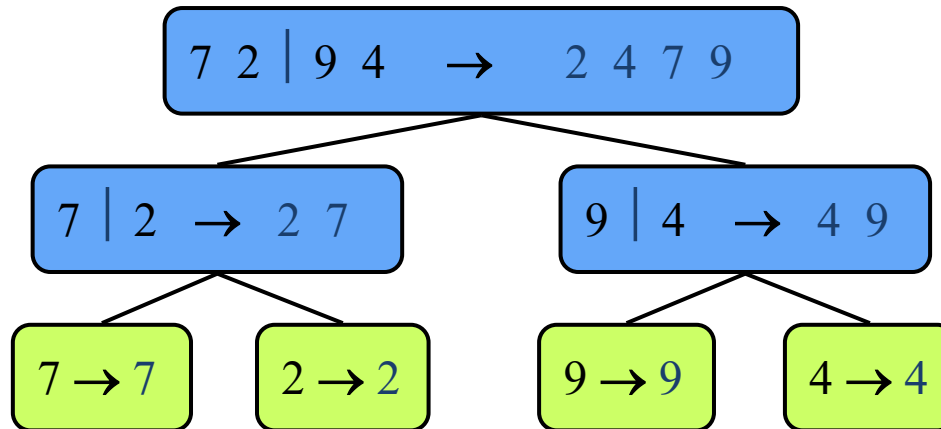


# Divide and Conquer

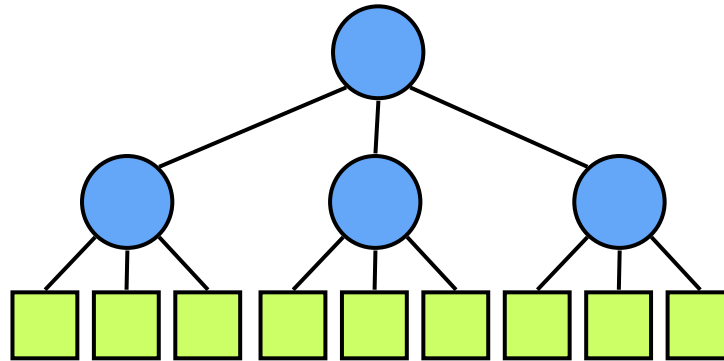


# Outline / Reading

- Divide-and-conquer paradigm (5.2)
- Review Merge-sort (4.1.1)
- Recurrence Equations (5.2.1)
  - Recursion trees
  - Induction
    - Iterative substitution
    - Guess-and-test
  - The master method
- Integer Multiplication (5.2.2)

# Divide-and-Conquer

- **Divide-and conquer** is a general algorithm design paradigm:
  - **Divide**: divide the input data in two or more disjoint subsets  $\mathcal{S}_1, \mathcal{S}_2, \dots$
  - **Recur**: solve the subproblems recursively
  - **Conquer**: combine the solutions for  $\mathcal{S}_1, \mathcal{S}_2, \dots$ , into a solution for  $\mathcal{S}$
- The base case for the recursion are subproblems of constant size
- Analysis can be done using **recurrence equations**



# Merge Sort Review

Merge-sort on an input sequence  $S$  with  $n$  elements consists of three steps:

- **Divide:** partition  $S$  into two sequences  $S_1$  and  $S_2$  of about  $n/2$  elements each
- **Recur:** recursively sort  $S_1$  and  $S_2$
- **Conquer:** merge  $S_1$  and  $S_2$  into a unique sorted sequence

**Algorithm** *mergeSort*( $S, C$ )

**Input** sequence  $S$  with  $n$  elements, comparator  $C$

**Output** sequence  $S$  sorted according to  $C$

**if**  $S.size() > 1$

$(S_1, S_2) \leftarrow \text{partition}(S, n/2)$

*mergeSort*( $S_1, C$ )

*mergeSort*( $S_2, C$ )

$S \leftarrow \text{merge}(S_1, S_2)$

# Recurrence Equation Analysis

- The conquer step of merge-sort consists of merging two sorted sequences, each with  $n/2$  elements and implemented by means of a doubly linked list, takes at most  $bn$  steps, for some constant  $b$ .
- Likewise, the basis case ( $n < 2$ ) will take at most  $b$  steps.
- Therefore, if we let  $T(n)$  denote the running time of merge-sort:

