CSE 613: Parallel Programming

Lectures 13 – 14
(Analyzing Divide-and-Conquer Algorithms)

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A Useful Recurrence

Consider the following recurrence:

$$T(n) = \begin{cases} \Theta(1), & if\ n \leq 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise; \end{cases}$$

where, $a \geq 1$ and $b > 1$.

Arises frequently in the analyses of *divide-and-conquer* algorithms.

Recall the following from the analyses of QSort (quicksort) in lecture 1.

Serial: $T(n) = 2T\left(\frac{n}{2}\right) + \Theta(n)$

Parallel (with serial partition): $T(n) = T\left(\frac{n}{2}\right) + \Theta(n)$

Parallel (with parallel partition): $T(n) = T\left(\frac{n}{2}\right) + \Theta(\log n)$

How the Recurrence Unfolds

$$T(n) = \begin{cases} \Theta(1), & if\ n \leq 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise. \end{cases}$$

How the Recurrence Unfolds

$$T(n) = \begin{cases} \Theta(1), & if\ n \leq 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise. \end{cases}$$

$$\boldsymbol{T(n)}$$

$$\downarrow$$

$$\boldsymbol{f(n) + aT\left(\frac{n}{b}\right)}$$

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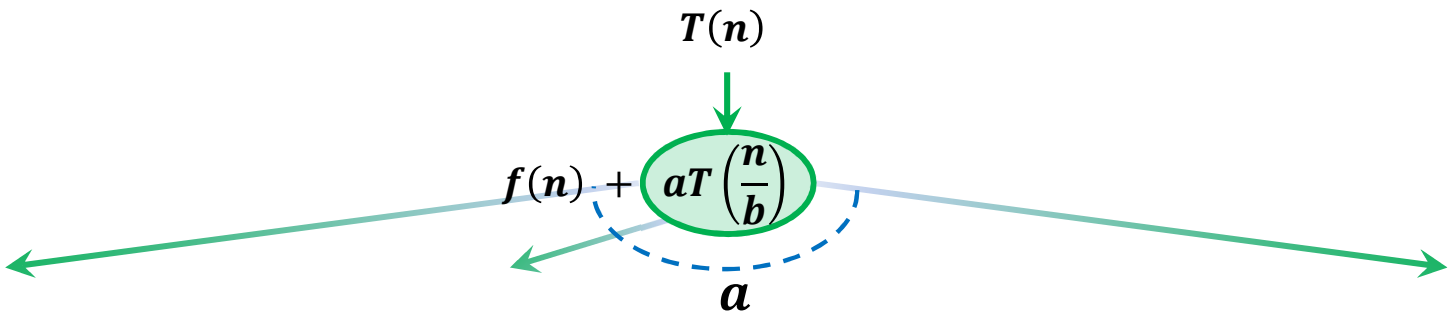

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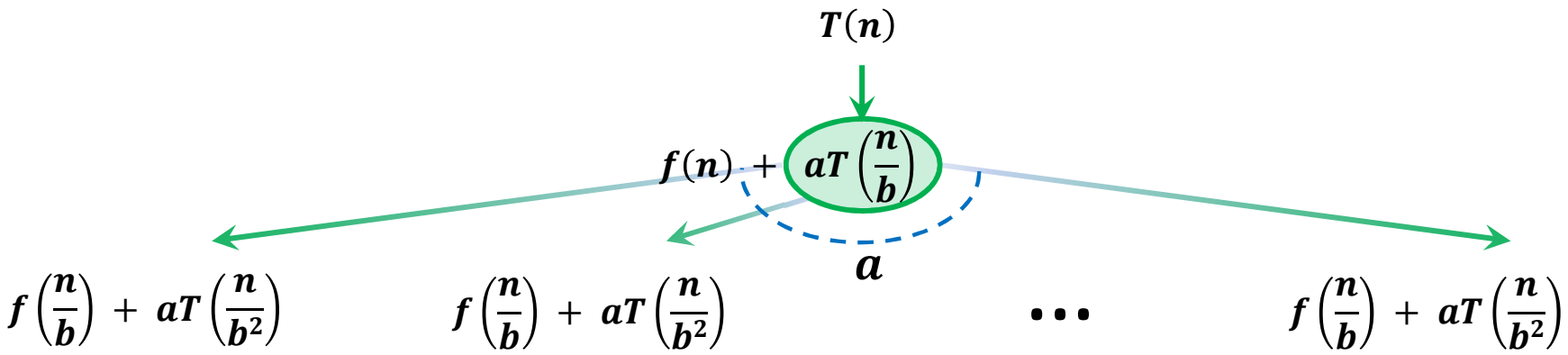

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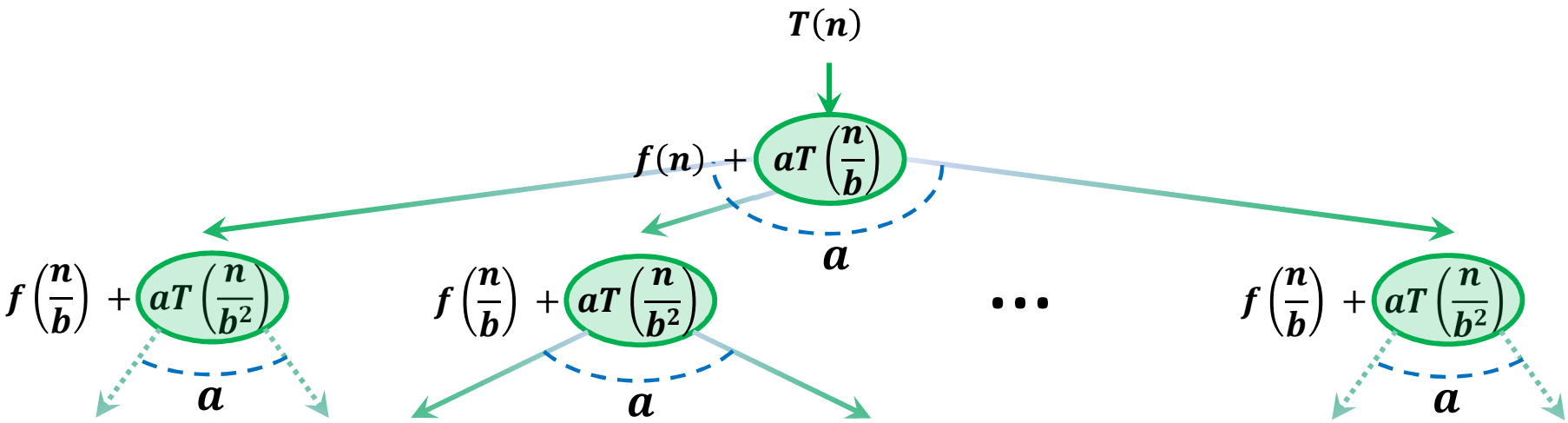

