

# Algorithms and Datastructures

## Divide and Conquer, Master theorem

Albert-Ludwigs-Universität Freiburg



**UNI  
FREIBURG**

Prof. Dr. Rolf Backofen

Bioinformatics Group / Department of Computer Science  
Algorithms and Datastructures, March 2018

## 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



UNI  
FREIBURG

## Concept:



### Concept:

- **Divide** the problem into smaller subproblems

### Concept:

- **Divide** the problem into smaller subproblems
- **Conquer** the subproblems through recursive solving.  
If subproblems are small enough solve them directly

### 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

### 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

### 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

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

Recursion Tree Method

Master theorem

Master theorem (Simple Form)

Master theorem (General Form)

# Divide and Conquer

Maximum Subtotal



UNI  
FREIBURG

**Input:**

**Output:**

# Divide and Conquer

## Maximum Subtotal

### Input:

- Sequence  $X$  of  $n$  integers

### Output:

### Input:

- Sequence  $X$  of  $n$  integers

### Output:

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

### 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

**Idea:**



### Idea:



- Solve the left / right half of the problem **recursive**

### Idea:



- Solve the left / right half of the problem **recursive**
- Combine both solutions into a overall solution



### 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)**

### 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)**

### Principle:

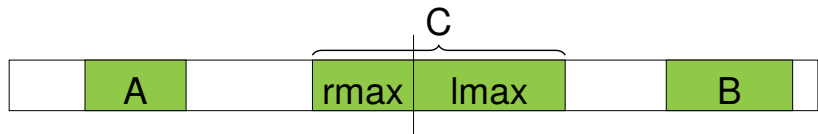


### Principle:



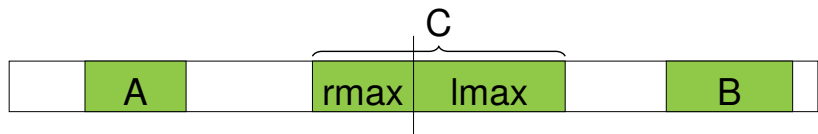
- Small problems are solved directly:  $n = 1 \Rightarrow \text{max} = X[0]$

### Principle:



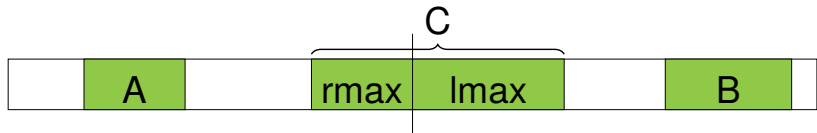
- Small problems are solved directly:  $n = 1 \Rightarrow \text{max} = X[0]$
- Big problems are decomposed into two subproblems and solved recursively. Subolutions  $A$  and  $B$  are returned

### Principle:



- Small problems are solved directly:  $n = 1 \Rightarrow \text{max} = X[0]$
- 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*

### Principle:



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

# Divide and Conquer

## Maximum Subtotal - Python



```
def maxSubArray(X, i, j):
```



# Divide and Conquer

## Maximum Subtotal - Python

```
def maxSubArray(X, i, j):  
    if i == j: # trivial case  
        return (X[i], i, i)  
  
    # recursive subsolutions for A, B  
    m = (i + j) / 2
```

```
def maxSubArray(X, i, j):  
    if i == j: # trivial case  
        return (X[i], i, i)  
  
    # recursive subsolutions for A, B  
    m = (i + j) / 2  
    A = maxSubArray(X, i, m)  
    B = maxSubArray(X, m + 1, j)
```

```
def maxSubArray(X, i, j):  
    if i == j: # trivial case  
        return (X[i], i, i)  
  
    # recursive subsolutions for A, B  
    m = (i + j) / 2  
    A = maxSubArray(X, i, m)  
    B = maxSubArray(X, m + 1, j)  
  
    # rmax and lmax for corner case C  
    C1, C2 = rmax(X, i, m), lmax(X, m + 1, j)  
    C = (C1[0] + C2[0], C1[1], C2[1])
```

```
def maxSubArray(X, i, j):  
    if i == j: # trivial case  
        return (X[i], i, i)  
  
    # recursive subsolutions 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):
```



