CS473 - Algorithms I

Lecture 4

The Divide-and-Conquer Design Paradigm

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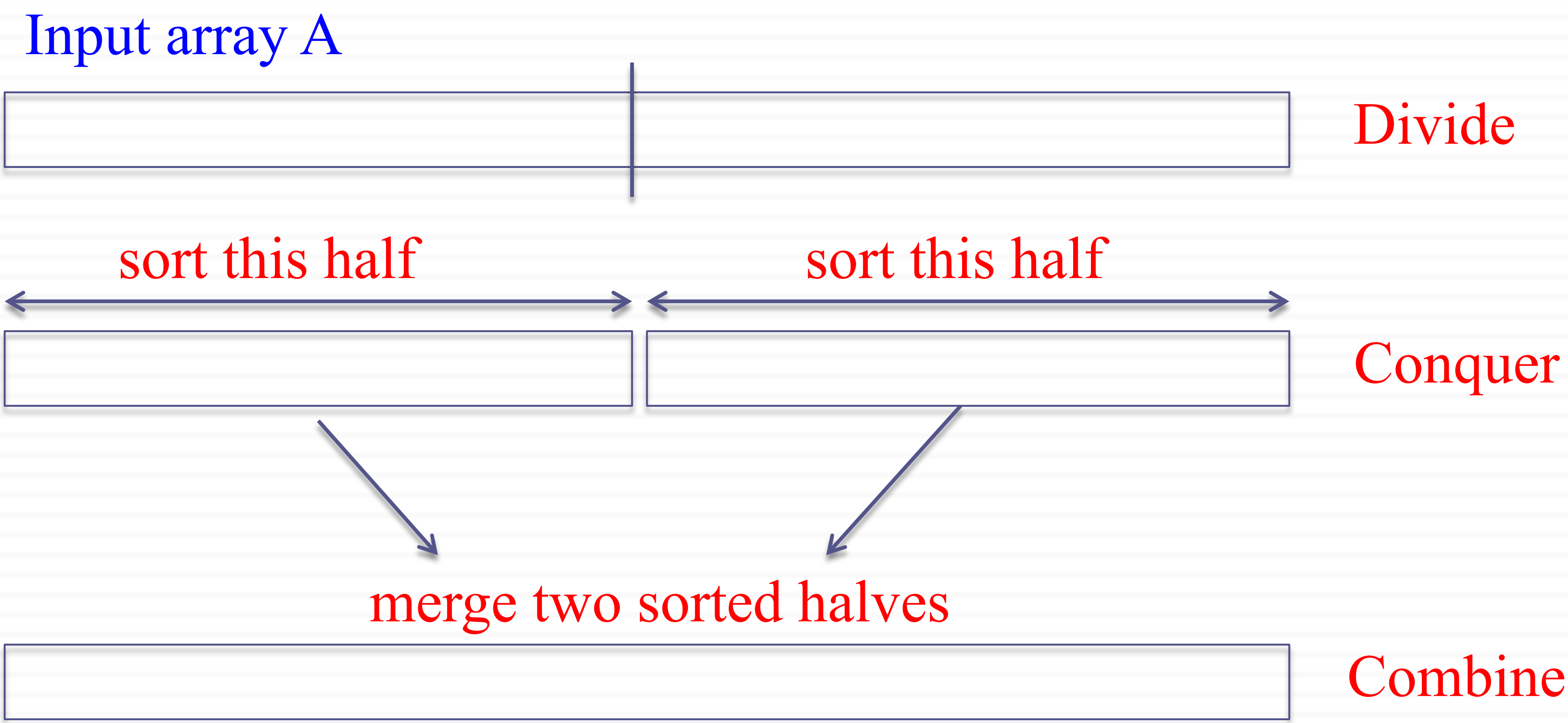
Cevdet Aykanat and Mustafa Ozdal
Computer Engineering Department, Bilkent University

Reminder: Merge Sort



The Divide-and-Conquer Design Paradigm

1. ***Divide*** **the problem (instance) into subproblems.**
2. ***Conquer*** **the subproblems by solving them recursively.**
3. ***Combine*** **subproblem solutions.**

Example: Merge Sort

1. ***Divide***: Trivial.
2. ***Conquer***: Recursively sort 2 subarrays.
3. ***Combine***: Linear- time merge.

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

 # subproblems

subproblem size

work dividing and combining

Master Theorem: Reminder

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

Case 1: $\dfrac{n^{\log_b a}}{f(n)} = \Omega(n^{\varepsilon}) \Rightarrow T(n) = \Theta(n^{\log_b a})$

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

Case 3: $\dfrac{n^{\log_b a}}{f(n)} = \Omega(n^{\varepsilon})$

and $a\, f(n/b) \le c\, f(n)$ for $c < 1$ $\Rightarrow T(n) = \Theta(f(n))$

Cevdet Aykanat and Mustafa Ozdal
Computer Engineering Department, Bilkent University

Merge Sort: Solving the Recurrence

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

➡ $a = 2, \quad b = 2, \quad f(n) = \Theta(n), \quad n^{\log_b a} = n$

Case 2: $\dfrac{f(n)}{n^{\log_b a}} = \Theta(\lg^k n)$ ➡ $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$

holds for k = 0

➡ $T(n) = \Theta\,(n\lg n)$

Binary Search

Find an element in a sorted array:

1. ***Divide***: Check middle element.