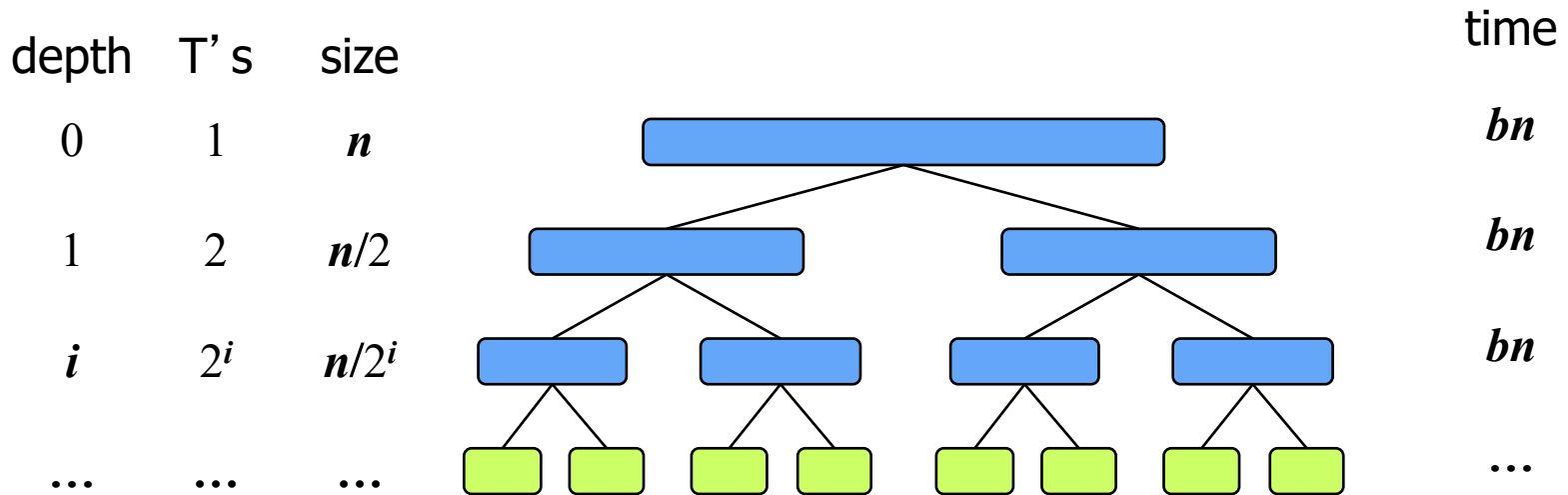
$$T(n) = \begin{cases} b & \text{if } n < 2 \\ 2T(n/2) + bn & \text{if } n \geq 2 \end{cases}$$

- We can analyze the running time of merge-sort by finding a **closed form solution** to the above equation.
  - That is, a solution that has  $T(n)$  only on the left-hand side.

# Recursion Tree

Draw the **recursion tree** for the recurrence relation and look for a pattern:

$$T(n) = \begin{cases} b & \text{if } n < 2 \\ 2T(n/2) + bn & \text{if } n \geq 2 \end{cases}$$



Total time =  $bn + bn \log n$

(last level plus all previous levels)

# Iterative Substitution

In the **iterative substitution**, or “plug-and-chug,” technique, we iteratively apply the recurrence equation to itself and see if we can find a pattern, then prove it is true by **induction**:

$$\begin{aligned}T(n) &= 2T(n/2) + bn \\&= 2(2T(n/2^2)) + b(n/2) + bn \\&= 2^2T(n/2^2) + 2bn \\&= 2^3T(n/2^3) + 3bn \\&= 2^4T(n/2^4) + 4bn \\&= \dots \\&= 2^i T(n/2^i) + ibn\end{aligned}$$

- Note that the base case,  $T(n) = b$ , case occurs when  $2^i = n$ . That is,  $i = \log n$ . So we have:  $T(n) = bn + bn \log n$
- Once we prove this by induction, then  $T(n)$  is  $O(n \log n)$ .

# Guess-and-Test Method

In the **guess-and-test method**, we guess a closed form solution and then try to prove it is true by **induction**:

$$T(n) = \begin{cases} b & \text{if } n < 2 \\ 2T(n/2) + bn \log n & \text{if } n \geq 2 \end{cases}$$

- Guess #1:  $T(n) \leq cn \log n$ .

$$\begin{aligned} T(n) &= 2T(n/2) + bn \log n \\ &\leq 2(c(n/2) \log(n/2)) + bn \log n \\ &= cn(\log n - \log 2) + bn \log n \\ &= cn \log n - cn + bn \log n \end{aligned}$$

- **Wrong**: we cannot make this last line be less than  $cn \log n$



# Guess-and-Test Method (2)

Recall the recurrence equation:

$$T(n) = \begin{cases} b & \text{if } n < 2 \\ 2T(n/2) + bn \log n & \text{if } n \geq 2 \end{cases}$$

- Guess #2:  $T(n) \leq cn \log^2 n$ .

$$\begin{aligned} T(n) &= 2T(n/2) + bn \log n \\ &\leq 2(c(n/2) \log^2(n/2)) + bn \log n \\ &= cn(\log n - \log 2)^2 + bn \log n \\ &= cn \log^2 n - 2cn \log n + cn + bn \log n \\ &\leq cn \log^2 n \quad \text{if } c > b. \end{aligned}$$

- So,  $T(n)$  is  $O(n \log^2 n)$ .