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

```
#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):
```



# Divide and Conquer

## Maximum Subtotal - Python

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

```
#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
```

#Alternative implementation max

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

#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)
```

```
#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
```

```
#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
```

Table: *lmax* example

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



Table: *lmax* example

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

- The *sum* and *lmax* are initialized with  $X[i]$

Table: *lmax* example

| index       | $i$ | $i + 1$ | ... | ... | $j - 1$ | $j$ |
|-------------|-----|---------|-----|-----|---------|-----|
| $X$         | 58  | -53     | 26  | 59  | -41     | 31  |
| <i>sum</i>  | 58  | 5       | 31  | 90  | 49      | 80  |
| <i>lmax</i> | 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*

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

`maxSubArray(-3,9,-4,7)`

in fact:

`maxSubArray(X,0,3)`  
with `X=[-3,9,-4,7]`

# Divide and Conquer

## Maximum Subtotal



Call with array of four elements

$\text{maxSubArray}(-3, 9, -4, 7)$

in fact:

$\text{maxSubArray}(X, 0, 3)$   
with  $X = [-3, 9, -4, 7]$

Call with array of two elements

$\text{maxSubArray}(-3, 9)$

$\text{maxSubArray}(-4, 7)$

# Divide and Conquer

## Maximum Subtotal



Call with array of four elements



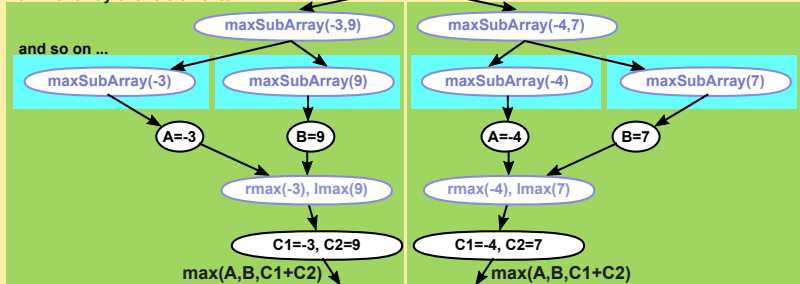
# Divide and Conquer

## Maximum Subtotal



Call with array of four elements

Call with array of two elements



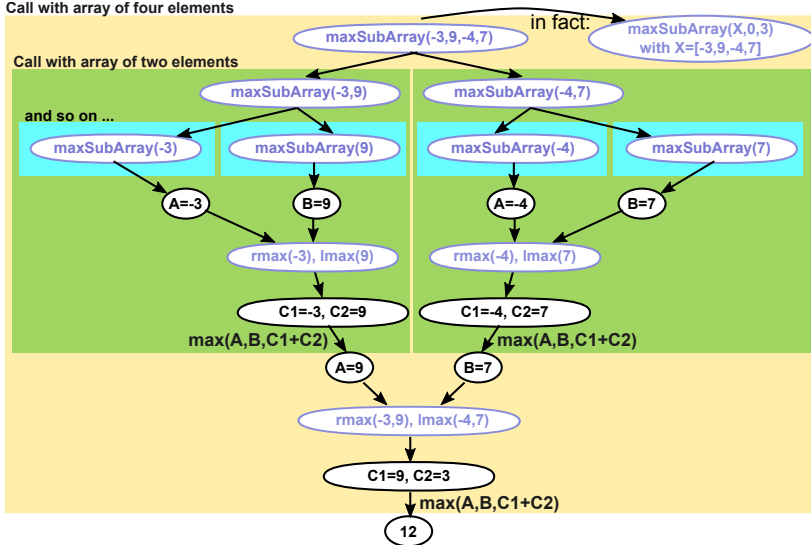
# Divide and Conquer

## Maximum Subtotal



Call with array of four elements

Call with array of two elements





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

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

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

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

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