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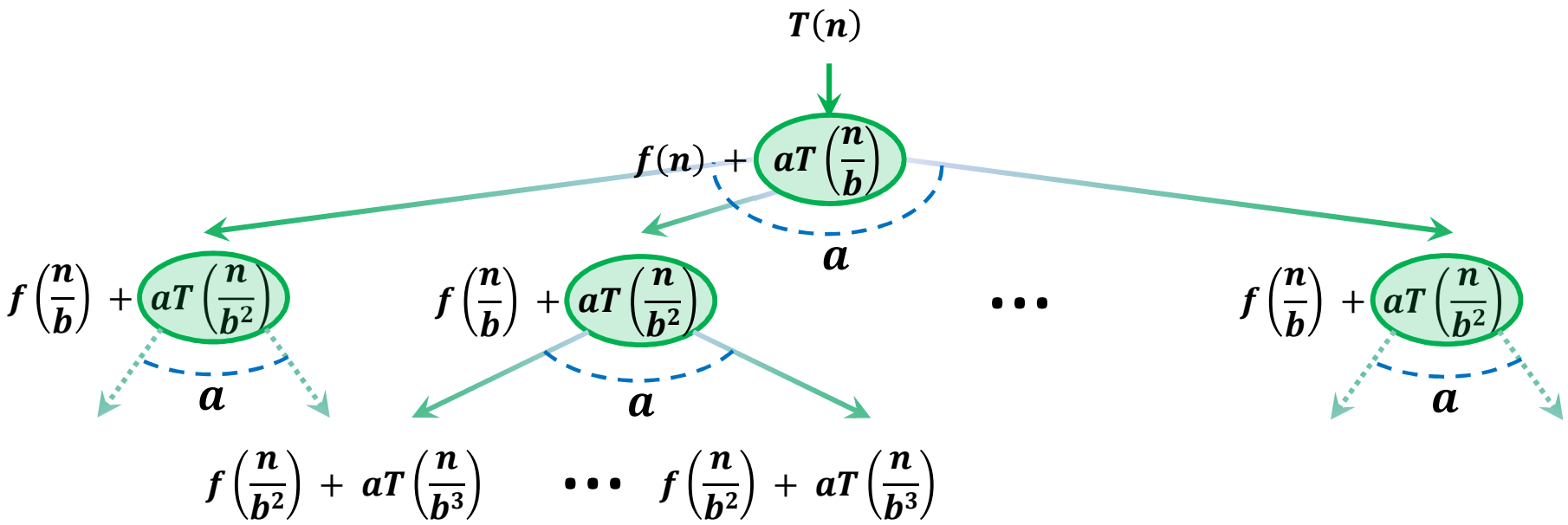

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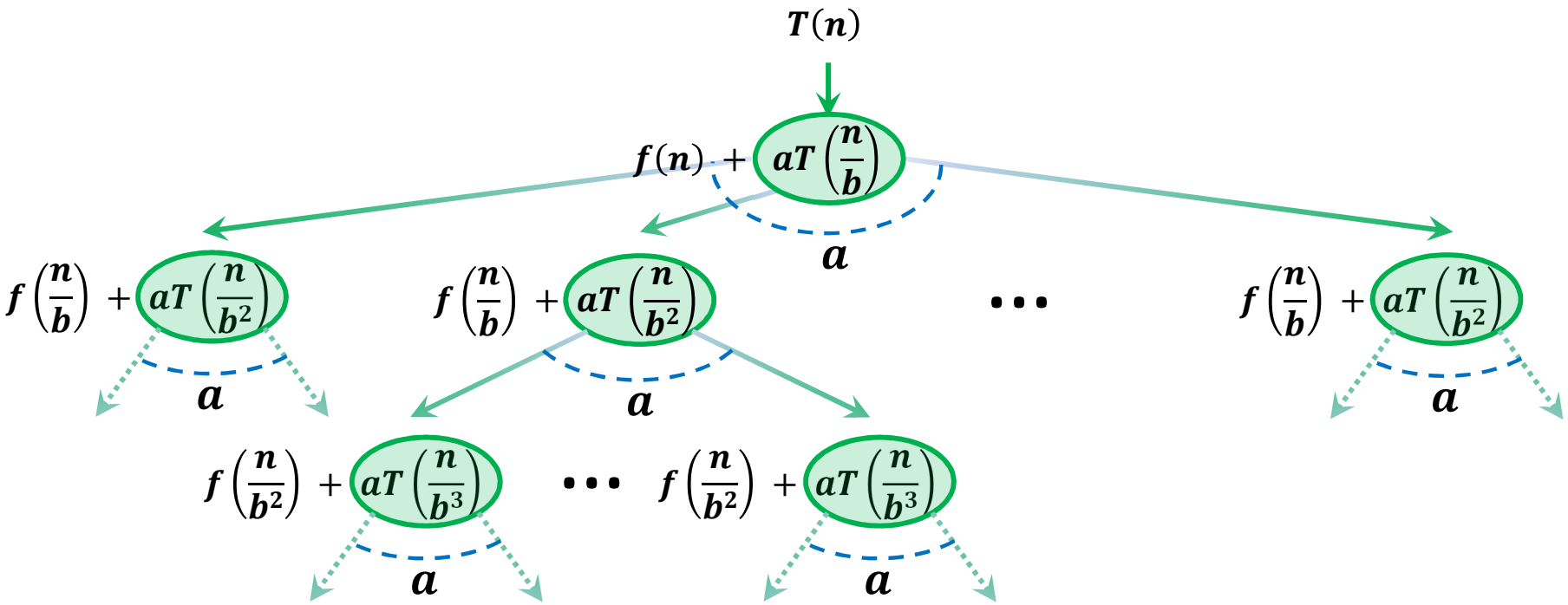

