text{if } a = b \\ \Theta(n) & \text{if } a < b \end{cases}$$

# Recursion Equations

## Master theorem (Simple Form)



Figure: Simple recursion equation with  $a = 3, b = 2$

### Case 1: $a > b$

- ▶ Three partial problems with  $\frac{1}{2}$  the size
- ▶ Solving the partial problems dominates (last layer, leaves)
- ▶ Runtime of  $\Theta(n^{\log_b a})$

# Recursion Equations

## Master theorem (Simple Form)

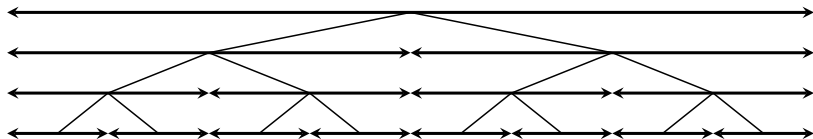


Figure: Simple recursion equation with  $a = 2, b = 2$

### Case 2: $a = b$

- ▶ Two partial problems with  $\frac{1}{2}$  the size
- ▶ Each layer has equal costs,  $\log n$  layers
- ▶ Runtime of  $\Theta(n \log n)$

# Recursion Equations

## Master theorem (Simple Form)



Figure: Simple recursion equation with  $a = 2, b = 3$

### Case 3: $a < b$

- ▶ Two partial problems with  $\frac{1}{3}$  the size
- ▶ Connecting all partial solutions dominates (first layer, root)
- ▶ Runtime of  $\Theta(n)$

# Recursion Equations

## Master theorem (Simple Form)

**For a recursion equation like**

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + c \cdot n, \quad a \geq 1, b > 1, c > 0$$

- ... yields to a runtime of:

$$T(n) = \begin{cases} \Theta(n^{\log_b a}) & \text{if } a > b \\ \Theta(n \log_b n) & \text{if } a = b \\ \Theta(n) & \text{if } a < b \end{cases}$$

- Proof with *geometric series*: Number of operations per layer grows / shrinks by constant factor  $\frac{a}{b}$

# Recursion Equations

## Master theorem (General Form)

### Master theorem (general form):

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + f(n), \quad a \geq 1, b > 1$$

- **Case 1:**  $T(n) \in \Theta(n^{\log_b a})$  if  $f(n) \in \mathcal{O}(n^{\log_b a - \varepsilon})$ ,  $\varepsilon > 0$

Solving the partial problems dominates  
(last layer, leaves)

- **Case 2:**  $T(n) \in \Theta(n^{\log_b a} \log n)$  if  $f(n) \in \Theta(n^{\log_b a})$

Each layer has equal costs,  $\log_b n$  layers

# Recursion Equations

## Master theorem (General Form)

### Master theorem (general form):

- **Case 3:**  $T(n) \in \Theta(f(n))$  if  $f(n) \in \Omega(n^{\log_b a + \varepsilon})$ ,  $\varepsilon > 0$   
Connecting all partial solutions in first layer (root) dominates

Regularity condition:

$$a \cdot f\left(\frac{n}{b}\right) \leq c \cdot f(n), \quad 0 \leq c \leq 1, \\ n > n_0$$

# Recursion Equations

## Master theorem (General Form) - Case 1

**Case 1 - Example:**  $T(n) \in \Theta(n^{\log_b a})$

if

$f(n) \in O(n^{\log_b a - \epsilon}), \epsilon > 0$

Solving the partial problems dominates (last layer, leaves)

►  $T(n) = 8 \cdot T\left(\frac{n}{2}\right) + 1000 \cdot n^2$

$$a = 8, b = 2, f(n) = 1000 \cdot n^2, \underbrace{\log_b a = \log_2 8 = 3}_{n^3 \text{ leaves}}$$

$$f(n) \in O(n^{3-\epsilon}) \Rightarrow T(n) \in \Theta(n^3)$$

►  $T(n) = 9 \cdot T\left(\frac{n}{3}\right) + 17 \cdot n$

$$a = 9, b = 3, f(n) = 17 \cdot n, \underbrace{\log_b a = \log_3 9 = 2}_{n^2 \text{ leaves}}$$

$$f(n) \in O(n^{2-\epsilon}) \Rightarrow T(n) \in \Theta(n^2)$$



# Recursion Equations

## Master theorem (General Form) - Case 2

**Case 2:**  $T(n) \in \Theta(n^{\log_b a} \log n)$  if  $f(n) \in \Theta(n^{\log_b a})$

Each layer has equal costs,  $\log n$  layers

►  $T(n) = 2 \cdot T\left(\frac{n}{2}\right) + 10 \cdot n$

$$a = 2, \quad b = 2, \quad f(n) = 10 \cdot n, \quad \underbrace{\log_b a = \log_2 2 = 1}_{n^1 \text{ leaves}}$$