```
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)  
  
    C1 = rmax(X, i, m)  
    C2 = lmax(X, m + 1, j)  
    C = (C1[0] + C2[0], C1[1], C2[1])  
  
    return max([A, B, C], \  
               key=lambda item: item[0])
```

```
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)  
    C2 = lmax(X, m + 1, j)  
    C = (C1[0] + C2[0], C1[1], C2[1])  
  
    return max([A, B, C], \  
               key=lambda item: item[0])
```

```
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)  
    C = (C1[0] + C2[0], C1[1], C2[1])  
  
    return max([A, B, C], \  
               key=lambda item: item[0])
```



```
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])  
  
    return max([A, B, C], \  
               key=lambda item: item[0])
```

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

```
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])
```

## Recursion equation:

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

trivial case

### 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:

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

### 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

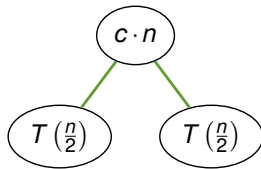
## Maximum Subtotal - Illustration of $T(n)$



Figure: Illustration of the runtime

# Divide and Conquer

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



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

Figure: Illustration of the runtime



# Divide and Conquer

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



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

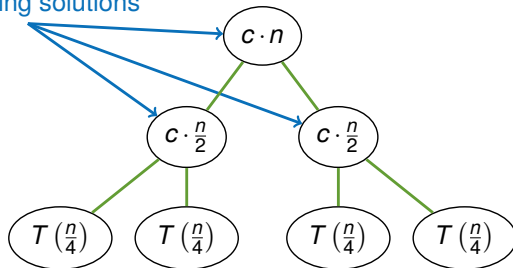
Figure: Illustration of the runtime

# Divide and Conquer

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



combining solutions



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

Figure: Illustration of the runtime

# Divide and Conquer

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



Figure: Illustration of the runtime

# Divide and Conquer

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

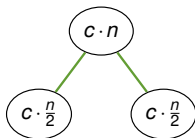
$$c \cdot n$$

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

Figure: Recursion tree method

# 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  
 $\Rightarrow 2c \cdot \frac{n}{2} = c \cdot n$

Figure: Recursion tree method

# Divide and Conquer

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



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

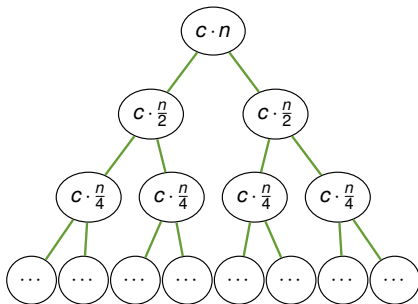
2 nodes processing  $\frac{n}{2}$  elements  
 $\Rightarrow 2c \cdot \frac{n}{2} = c \cdot n$

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

Figure: Recursion tree method

# 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  
 $\Rightarrow 2c \cdot \frac{n}{2} = c \cdot n$

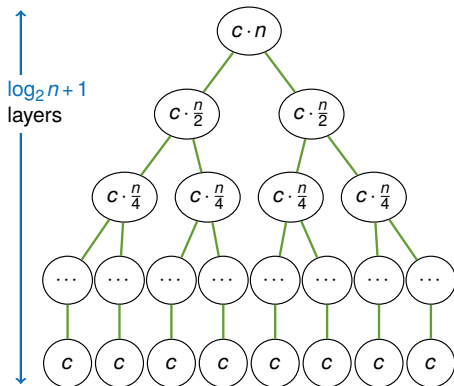
4 nodes processing  $\frac{n}{4}$  elements  
 $\Rightarrow 4c \cdot \frac{n}{4} = c \cdot n$

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

Figure: Recursion tree method

# 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  
 $\Rightarrow 2c \cdot \frac{n}{2} = c \cdot n$

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

$2^i$  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  $T(n)$



UNI  
FREIBURG

**Depth:**

# Divide and Conquer

Maximum Subtotal - Illustration of  $T(n)$



UNI  
FREIBURG

## Depth:

- Top level with depth  $i = 0$

### Depth:

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

$$\Rightarrow i = \log_2 n$$

# 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:

### 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

### 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:

### Summary:

- Direct solution is slow with  $\mathcal{O}(n^3)$



### Summary:

- Direct solution is slow with  $\mathcal{O}(n^3)$
- Better solution with incremental update of sum was  $\mathcal{O}(n^2)$

### 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  $\mathcal{O}(n \log n)$

### 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



Figure: Scanning the array in linear time

# Divide and Conquer

## Maximum Subtotal - Python