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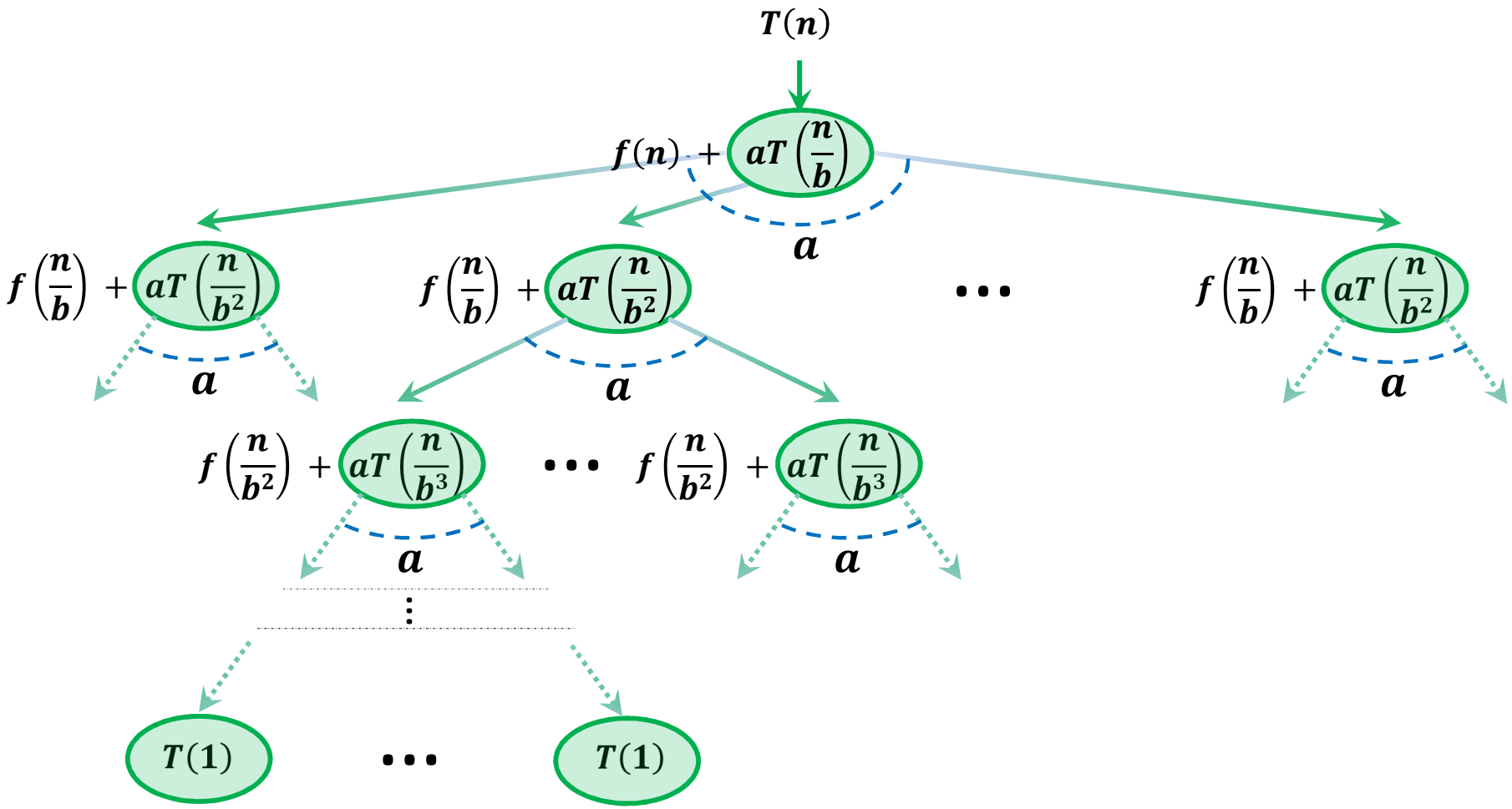

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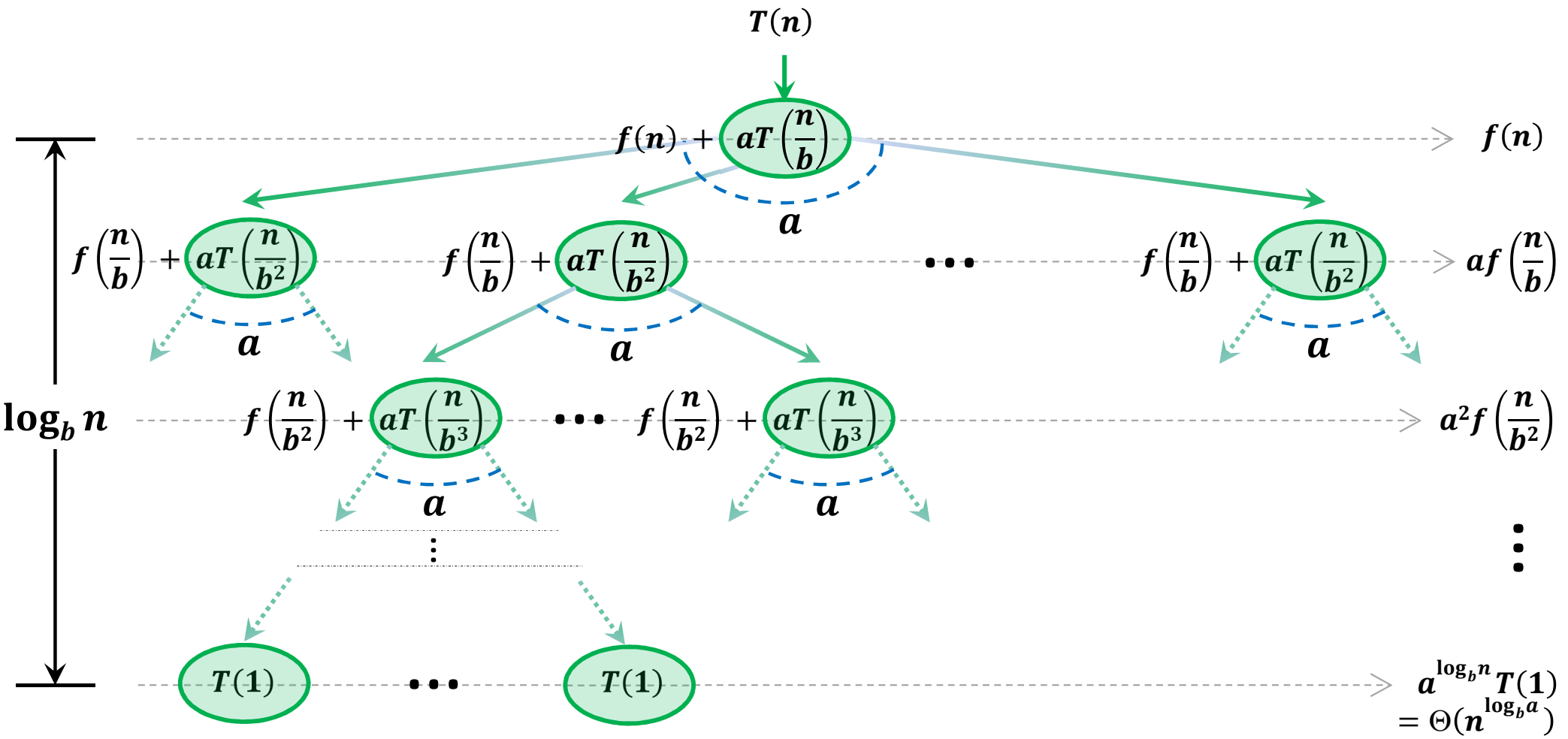
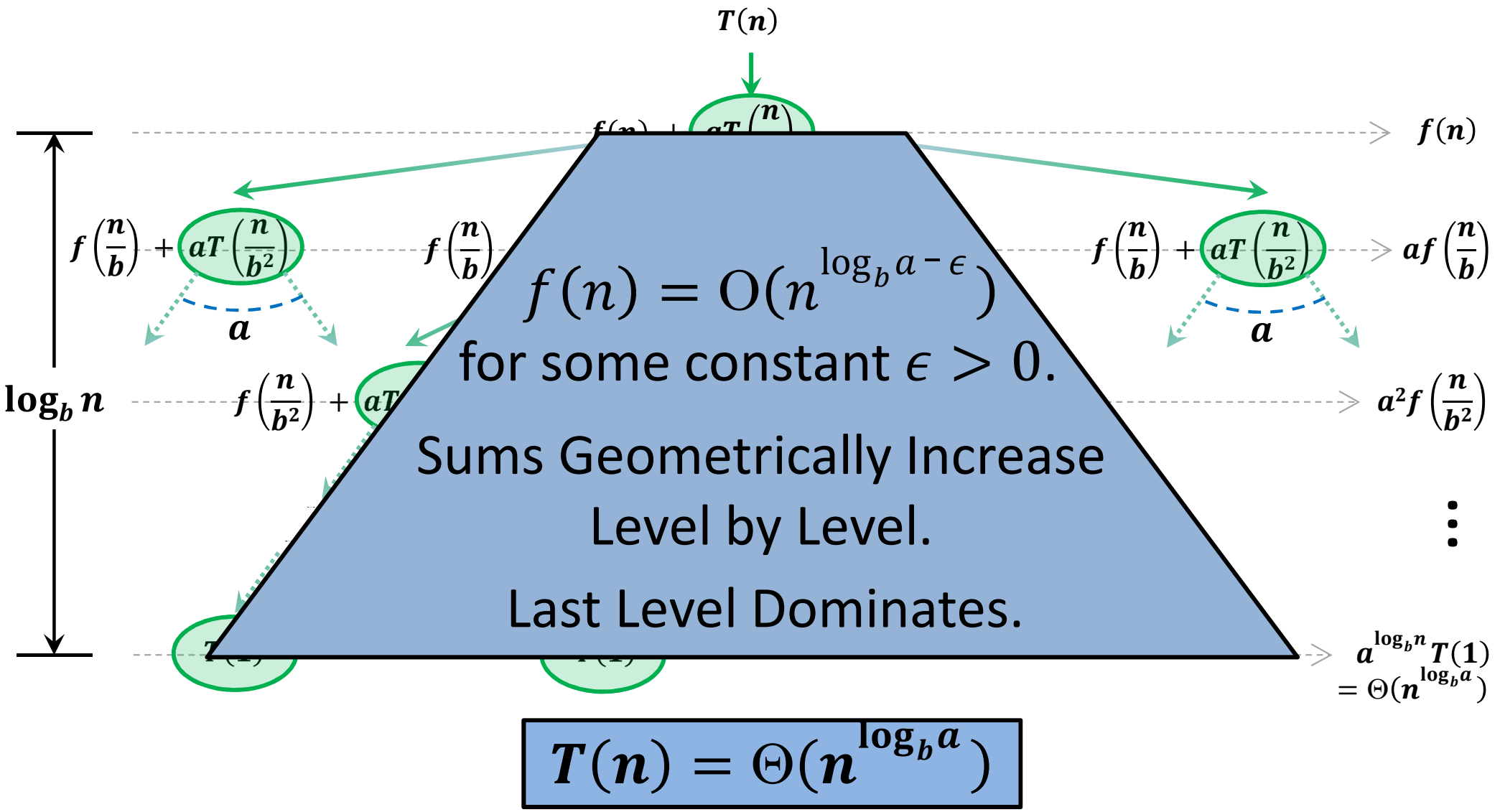