2. ***Conquer***: Recursively search 1 subarray.

3. ***Combine***: Trivial.

Example: Find **9**

3	**5**	**7**	**8**	**9**	**12**	**15**

Binary Search

Find an element in a sorted array:

1. Divide: Check middle element.

2. Conquer: Recursively search 1 subarray.

3. Combine: Trivial.

Example: Find **9**

3	**5**	**7**	**8**	**9**	**12**	**15**

Binary Search

Find an element in a sorted array:

1. ***Divide:*** Check middle element.

2. ***Conquer:*** Recursively search 1 subarray.

3. ***Combine:*** Trivial.

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Binary Search

Find an element in a sorted array:

*1. **Divide**:* Check middle element.

*2. **Conquer**:* Recursively search 1 subarray.

*3. **Combine**:* Trivial.

Example: Find **9**

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Binary Search

Find an element in a sorted array:

1. ***Divide*****:** Check middle element.

2. ***Conquer*****:** Recursively search 1 subarray.

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Example: Find **9**

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Binary Search

Find an element in a sorted array:

1. ***Divide*:** Check middle element.

2. ***Conquer*:** Recursively search 1 subarray.

3. ***Combine*:** Trivial.

Example: Find **9**

3	**5**	**7**	**8**	**9**	**12**	**15**

Recurrence for Binary Search

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

 # subproblems

subproblem size

work dividing and combining

Binary Search: Solving the Recurrence

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

$\Rightarrow$ $a = 1$, $b = 2$, $f(n) = \Theta(1)$, $n^{\log_b a} = n^0 = 1$

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

holds for k = 0

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

Powering a Number

- Problem: Compute a^n, where n is a natural number

```
Naive-Power (a, n)
    powerVal ← 1
    for i ← 1 to n
        powerVal ← powerVal . a
    return powerVal
```

- What is the complexity?

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

Powering a Number: Divide & Conquer

Basic idea:

$$a^n = \begin{cases} a^{n/2} \cdot a^{n/2} & \text{if n is } \underline{\text{even}} \\ a^{(n-1)/2} \cdot a^{(n-1)/2} \cdot a & \text{if n is } \underline{\text{odd}} \end{cases}$$

Powering a Number: Divide & Conquer

```
POWER (a, n)
    if n = 0 then return 1

    else if n is even then
        val ← POWER (a, n/2)
        return val * val

    else if n is odd then
        val ← POWER (a, (n-1)/2)
        return val * val * a
```


Cevdet Aykanat and Mustafa Ozdal
Computer Engineering Department, Bilkent University

Powering a Number: Solving the Recurrence

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

➡ $a = 1, \quad b = 2, \quad f(n) = \Theta(1), \quad n^{\log_b a} = n^0 = 1$

Case 2: $\dfrac{f(n)}{n^{\log_b a}} = \Theta(\lg^k n)$ ➡ $T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$

holds for k = 0

➡ $T(n) = \Theta(\lg n)$

Matrix Multiplication

Input : $A = [a_{ij}], B = [b_{ij}].$
Output: $C = [c_{ij}] = A \cdot B.$

$i, j = 1, 2, \ldots, n.$

$$\begin{pmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ \boxed{c_{21}} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{nn} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \cdot \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{pmatrix}$$

$$c_{ij} = \sum_{1 \le k \le n} a_{ik} \, . b_{kj}$$

Standard Algorithm

for $i \leftarrow 1$ to n

do for $j \leftarrow 1$ to n

do $c_{ij} \leftarrow 0$

for $k \leftarrow 1$ to n

do $c_{ij} \leftarrow c_{ij} + a_{ik} \,.\, b_{kj}$

Running time = $\Theta(n^3)$

Matrix Multiplication: Divide & Conquer

IDEA: Divide the n x n matrix into

2x2 matrix of (n/2)x(n/2) submatrices

$$\begin{array}{ccccc} C & & A & & B \\ \left(\begin{array}{c|c} c_{11} & c_{12} \\ \hline c_{21} & c_{22} \end{array}\right) & = & \left(\begin{array}{c|c} a_{11} & a_{12} \\ \hline a_{21} & a_{22} \end{array}\right) & \cdot & \left(\begin{array}{c|c} b_{11} & b_{12} \\ \hline b_{21} & b_{22} \end{array}\right) \end{array}$$

$$c_{11} = a_{11} b_{11} + a_{12} b_{21}$$

Matrix Multiplication: Divide & Conquer

IDEA: Divide the n x n matrix into

2x2 matrix of (n/2)x(n/2) submatrices

$$
\overset{C}{\begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}} = \overset{A}{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}} \cdot \overset{B}{\begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}}
$$

$$
c_{12} = a_{11} b_{12} + a_{12} b_{22}
$$

Matrix Multiplication: Divide & Conquer

IDEA: Divide the n x n matrix into

2x2 matrix of (n/2)x(n/2) submatrices

$$
\overset{C}{\begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}} = \overset{A}{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}} \cdot \overset{B}{\begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}}
$$