```
#Implementation - linear runtime  
def maxSubArray(X):
```

#Implementation - linear runtime

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

#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])
```

#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)
```



## Divide and Conquer

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

Recursion Tree Method

Master theorem

Master theorem (Simple Form)

Master theorem (General Form)

### 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 equation:**

### Recursion equation:

- Describes the runtime for recursive functions:

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

### 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,  $f_0(n_0) \in \Theta(1)$

### 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  $b > 1$

### 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

### 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



## Divide and Conquer

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

Recursion Tree Method

Master theorem

Master theorem (Simple Form)

Master theorem (General Form)



### Substitution Method:



### **Substitution Method:**

- Guess the solution and prove it with induction

### Substitution Method:

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

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

### 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:  $T(n) = n + n \cdot \log_2 n$



### Induction:

### Induction:

- Induction basis (for  $n = 1$ ):  $T(1) = 1 + 1 \cdot \log_2 1 = 1$

### Induction:

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



### Induction:

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

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

### Induction:

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

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

### Induction:

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

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

### Induction:

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

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

### Induction:

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

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



### **Substitution Method:**



### Substitution Method:

- Alternative assumption

### Substitution Method:

- Alternative assumption
- Example:

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



### 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:  $T(n) \in O(n \log n)$

### 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  $T(n) \leq c \cdot n \log_2 n$



### Induction:

### Induction:

- Solution: Find  $c > 0$  with  $T(n) \leq c \cdot n \log_2 n$

### Induction:

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

### Induction:

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

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

### Induction:

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

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

### Induction:

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

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



### Induction:

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

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

### Induction:

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

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

## Divide and Conquer

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

**Recursion Tree Method**

Master theorem

Master theorem (Simple Form)

Master theorem (General Form)



### **Recursion tree method:**

### **Recursion tree method:**

- Can be used to make assumptions about the runtime

### Recursion tree method:

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

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

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



Figure: Recursion tree of example

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



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

Figure: Recursion tree of example



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



$$T(n) = 12 \cdot T\left(\frac{n}{16}\right) + 3c \cdot \left(\frac{n}{4}\right)^2 + c \cdot n^2$$

Figure: Recursion tree of example



Figure: Levels of the recursion tree



**Costs of connecting the partial solutions:**  
(excludes the last layer)

### 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 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  $i$ :

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

### 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 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  $i$ :

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

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





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

- Size of partial problems on the **last level**:  $s_{i+1}(n) = 1$

### **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**:  $T_{i+1_p}(n) = d$

### 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:

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