How the Recurrence Unfolds: Case 1

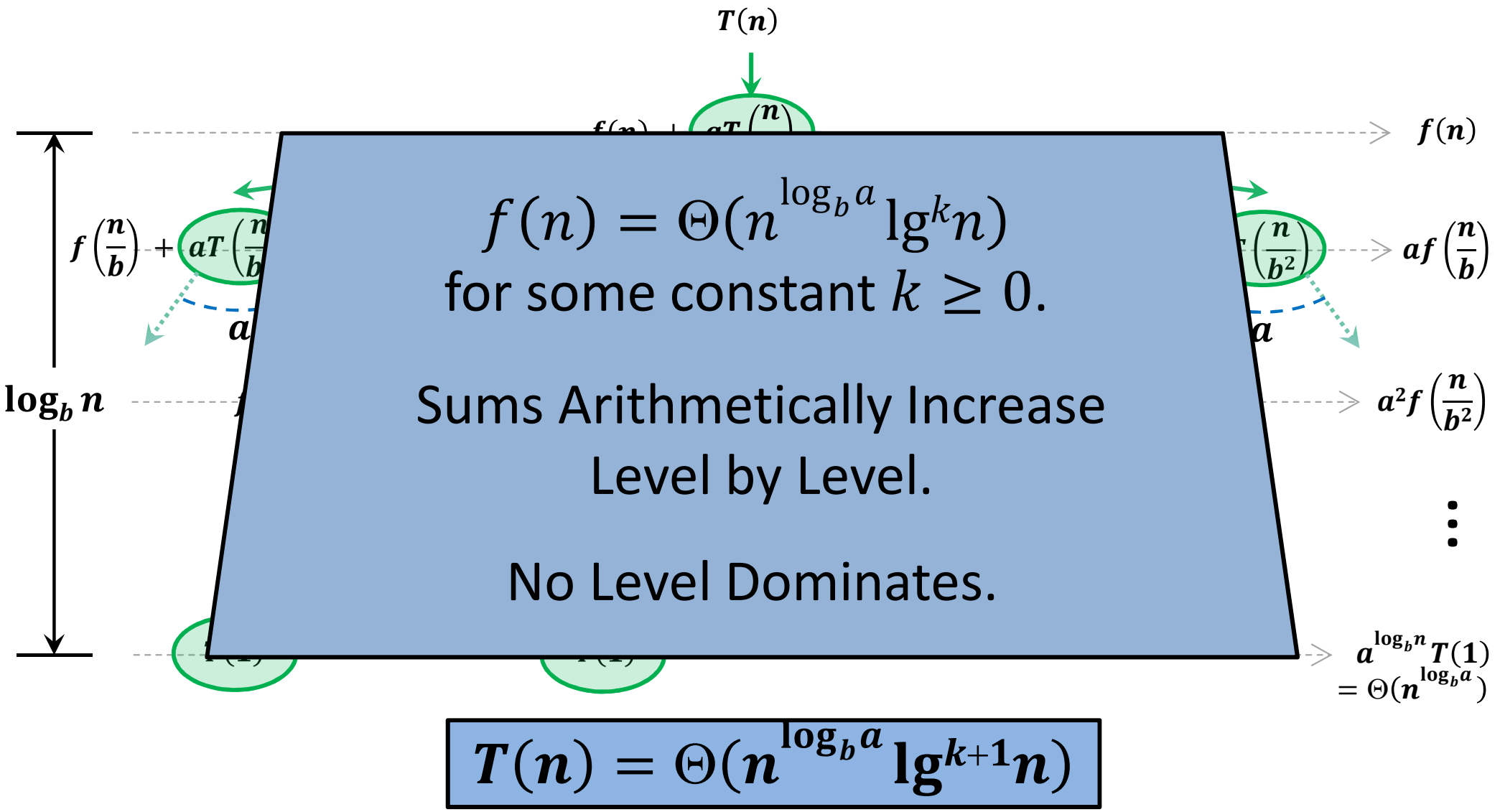
$$T(n) = \begin{cases} \Theta(1), & if\ n \le 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise. \end{cases}$$



$$\boldsymbol{T(n) = \Theta(n^{\log_b a})}$$

How the Recurrence Unfolds: Case 2

$$T(n) = \begin{cases} \Theta(1), & if\ n \le 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise. \end{cases}$$



$$f(n) = \Theta(n^{\log_b a} \lg^k n)$$
for some constant $k \ge 0$.