$$
c_{21} = a_{21}\, b_{11} + a_{22}\, b_{21}
$$

Matrix Multiplication: Divide & Conquer

IDEA: Divide the n x n matrix into

2x2 matrix of (n/2)x(n/2) submatrices

$$
\begin{array}{ccccc}
C & & A & & B \\
\begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix} & = & \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} & \cdot & \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}
\end{array}
$$

$$c_{22} = a_{21}\, b_{12} + a_{22}\, b_{22}$$

Matrix Multiplication: Divide & Conquer

$$\overset{C}{\left(\begin{array}{c|c} c_{11} & c_{12} \\ \hline c_{21} & c_{22} \end{array}\right)} = \overset{A}{\left(\begin{array}{c|c} a_{11} & a_{12} \\ \hline a_{21} & a_{22} \end{array}\right)} \cdot \overset{B}{\left(\begin{array}{c|c} b_{11} & b_{12} \\ \hline b_{21} & b_{22} \end{array}\right)}$$

$$\left.\begin{aligned} c_{11} &= a_{11}\, b_{11} + a_{12}\, b_{21} \\ c_{12} &= a_{11}\, b_{12} + a_{12}\, b_{22} \\ c_{21} &= a_{21}\, b_{11} + a_{22}\, b_{21} \\ c_{22} &= a_{21}\, b_{12} + a_{22}\, b_{22} \end{aligned}\right\}$$

8 mults of (n/2)x(n/2) submatrices

4 adds of (n/2)x(n/2) submatrices

Matrix Multiplication: Divide & Conquer

MATRIX-MULTIPLY (A, B)

// Assuming that both A and B are nxn matrices

if $n = 1$ **then return** $A * B$

else

partition A, B, and C as shown before

c_{11} = MATRIX-MULTIPLY (a_{11}, b_{11}) + MATRIX-MULTIPLY (a_{12}, b_{21})

c_{12} = MATRIX-MULTIPLY (a_{11}, b_{12}) + MATRIX-MULTIPLY (a_{12}, b_{22})

c_{21} = MATRIX-MULTIPLY (a_{21}, b_{11}) + MATRIX-MULTIPLY (a_{22}, b_{21})

c_{22} = MATRIX-MULTIPLY (a_{21}, b_{12}) + MATRIX-MULTIPLY (a_{22}, b_{22})

return C

Matrix Multiplication: Divide & Conquer Analysis

$$T(n) = 8\,T(n/2) + \Theta(n^2)$$

8 recursive calls

each subproblem has size n/2

submatrix addition

Matrix Multiplication: Solving the Recurrence

$$T(n) = 8\,T(n/2) + \Theta(n^2)$$

→ $a = 8$, $b = 2$, $f(n) = \Theta(n^2)$, $n^{\log_b a} = n^3$

Case 1: $\dfrac{n^{\log_b a}}{f(n)} = \Omega(n^{\varepsilon})$ → $T(n) = \Theta(n^{\log_b a})$

→ $T(n) = \Theta\,(n^3)$

No better than the ordinary algorithm!

Matrix Multiplication: Strassen's Idea

$$\overset{\textstyle C}{\begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix}} = \overset{\textstyle A}{\begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}} \cdot \overset{\textstyle B}{\begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}}$$

Compute $\mathbf{c_{11}}$, $\mathbf{c_{12}}$, $\mathbf{c_{21}}$, and $\mathbf{c_{22}}$ using **7** recursive multiplications

Matrix Multiplication: Strassen's Idea

$$P_1 = a_{11} \mathbf{x} (b_{12} - b_{22})$$
$$P_2 = (a_{11} + a_{12}) \mathbf{x} b_{22}$$
$$P_3 = (a_{21} + a_{22}) \mathbf{x} b_{11}$$
$$P_4 = a_{22} \mathbf{x} (b_{21} - b_{11})$$
$$P_5 = (a_{11} + a_{22}) \mathbf{x} (b_{11} + b_{22})$$
$$P_6 = (a_{12} - a_{22}) \mathbf{x} (b_{21} + b_{22})$$
$$P_7 = (a_{11} - a_{21}) \mathbf{x} (b_{11} + b_{12})$$

Reminder: Each submatrix is of size $(n/2)x(n/2)$

Each add/sub operation takes $\Theta(n^2)$ time

Compute $P_1..P_7$ using 7 recursive calls to matrix-multiply

How to compute c_{ij} using $P_1.. P_7$?

Matrix Multiplication: Strassen's Idea

$$P_1 = a_{11} \mathbf{x} (b_{12} - b_{22})$$
$$P_2 = (a_{11} + a_{12}) \mathbf{x} b_{22}$$
$$P_3 = (a_{21} + a_{22}) \mathbf{x} b_{11}$$
$$P_4 = a_{22} \mathbf{x} (b_{21} - b_{11})$$
$$P_5 = (a_{11} + a_{22}) \mathbf{x} (b_{11} + b_{22})$$
$$P_6 = (a_{12} - a_{22}) \mathbf{x} (b_{21} + b_{22})$$
$$P_7 = (a_{11} - a_{21}) \mathbf{x} (b_{11} + b_{12})$$

$$c_{11} = P_5 + P_4 - P_2 + P_6$$
$$c_{12} = P_1 + P_2$$
$$c_{21} = P_3 + P_4$$
$$c_{22} = P_5 + P_1 - P_3 - P_7$$