### 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:

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

- Number of partial problems on the **last level**:

$$n_{i+1} = 3^{\log_4 n}$$

### 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:

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

- 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 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:

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

- 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**:  $T_{i+1}(n) = d \cdot n^{\log_4 3}$

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

$$\log_4 n = \log_4 \left( 3^{\log_3 n} \right) \quad \text{uses } n = 3^{\log_3 n}$$

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

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

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

uses  $\log a^b = b \cdot \log a$



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

$$\log_4 n = \log_4 \left( 3^{\log_3 n} \right)$$

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

$$= \log_3 n \cdot \log_4 3$$

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

- This proves the general log rule  $\log_b c = \log_a c \cdot \log_b a$

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

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

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

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:

$$3^{\log_4 n} = 3^{\log_3 n \cdot \log_4 3}$$

uses reformulation above

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

$$\log_4 n = \log_4 \left( 3^{\log_3 n} \right)$$

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

$$= \log_3 n \cdot \log_4 3$$

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:

$$3^{\log_4 n} = 3^{\log_3 n \cdot \log_4 3}$$

uses reformulation above

$$= \left( 3^{\log_3 n} \right)^{\log_4 3}$$

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

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

$$\log_4 n = \log_4 \left( 3^{\log_3 n} \right)$$

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

$$= \log_3 n \cdot \log_4 3$$

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:

$$3^{\log_4 n} = 3^{\log_3 n \cdot \log_4 3}$$

uses reformulation above

$$= \left( 3^{\log_3 n} \right)^{\log_4 3}$$

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

$$= n^{\log_4 3}$$

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

$$\log_4 n = \log_4 \left( 3^{\log_3 n} \right)$$

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

$$= \log_3 n \cdot \log_4 3$$

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

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

$$3^{\log_4 n} = 3^{\log_3 n \cdot \log_4 3}$$

uses reformulation above

$$= \left( 3^{\log_3 n} \right)^{\log_4 3}$$

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

$$= n^{\log_4 3}$$

- This term will recur in the master theorem

# Recursion Equations

Total costs



UNI  
FREIBURG

**Total costs:**

### Total costs:

- Costs of level  $i$ :  $T_i(n) = \left(\frac{3}{16}\right)^i \cdot c \cdot n^2$

### Total costs:

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



### Total costs:

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

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

### Total costs:

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

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

- Here: The costs of connecting the partial problems dominate

- **Geometric progression:**

Quotient of two neighboring sequence parts is constant

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

- **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

- **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  $|q| < 1$ :

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

# Recursion Equations

Proof of  $O(n^2)$



UNI  
FREIBURG

**Proof of  $\mathcal{O}(n^2)$ :**

### Proof of $\mathcal{O}(n^2)$ :

■ We know:

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

### Proof of $\mathcal{O}(n^2)$ :

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

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



# Recursion Equations

Proof of  $O(n^2)$



UNI  
FREIBURG

**Proof of  $\mathcal{O}(n^2)$ :**



### **Proof of $\mathcal{O}(n^2)$ :**

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

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

### **Proof of $\mathcal{O}(n^2)$ :**

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

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

- Substitution method:

### Proof of $\mathcal{O}(n^2)$ :

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

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

- Substitution method:

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

### Proof of $\mathcal{O}(n^2)$ :

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

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

- Substitution method:

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

### Proof of $\mathcal{O}(n^2)$ :

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

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

- Substitution method:

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

### Proof of $\mathcal{O}(n^2)$ :

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

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

- Substitution method:

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

## Divide and Conquer

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

Recursion Tree Method

### Master theorem

Master theorem (Simple Form)

Master theorem (General Form)





## Master theorem:

### Master theorem:

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

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

### 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 ...

### 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

### 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  $T\left(\frac{n}{b}\right)$**

### 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



### **Master theorem:**

### Master theorem:

- In the examples we have seen that ...



### Master theorem:

- In the examples we have seen that ...
  - Either the runtime of **connecting the solutions** dominates

### 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

### 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**

### 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:**

### Simple form:

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

in general form

### Simple form:

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

in general form

- This yields a runtime of:

### Simple form:

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

- 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)

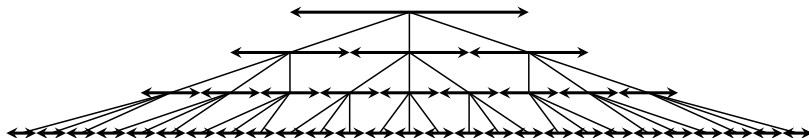


Figure: Simple recursion equation with  $a = 3, b = 2$

# Recursion Equations

## Master theorem (Simple Form)



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

### Case 1: $a > b$

# Recursion Equations

## Master theorem (Simple Form)

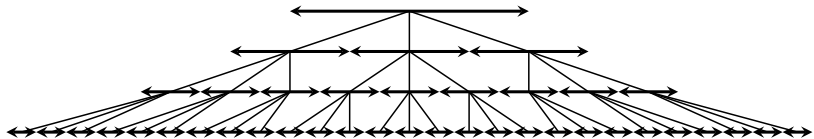


Figure: Simple recursion equation with  $a = 3, b = 2$

### Case 1: $a > b$

- Three partial problems with  $\frac{1}{2}$  the size

# Recursion Equations

## Master theorem (Simple Form)

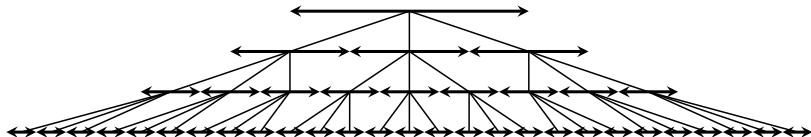


Figure: Simple recursion equation with  $a = 3, b = 2$

### Case 1: $a > b$

- Three partial problems with  $\frac{1}{2}$  the size
- Solving the partial problems dominates (last layer, leaves)

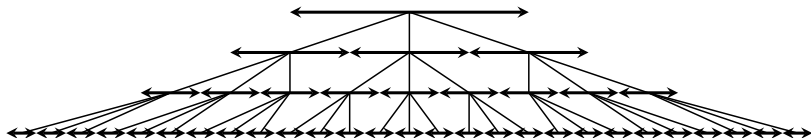


Figure: Simple recursion equation with  $a = 3, b = 2$

### 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)

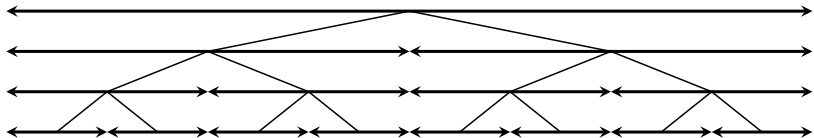


Figure: Simple recursion equation with  $a = 2, b = 2$

# Recursion Equations

## Master theorem (Simple Form)

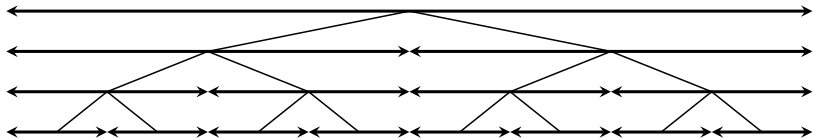


Figure: Simple recursion equation with  $a = 2, b = 2$

### Case 2: $a = b$

# 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



# Recursion Equations

## Master theorem (Simple Form)

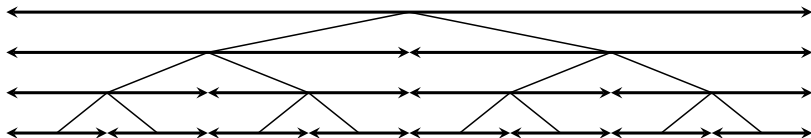


Figure: Simple recursion equation with  $a = 2, b = 2$

### Case 2: $a = b$

- Two partial problems with  $\frac{1}{2}$  the size
- Each layer has equal costs,  $\log n$  layers

# 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  $a = 2, b = 3$

# Recursion Equations

## Master theorem (Simple Form)



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

### Case 3: $a < b$

# Recursion Equations

## Master theorem (Simple Form)

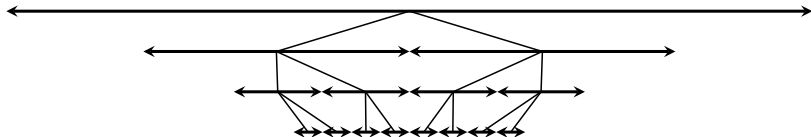


Figure: Simple recursion equation with  $a = 2, b = 3$

### Case 3: $a < b$

- Two partial problems with  $\frac{1}{3}$  the size

# Recursion Equations

## Master theorem (Simple Form)

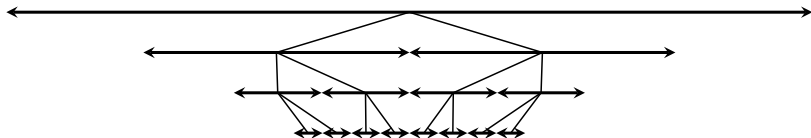


Figure: Simple recursion equation with  $a = 2, b = 3$

### Case 3: $a < b$

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

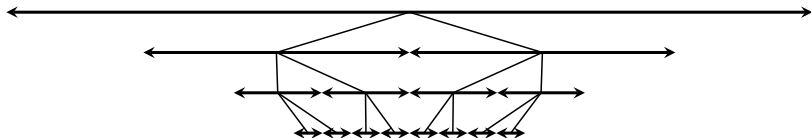


Figure: Simple recursion equation with  $a = 2, b = 3$

### Case 3: $a < b$

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



**For a recursion equation like**

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



**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:

**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:

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

**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  $\frac{a}{b}$

## Divide and Conquer

Concept

Maximum Subtotal

## Recursion Equations

Substitution Method

Recursion Tree Method

**Master theorem**

Master theorem (Simple Form)

Master theorem (General Form)



### **Master theorem (general form):**

### Master theorem (general form):

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

### 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)

### 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



### 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:

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