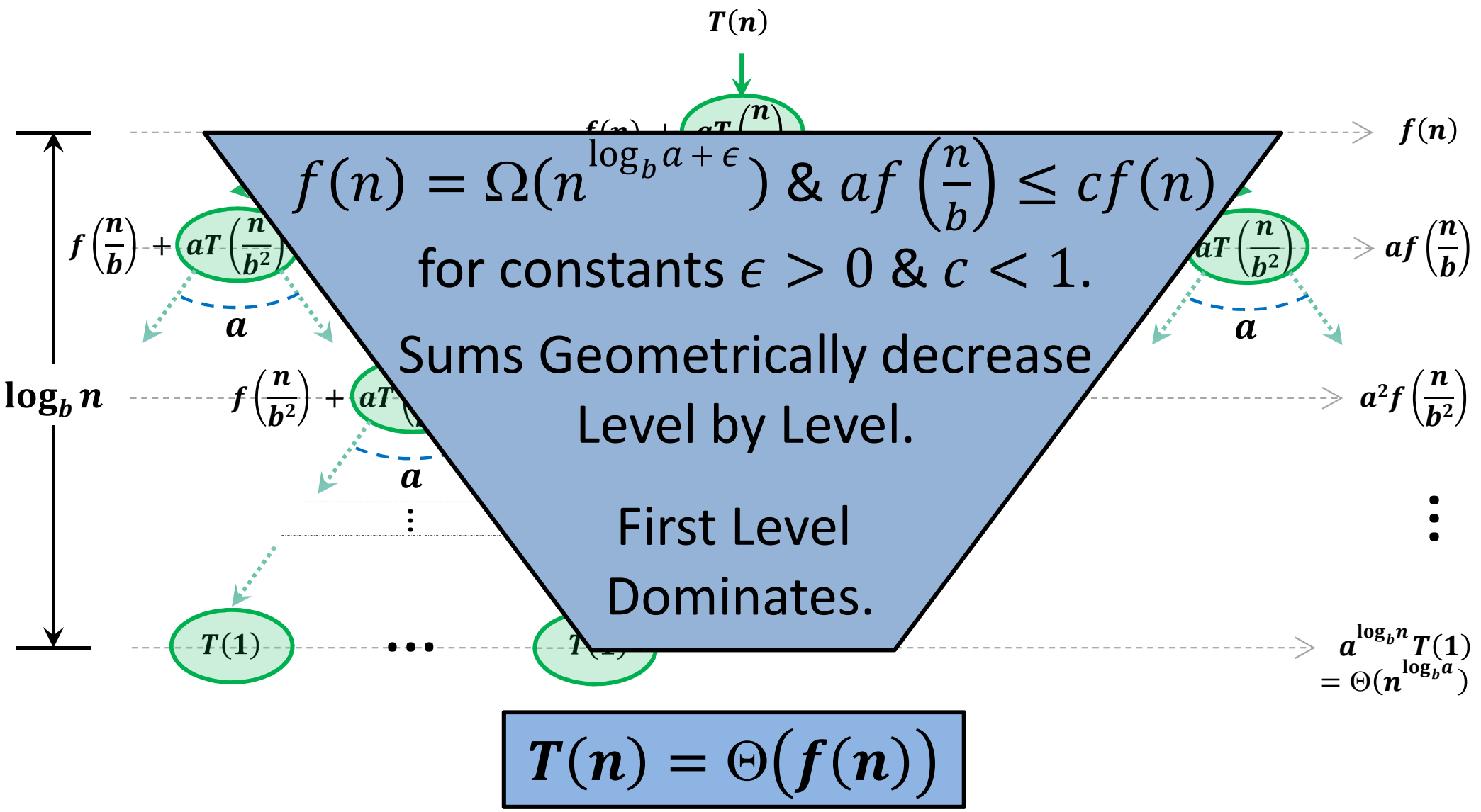
Sums Arithmetically Increase Level by Level.

No Level Dominates.

$$\boldsymbol{T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)}$$

How the Recurrence Unfolds: Case 3

$$T(n) = \begin{cases} \Theta(1), & if\ n \le 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise. \end{cases}$$



$$\boldsymbol{T(n) = \Theta\big(f(n)\big)}$$

The Master Theorem

$$T(n) = \begin{cases} \Theta(1), & if\ n \le 1, \\ aT\left(\frac{n}{b}\right) + f(n), & otherwise\ (a \ge 1, b > 1). \end{cases}$$

Case 1: $f(n) = \mathrm{O}(n^{\log_b a - \epsilon})$ for some constant $\epsilon > 0$

$$T(n) = \Theta(n^{\log_b a})$$

Case 2: $f(n) = \Theta(n^{\log_b a} \lg^k n)$ for some constant $k \ge 0$.

$$T(n) = \Theta(n^{\log_b a} \lg^{k+1} n)$$

Case 3: $f(n) = \Omega(n^{\log_b a + \epsilon})$ and $af\left(\frac{n}{b}\right) \le cf(n)$

for constants $\epsilon > 0$ and $c < 1$.

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

Back to QSort Complexities

Now let's try the QSort (quicksort) recurrences from lecture 1.

Serial: $T(n) = 2T\left(\frac{n}{2}\right) + \Theta(n)$

Master Theorem Case 2: $T(n) = \Theta(n \log n)$

Parallel (with serial partition): $T(n) = T\left(\frac{n}{2}\right) + \Theta(n)$

Master Theorem Case 3: $T(n) = \Theta(n)$

Parallel (with parallel partition): $T(n) = T\left(\frac{n}{2}\right) + \Theta(\log n)$

Master Theorem Case 2: $T(n) = \Theta(\log^2 n)$

More Example Applications of Master Theorem

Karatsuba's Algorithm: $T(n) = 3T\left(\frac{n}{2}\right) + \Theta(n)$

Master Theorem Case 1: $T(n) = \Theta\left(n^{\log_2 3}\right)$

Strassen's Matrix Multiplication: $T(n) = 7T\left(\frac{n}{2}\right) + \Theta(n^2)$

Master Theorem Case 1: $T(n) = \Theta\left(n^{\log_2 7}\right)$

Fast Fourier Transform: $T(n) = 2T\left(\frac{n}{2}\right) + \Theta(n)$

Master Theorem Case 2: $T(n) = \Theta(n\log n)$

Recurrences not Solvable using the Master Theorem

Example 1: $T(n) = \sqrt{n}\, T\left(\frac{n}{2}\right) + n$

$a = \sqrt{n}$ is not a constant

Example 2: $T(n) = 2T\left(\frac{n}{\log n}\right) + n^2$

$b = \log n$ is not a constant

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

$a = \frac{1}{2}$ is not ≥ 1

Example 4: $T(n) = 2T\left(\frac{4n}{3}\right) + n$

$b = \frac{3}{4}$ is not > 1.