7 recursive multiply calls

18 add/sub operations

Does not rely on commutativity of multiplication

Matrix Multiplication: Strassen's Idea

$P_1 = a_{11} \mathbf{x} (b_{12} - b_{22})$

$P_2 = (a_{11} + a_{12}) \mathbf{x} b_{22}$

$P_3 = (a_{21} + a_{22}) \mathbf{x} b_{11}$

$P_4 = a_{22} \mathbf{x} (b_{21} - b_{11})$

$P_5 = (a_{11} + a_{22}) \mathbf{x} (b_{11} + b_{22})$

$P_6 = (a_{12} - a_{22}) \mathbf{x} (b_{21} + b_{22})$

$P_7 = (a_{11} - a_{21}) \mathbf{x} (b_{11} + b_{12})$

e.g. Show that $c_{12} = P_1 + P_2$

$$
\begin{aligned}
c_{12} &= P_1 + P_2 \\
&= a_{11}(b_{12} - b_{22}) + (a_{11} + a_{12})b_{22} \\
&= a_{11}b_{12} - a_{11}b_{22} + a_{11}b_{22} + a_{12}b_{22} \\
&= a_{11}b_{12} + a_{12}b_{22}
\end{aligned}
$$

Strassen's Algorithm

1. **Divide**: Partition A and B into $(n/2) \times (n/2)$ submatrices. Form terms to be multiplied using + and –.

2. **Conquer**: Perform **7** multiplications of $(n/2) \times (n/2)$ submatrices recursively.

3. **Combine**: Form C using + and – on $(n/2) \times (n/2)$ submatrices.

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

Strassen's Algorithm: Solving the Recurrence

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

$\Rightarrow$ $a = 7$, $b = 2$, $f(n) = \Theta(n^2)$, $n^{\log_b a} = n^{\lg 7}$

Case 1: $\dfrac{n^{\log_b a}}{f(n)} = \Omega(n^{\varepsilon})$ $\Rightarrow$ $T(n) = \Theta(n^{\log_b a})$

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

Note: $\lg 7 \approx 2.81$

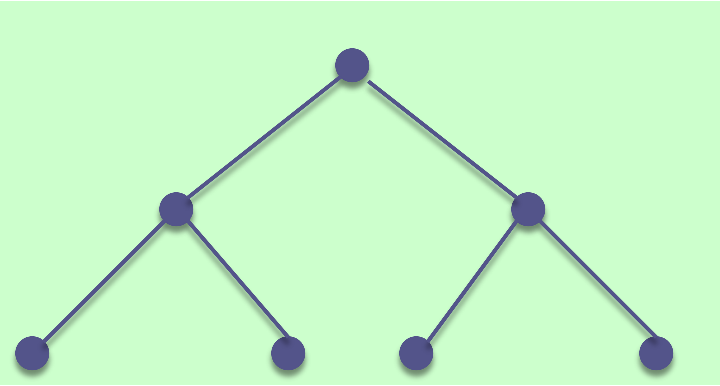
Strassen's Algorithm

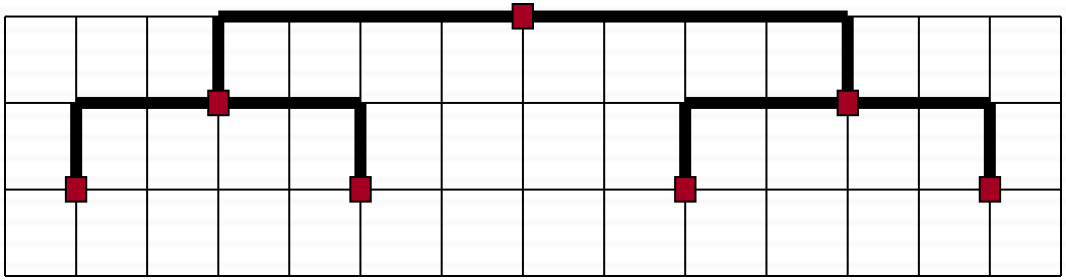
- The number 2.81 may not seem much smaller than 3
- But, it is significant because the difference is in the exponent.
- Strassen's algorithm beats the ordinary algorithm on today's machines for $n \geq 30$ or so.
- Best to date: $\Theta(n^{2.376\ldots})$ *(of theoretical interest only)*

VLSI Layout: Binary Tree Embedding

- Problem: Embed a complete binary tree with n leaves into a 2D grid with minimum area.