In general, to use this method, you need to have a good guess.

# Master Method

Many divide-and-conquer recurrence equations have the form:

$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

## The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \epsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \epsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

# Master Method: Ex. 1

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = 4T(n/2) + n$$

Solution:  $\log_b a = 2$ , so case 1 says  $T(n)$  is  $\Theta(n^2)$ .

# Master Method: Ex. 2

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = 2T(n/2) + n \log n$$

Solution:  $\log_b a = 1$ , so case 2 says  $T(n)$  is  $\Theta(n \log^2 n)$ .

# Master Method: Ex. 3

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = T(n/3) + n \log n$$

Solution:  $\log_b a = 0$ , so case 3 says  $T(n)$  is  $\Theta(n \log n)$ .

# Master Method: Ex. 4

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = 8T(n/2) + n^2$$

Solution:  $\log_b a = 3$ , so case 1 says  $T(n)$  is  $\Theta(n^3)$ .

# Master Method: Ex. 5

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = 9T(n/3) + n^3$$

Solution:  $\log_b a = 2$ , so case 3 says  $T(n)$  is  $\Theta(n^3)$ .

# Master Method: Ex. 6

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = T(n/2) + 1 \quad (\text{binary search})$$

Solution:  $\log_b a = 0$ , so case 2 says  $T(n)$  is  $\Theta(\log n)$ .



# Master Method: Ex. 7

The form: 
$$T(n) = \begin{cases} c & \text{if } n < d \\ aT(n/b) + f(n) & \text{if } n \geq d \end{cases}$$

The Master Theorem:

1. if  $f(n)$  is  $O(n^{\log_b a - \varepsilon})$ , then  $T(n)$  is  $\Theta(n^{\log_b a})$
2. if  $f(n)$  is  $\Theta(n^{\log_b a} \log^k n)$ , then  $T(n)$  is  $\Theta(n^{\log_b a} \log^{k+1} n)$
3. if  $f(n)$  is  $\Omega(n^{\log_b a + \varepsilon})$ , then  $T(n)$  is  $\Theta(f(n))$ ,  
provided  $af(n/b) \leq \delta f(n)$  for some  $\delta < 1$ .

Example:

$$T(n) = 2T(n/2) + \log n \quad (\text{heap construction})$$

Solution:  $\log_b a = 1$ , so case 1 says  $T(n)$  is  $\Theta(n)$ .

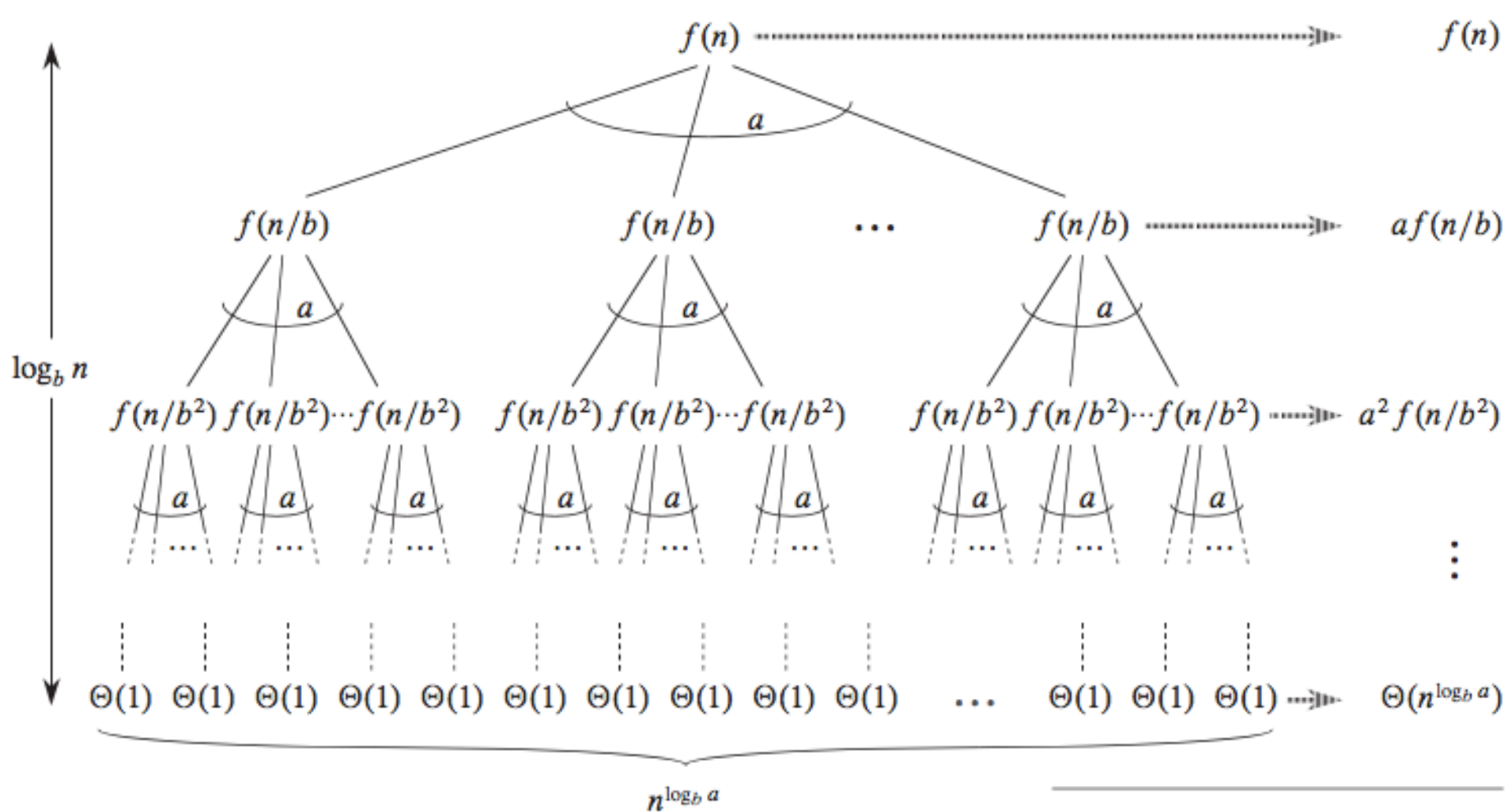
# Iterative Justification of the Master Theorem