Recurrences not Solvable using the Master Theorem

Example 5: $T(n) = 3T\left(\frac{n}{2}\right) - n$

$f(n) = -n$ is not positive

Example 6: $T(n) = 2\,T\left(\frac{n}{2}\right) + n^2 \sin n$

violates regularity condition of case 3

Example 7: $T(n) = 2T\left(\frac{n}{2}\right) + \frac{n}{\log n}$

$f(n) = \mathrm{O}\left(n^{\log_b a}\right)$, but $\neq \mathrm{O}\left(n^{\log_b a - \epsilon}\right)$ for any constant $\epsilon > 0$

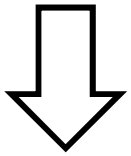
Example 8: $T(n) = T\left(\frac{n}{2}\right) + 2T\left(\frac{n}{4}\right) + n$

a and b are not fixed

Multithreaded Matrix Multiplication

Parallel Iterative MM

```
Iter-MM ( Z, X, Y )          { X, Y, Z are n × n matrices,
                               where n is a positive integer }
1.  for i ← 1 to n do
2.      for j ← 1 to n do
3.          Z[ i ][ j ] ← 0
4.          for k ← 1 to n do
5.              Z[ i ][ j ] ← Z[ i ][ j ] + X[ i ][ k ] · Y[ k ][ j ]
```



```
Par-Iter-MM ( Z, X, Y )      { X, Y, Z are n × n matrices,
                               where n is a positive integer }
1.  parallel for i ← 1 to n do
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Parallel Iterative MM

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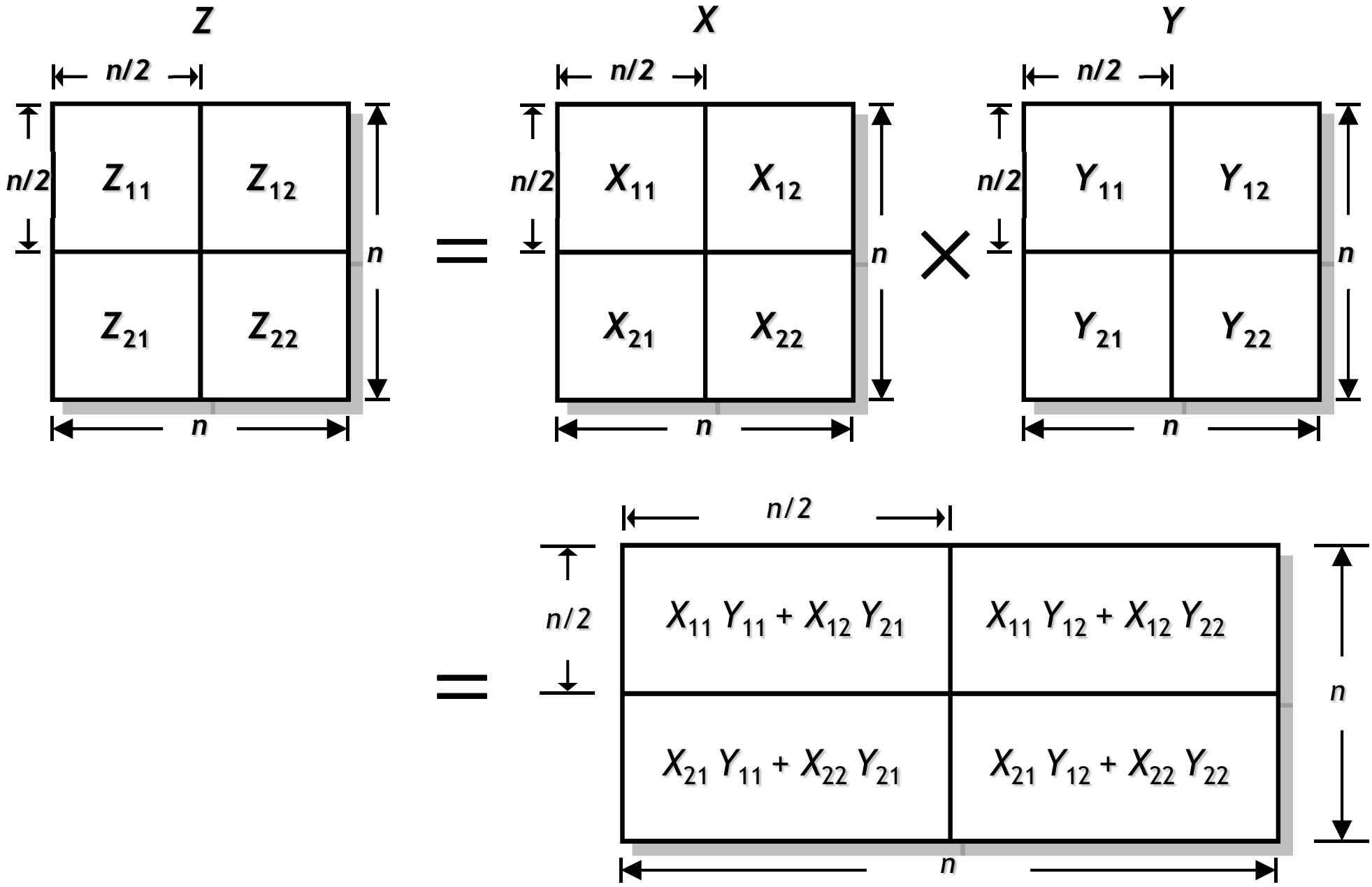
```

Work: $T_1(n) = \Theta(n^3)$

Span: $T_\infty(n) = \Theta(\log n + \log n + n) = \Theta(n)$

Parallelism: $\frac{T_1(n)}{T_\infty(n)} = \Theta(n^2)$

Parallel Recursive MM



Parallel Recursive MM

```
Par-Rec-MM ( Z, X, Y )     { X, Y, Z are n × n matrices,
                               where n = 2^k for integer k ≥ 0 }
 1. if n = 1 then
 2.     Z ← Z + X · Y
 3. else
 4.     spawn Par-Rec-MM ( Z11, X11, Y11 )
 5.     spawn Par-Rec-MM ( Z12, X11, Y12 )
 6.     spawn Par-Rec-MM ( Z21, X21, Y11 )
 7.           Par-Rec-MM ( Z21, X21, Y12 )
 8.     sync
 9.     spawn Par-Rec-MM ( Z11, X12, Y21 )
10.     spawn Par-Rec-MM ( Z12, X12, Y22 )
11.     spawn Par-Rec-MM ( Z21, X22, Y21 )
12.           Par-Rec-MM ( Z22, X22, Y22 )
13.     sync
14. endif
```