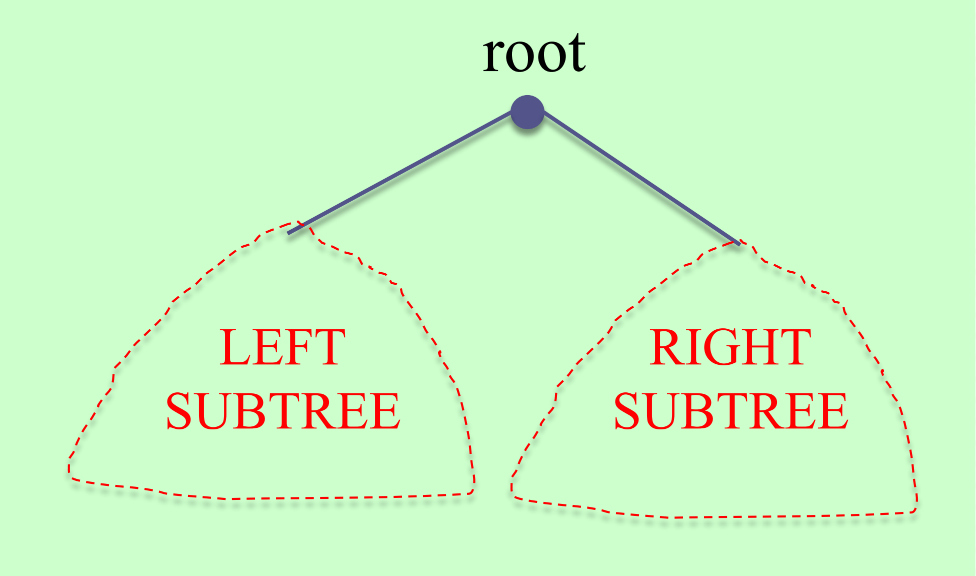
- Example:





Binary Tree Embedding

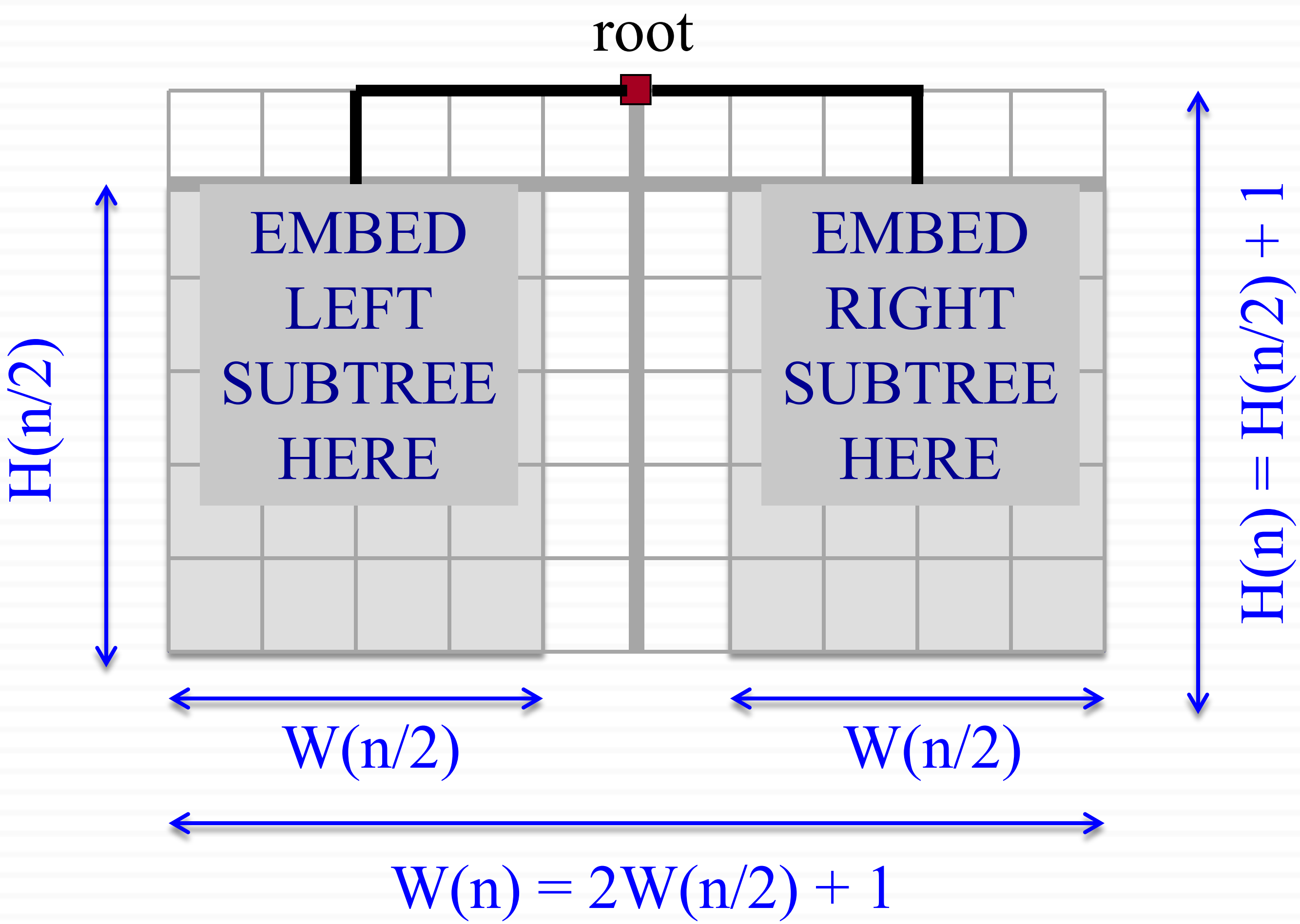
- Use divide and conquer



1. Embed the root node
2. Embed the left subtree
3. Embed the right subtree

What is the min-area required for n leaves?