Use iterative substitution to find a pattern:

$$\begin{aligned}T(n) &= aT(n/b) + f(n) \\&= a(aT(n/b^2)) + f(n/b) + f(n) \\&= a^2T(n/b^2) + af(n/b) + f(n) \\&= a^3T(n/b^3) + a^2f(n/b^2) + af(n/b) + f(n) \\&= \dots \\&= a^{\log_b n}T(1) + \sum_{i=0}^{(\log_b n)-1} a^i f(n/b^i) \\&= n^{\log_b a}T(1) + \sum_{i=0}^{(\log_b n)-1} a^i f(n/b^i)\end{aligned}$$

We then distinguish the three cases as

- Case 1: The first term is dominant
- Case 2: Each part of the summation is equally dominant
- Case 3: The second term is dominant



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- Case 1: The first term is dominant
- Case 2: Each part of the summation is equally dominant
- Case 3: The second term is dominant

# Integer Multiplication

**Algorithm:** Multiply two n-bit integers I and J.

- Divide step: Split I and J into high-order and low-order bits

$$I = I_h 2^{n/2} + I_l$$

$$J = J_h 2^{n/2} + J_l$$

- We can then define  $I * J$  by multiplying the parts and adding:

$$\begin{aligned} I * J &= (I_h 2^{n/2} + I_l) * (J_h 2^{n/2} + J_l) \\ &= I_h J_h 2^n + I_h J_l 2^{n/2} + I_l J_h 2^{n/2} + I_l J_l \end{aligned}$$

- So,  $T(n) = 4T(n/2) + n$ , which implies  $T(n)$  is  $\Theta(n^2)$ .
- But that is no better than the algorithm we learned in grade school.

# Improved Integer Multiplication

**Algorithm:** Multiply two n-bit integers I and J.

- Divide step: Split I and J into high-order and low-order bits

$$I = I_h 2^{n/2} + I_l$$

$$J = J_h 2^{n/2} + J_l$$

- Observe that there is a different way to multiply parts:

$$\begin{aligned} I * J &= I_h J_h 2^n + [(I_h - I_l)(J_l - J_h) + I_h J_h + I_l J_l] 2^{n/2} + I_l J_l \\ &= I_h J_h 2^n + [(I_h J_l - I_l J_l - I_h J_h + I_l J_h) + I_h J_h + I_l J_l] 2^{n/2} + I_l J_l \\ &= I_h J_h 2^n + (I_h J_l + I_l J_h) 2^{n/2} + I_l J_l \end{aligned}$$

- So,  $T(n) = 3T(n/2) + n$ , which implies  $T(n)$  is  $\Theta(n^{\log_2 3})$ .
- Thus,  $T(n)$  is  $O(n^{1.585})$ .