Parallel Recursive MM

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Work:

$$T_1(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 8T_1\left(\frac{n}{2}\right) + \Theta(1), & otherwise. \end{cases}$$

$$= \Theta(n^3) \qquad \text{[MT Case 1]}$$

Span:

$$T_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 2T_\infty\left(\frac{n}{2}\right) + \Theta(1), & otherwise. \end{cases}$$

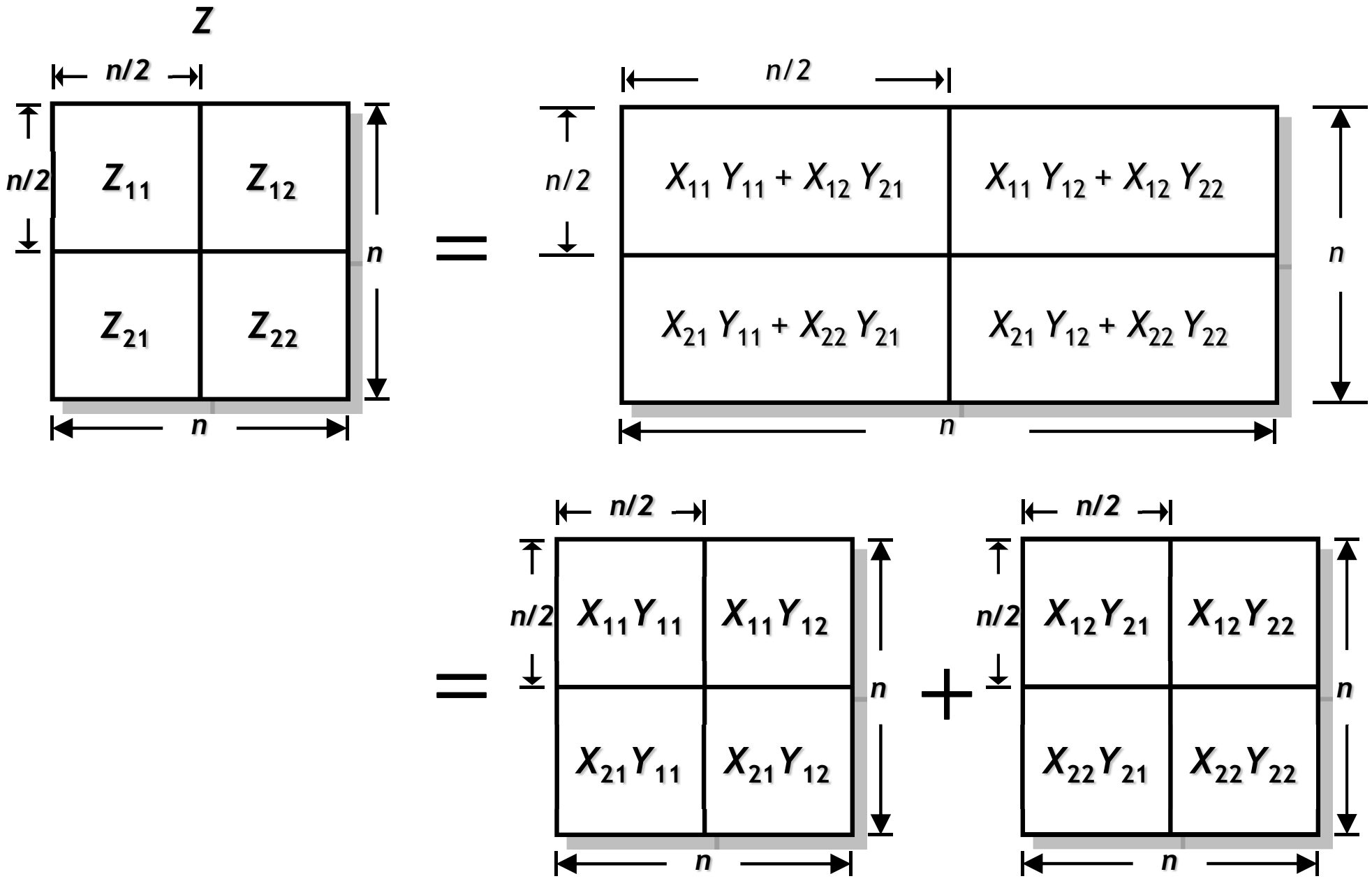
$$= \Theta(n) \qquad \text{[MT Case 1]}$$

Parallelism: $\frac{T_1(n)}{T_\infty(n)} = \Theta(n^2)$

Additional Space:

$$s_\infty(n) = \Theta(1)$$

Recursive MM with More Parallelism



Recursive MM with More Parallelism

```
Par-Rec-MM2 ( Z, X, Y )      { X, Y, Z are n × n matrices,
                               where n = 2^k for integer k ≥ 0 }
 1. if n = 1 then
 2.     Z ← Z + X · Y
 3. else          { T is a temporary n × n matrix }
 4.     spawn Par-Rec-MM2 ( Z11, X11, Y11 )
 5.     spawn Par-Rec-MM2 ( Z12, X11, Y12 )
 6.     spawn Par-Rec-MM2 ( Z21, X21, Y11 )
 7.     spawn Par-Rec-MM2 ( Z21, X21, Y12 )
 8.     spawn Par-Rec-MM2 ( T11, X12, Y21 )
 9.     spawn Par-Rec-MM2 ( T12, X12, Y22 )
10.     spawn Par-Rec-MM2 ( T21, X22, Y21 )
11.           Par-Rec-MM2 ( T22, X22, Y22 )
12.     sync
13.     parallel for i ← 1 to n do
14.         parallel for j ← 1 to n do
15.             Z[ i ][ j ] ← Z[ i ][ j ] + T[ i ][ j ]
16. endif
```

Recursive MM with More Parallelism

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Par-Rec-MM2 ( Z, X, Y )      { X, Y, Z are n × n matrices,
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Work:

$$T_1(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 8T_1\left(\frac{n}{2}\right) + \Theta(n^2), & otherwise. \end{cases}$$

$$= \Theta(n^3) \qquad [\text{ MT Case 1 }]$$

Span:

$$T_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ T_\infty\left(\frac{n}{2}\right) + \Theta(\log n), & otherwise. \end{cases}$$

$$= \Theta(\log^2 n) \qquad [\text{ MT Case 2 }]$$

Parallelism: $\frac{T_1(n)}{T_\infty(n)} = \Theta\left(\frac{n^3}{\log^2 n}\right)$

Additional Space:

$$s_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 8s_\infty\left(\frac{n}{2}\right) + \Theta(n^2), & otherwise. \end{cases}$$

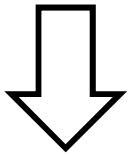
$$= \Theta(n^3) \qquad [\text{ MT Case 1 }]$$