$$f(n) \in \Theta(n^{\log_2 2}) \Rightarrow T(n) \in \Theta(n \log n)$$

►  $T(n) = T\left(\frac{2n}{3}\right) + 1$

$$a = 1, \quad b = \frac{2}{3}, \quad f(n) = 1, \quad \underbrace{\log_b a = \log_{3/2} 1 = 0}_{n^0 \text{ leaves} = 1 \text{ leaf}}$$

$$f(n) \in \Theta(n^{\log_{3/2} 1}) \Rightarrow T(n) \in \Theta(n^0 \log n) = \Theta(\log n)$$

# Recursion Equations

## Master theorem (General Form) - Case 3

**Case 3:**  $T(n) \in \Theta(f(n))$  if  $f(n) \in \Omega(n^{\log_b a + \varepsilon})$ ,  $\varepsilon > 0$

Connecting all partial solutions in first layer (root) dominates

►  $T(n) = 2 \cdot T\left(\frac{n}{2}\right) + n^2$

$$a = 2, b = 2, f(n) = n^2, \underbrace{\log_b a = \log_2 2 = 1}_{n^1 \text{ leaves}}$$

$$f(n) \in \Omega(n^{1+\varepsilon})$$

# Recursion Equations

## Master theorem (General Form) - Case 3

**Case 3:**  $T(n) \in \Theta(f(n))$  if  $f(n) \in \Omega(n^{\log_b a + \varepsilon})$ ,  $\varepsilon > 0$

Connecting all partial solutions in first layer (root) dominates

- ▶  $T(n) = 2 \cdot T\left(\frac{n}{2}\right) + n^2$
- ▶  $f(n) \in \Omega(n^{1+\varepsilon})$
- ▶ Check if **regularity condition** also holds:

$$a \cdot f\left(\frac{n}{b}\right) \leq c \cdot f(n)$$

$$2 \cdot \left(\frac{n}{2}\right)^2 \leq c \cdot n^2 \quad \Rightarrow \quad \frac{1}{2} \cdot n^2 \leq c \cdot n^2 \quad \Rightarrow \quad c \geq \frac{1}{2}$$

$$\Rightarrow T(n) \in \Theta(n^2)$$

# Recursion Equations

## Master theorem (General Form)

### Master theorem:

- ▶ Not always applicable:  $T(n) = 2 \cdot T(\frac{n}{2}) + n \log n$

$$a = 2, \quad b = 2, \quad f(n) = n \log n, \quad \underbrace{\log_b a = \log_2 2 = 1}_{n^1 \text{ leaves}}$$

- ▶ **Case 1:**  $f(n) \notin O(n^{1-\epsilon})$
- ▶ **Case 2:**  $f(n) \notin \Theta(n^1)$
- ▶ **Case 3:**  $f(n) \notin \Omega(n^{1+\epsilon})$

$n \log n$  is *asymptotically* larger than  $n$ ,  
but not *polynomial* larger

# Recursion Equations

## Master theorem - Summary

### Master theorem:

$$T(n) = a \cdot T\left(\frac{n}{b}\right) + f(n)$$

- ▶ Three cases depending on the dominance of the terms
- ▶ **Case 1:** Solving the partial problems is *polynomial* bigger than merging all solutions  
 $T(n) \in \Theta(n^{\log_b a})$ ,  $T(n) \in \Theta(\text{number of leaves})$
- ▶ **Case 2:** Each layer has equal costs  
 $T(n) \in \Theta(n^{\log_b a} \log n)$ ,  $\log n$  layers
- ▶ **Case 3:** Connecting all partial solutions is *polynomial* bigger than solving all partial problems  
 $T(n) \in \Theta(f(n))$

# Further Literature

## ► General

[CRL01] Thomas H. Cormen, Ronald L. Rivest, and Charles E. Leiserson.

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MIT Press, Cambridge, Mass, 2001.

[MS08] Kurt Mehlhorn and Peter Sanders.

Algorithms and data structures, 2008.

<https://people.mpi-inf.mpg.de/~mehlhorn/ftp/Mehlhorn-Sanders-Toolbox.pdf>.

# Further Literature

- ▶ **Master theorem**

[Wik] [Master theorem](https://en.wikipedia.org/wiki/Master_theorem)

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