### Case 1 - Example:

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

Solving the partial problems dominates (last layer, leaves)



**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)

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

Solving the partial problems dominates (last layer, leaves)

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

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

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

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

Solving the partial problems dominates (last layer, leaves)

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

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

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

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

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

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



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

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

# 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

**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

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

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

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



**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

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

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

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

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

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

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

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

**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

**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

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

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

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



**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

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



**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

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



**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

- $T(n) = 2 \cdot T(\frac{n}{2}) + n^2$
- $f(n) \in \Omega(n^{1+\varepsilon})$

**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:

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

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

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





### **Master theorem:**



### Master theorem:

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

### Master theorem:

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

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

### Master theorem:

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

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

- **Case 1:**  $f(n) \notin O(n^{1-\varepsilon})$

### Master theorem:

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

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

- **Case 1:**  $f(n) \notin O(n^{1-\varepsilon})$
- **Case 2:**  $f(n) \notin \Theta(n^1)$

### Master theorem:

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

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

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

### Master theorem:

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

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

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

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



### **Master theorem:**





### Master theorem:

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

### Master theorem:

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

- Three cases depending on the dominance of the terms

### 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

$$T(n) \in \Theta(n^{\log_b a}), \quad T(n) \in \Theta(\text{number of leaves})$$

### 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

$$T(n) \in \Theta(n^{\log_b a}), \quad T(n) \in \Theta(\text{number of leaves})$$

- **Case 2:** Each layer has equal costs

$$T(n) \in \Theta(n^{\log_b a} \log n), \quad \log n \text{ layers}$$

### 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

$$T(n) \in \Theta(n^{\log_b a}), \quad T(n) \in \Theta(\text{number of leaves})$$

- **Case 2:** Each layer has equal costs

$$T(n) \in \Theta(n^{\log_b a} \log n), \quad \log n \text{ layers}$$

- **Case 3:** Connecting all partial solutions is *polynomial* bigger than solving all partial problems

$$T(n) \in \Theta(f(n))$$

## ■ General

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

**Introduction to Algorithms.**

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>.

## ■ Master theorem

[Wik] [Master theorem](#)

[https://en.wikipedia.org/wiki/Master\\_theorem](https://en.wikipedia.org/wiki/Master_theorem)