Binary Tree Embedding



Binary Tree Embedding

- Solve the recurrences:

  $W(n) = 2W(n/2) + 1$

  $H(n) = H(n/2) + 1$

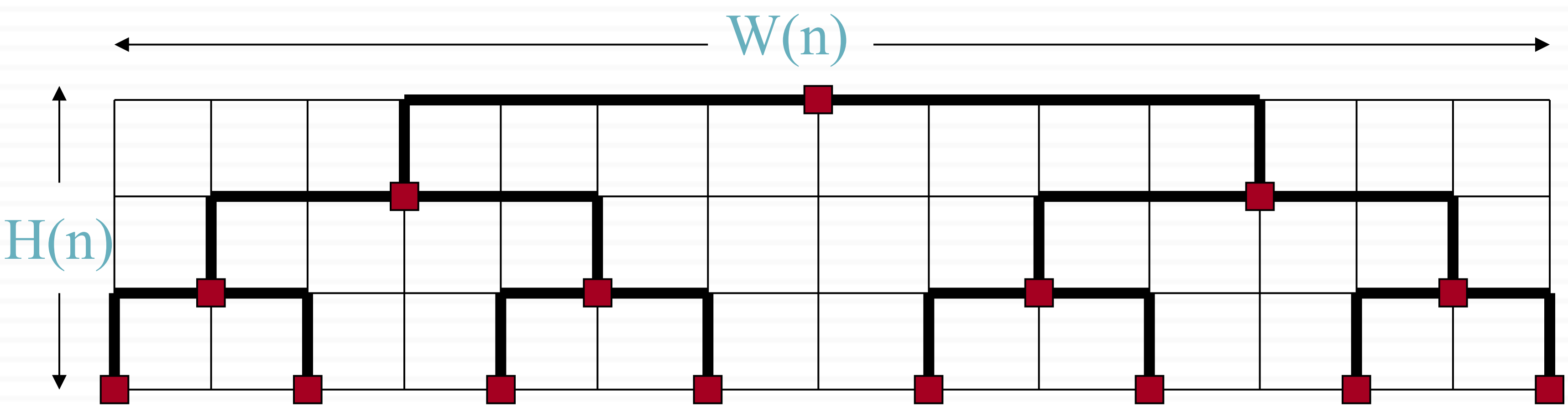
  $\rightarrow W(n) = \Theta(n)$

  $\rightarrow H(n) = \Theta(\lg n)$

- $Area(n) = \Theta(n\lg n)$

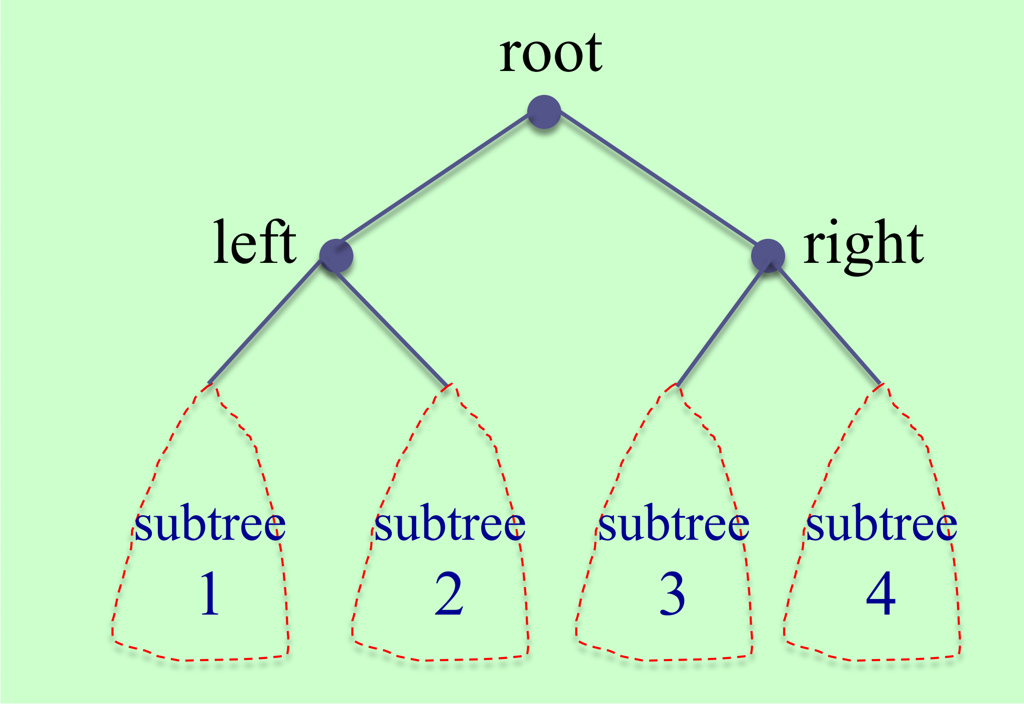
Binary Tree Embedding

Example:



Binary Tree Embedding: H-Tree

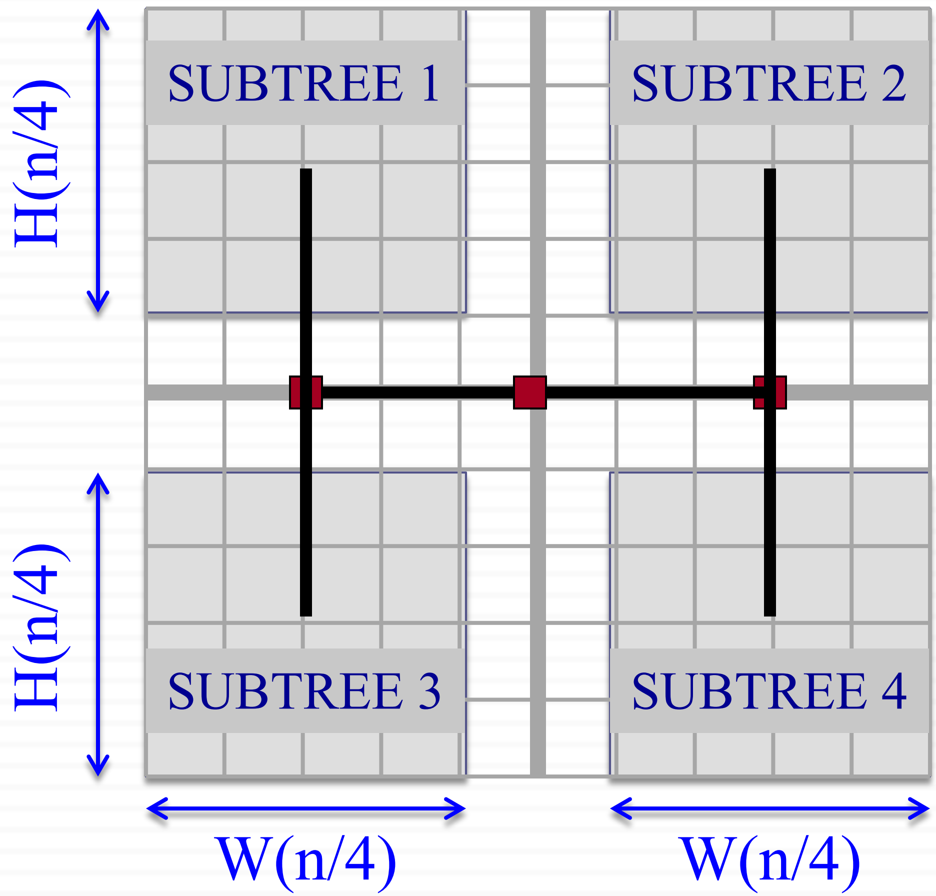
- Use a different divide and conquer method



1. Embed root, left, right nodes
2. Embed subtree 1
3. Embed subtree 2
4. Embed subtree 3
5. Embed subtree 4

What is the min-area required for n leaves?

Binary Tree Embedding: H-Tree



$$W(n) = 2W(n/4) + 1$$

$$H(n) = 2H(n/4) + 1$$

Binary Tree Embedding: H-Tree

- Solve the recurrences:

  $$W(n) = 2W(n/4) + 1$$

  $$H(n) = 2H(n/4) + 1$$

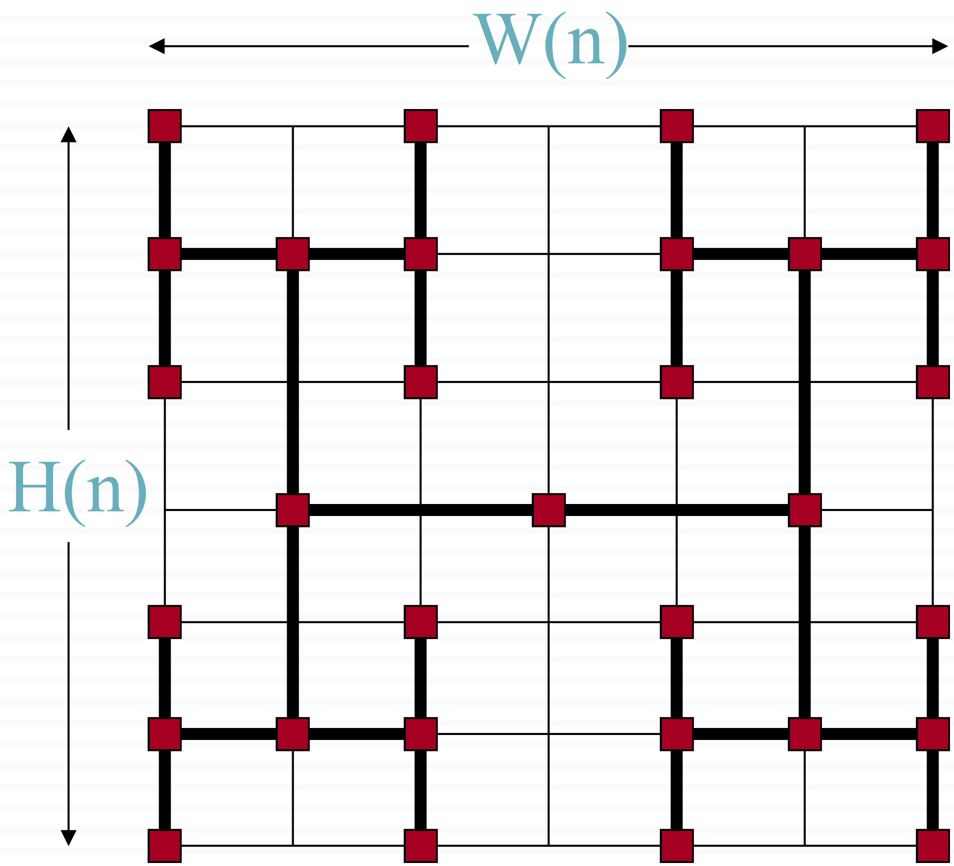
  $$\rightarrow W(n) = \Theta(\sqrt{n})$$

  $$\rightarrow H(n) = \Theta(\sqrt{n})$$

- $\text{Area}(n) = \Theta(n)$

Binary Tree Embedding: H-Tree

Example:



Correctness Proofs

- ***Proof by induction*** commonly used for D&C algorithms
- *Base case*: Show that the algorithm is correct when the recursion bottoms out (i.e., for sufficiently small n)
- *Inductive hypothesis*: Assume the alg. is correct for any recursive call on any smaller subproblem of size k ($k < n$)
- *General case*: Based on the inductive hypothesis, prove that the alg. is correct for any input of size n

Example Correctness Proof: Powering a Number

```
POWER (a, n)
        if n = 0 then return 1

        else if n is even then
                val ← POWER (a, n/2)
                return val * val

        else if n is odd then
                val ← POWER (a, (n-1)/2)
                return val * val * a
```

Example Correctness Proof: Powering a Number

- *Base case*: POWER (a, 0) is correct, because it returns 1
- *Ind. hyp*: Assume POWER (a, k) is correct for any $k < n$
- *General case*:

In POWER (a, n) function:

If n is even:

$val = a^{n/2}$ *(due to ind. hyp.)*

it returns $val \,.\, val = a^n$

If n is odd:

$val = a^{(n-1)/2}$ *(due to ind. hyp.)*

it returns $val.\, val \,.\, a = a^n$

➔ *The correctness proof is complete*

Maximum Subarray Problem

- *Input*: An array of values
- *Output*: The contiguous subarray that has the largest sum of elements

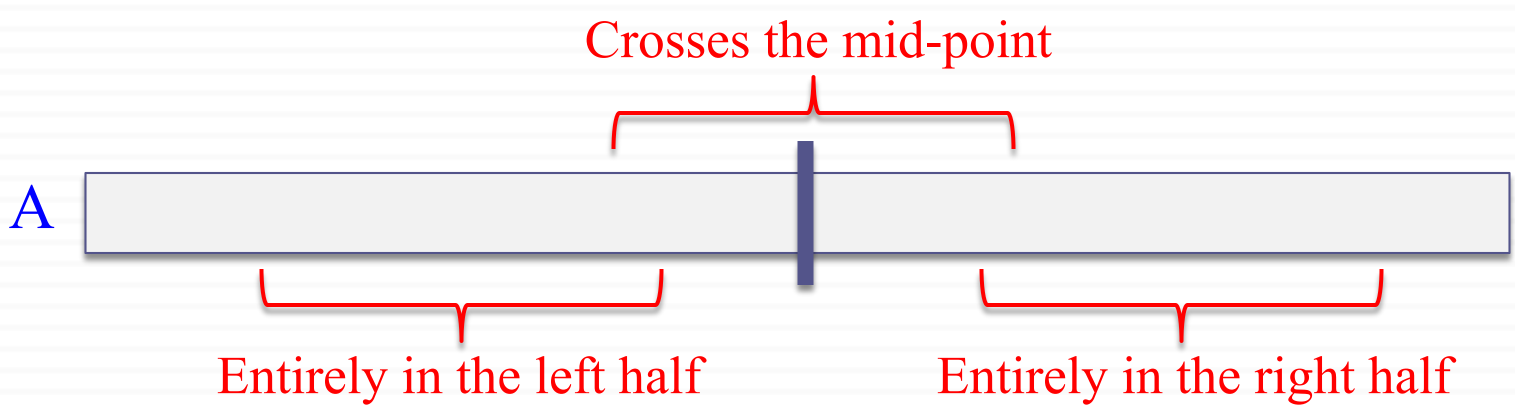
Input array:

13	-3	-25	20	-3	-16	-23	18	20	-7	12	-22	-4	7

the maximum contiguous subarray

Maximum Subarray Problem: Divide & Conquer

- ***Basic idea***:
  - Divide the input array into 2 from the middle
  - Pick the best solution among the following:
    1. The max subarray of the left half
    2. The max subarray of the right half
    3. The max subarray crossing the mid-point



Maximum Subarray Problem: Divide & Conquer

- *Divide*: Trivial (divide the array from the middle)
- *Conquer*: Recursively compute the max subarrays of the left and right halves
- *Combine*: Compute the max-subarray crossing the mid-point *(can be done in $\Theta(n)$ time)*. Return the max among the following:
    1. the max subarray of the left subarray
    2. the max subarray of the right subarray
    3. the max subarray crossing the mid-point

See textbook for the detailed solution.

Conclusion

- Divide and conquer is just one of several powerful techniques for algorithm design.
- Divide-and-conquer algorithms can be analyzed using recurrences and the master method (so practice this math).
- Can lead to more efficient algorithms