Multithreaded Merge Sort

Parallel Merge Sort

```
Merge-Sort ( A, p, r )        { sort the elements in A[ p ... r ] }

1.  if p < r then
2.      q ← ⌊ ( p + r ) / 2 ⌋
3.      Merge-Sort ( A, p, q )
4.      Merge-Sort ( A, q + 1, r )
5.      Merge ( A, p, q, r )
```



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Parallel Merge Sort

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```

Work: $$T_1(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 2T_1\left(\frac{n}{2}\right) + \Theta(n), & otherwise. \end{cases}$$

$$= \Theta(n \log n) \qquad [\text{ MT Case 2 }]$$

Span: $$T_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ T_\infty\left(\frac{n}{2}\right) + \Theta(n), & otherwise. \end{cases}$$

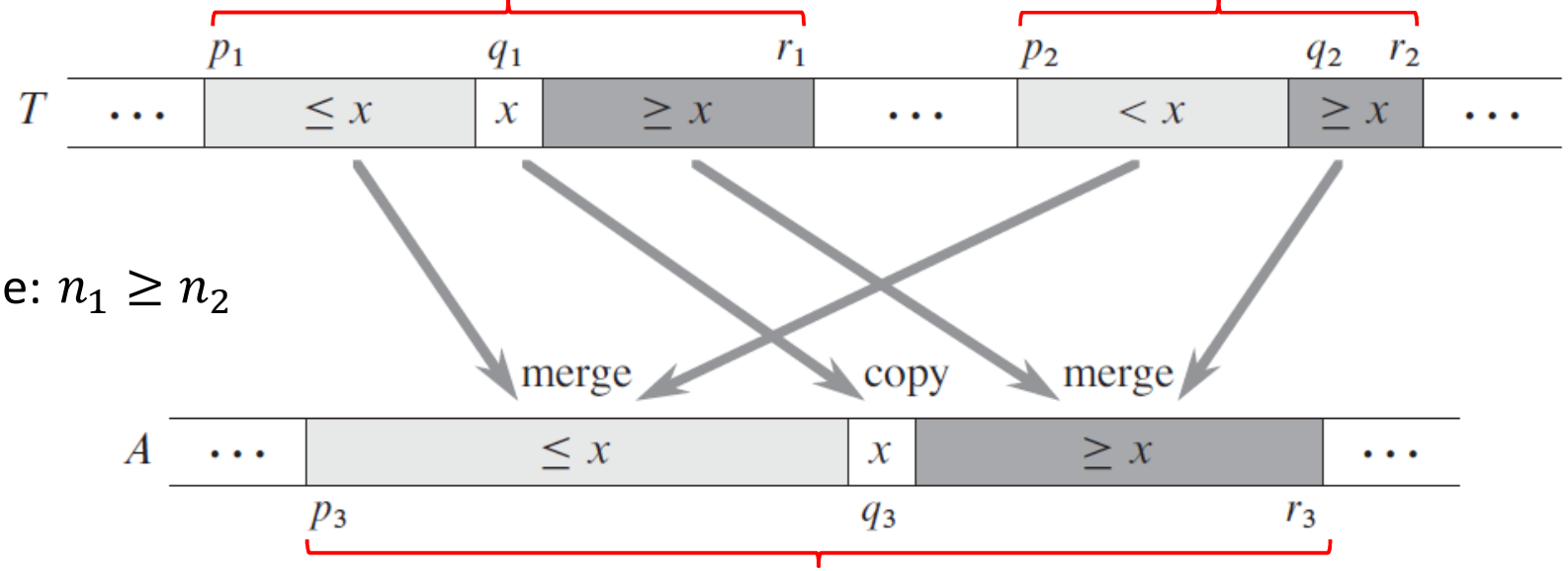
$$= \Theta(n) \qquad [\text{ MT Case 3 }]$$

Parallelism: $$\frac{T_1(n)}{T_\infty(n)} = \Theta(\log n)$$

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

subarrays to merge: $T[p_1..r_1]$ $\quad$ $T[p_2..r_2]$



suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

Source: Cormen et al., "Introduction to Algorithms", 3rd Edition

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

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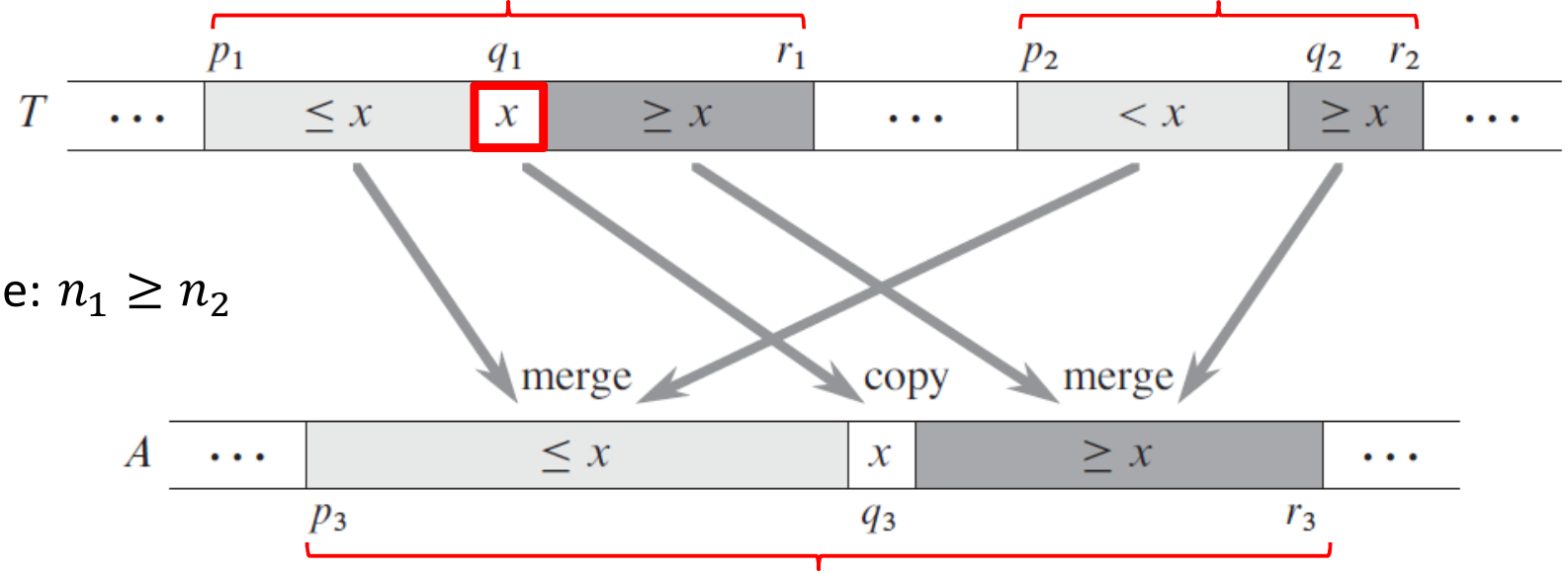


Source: Cormen et al., "Introduction to Algorithms", 3rd Edition

suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

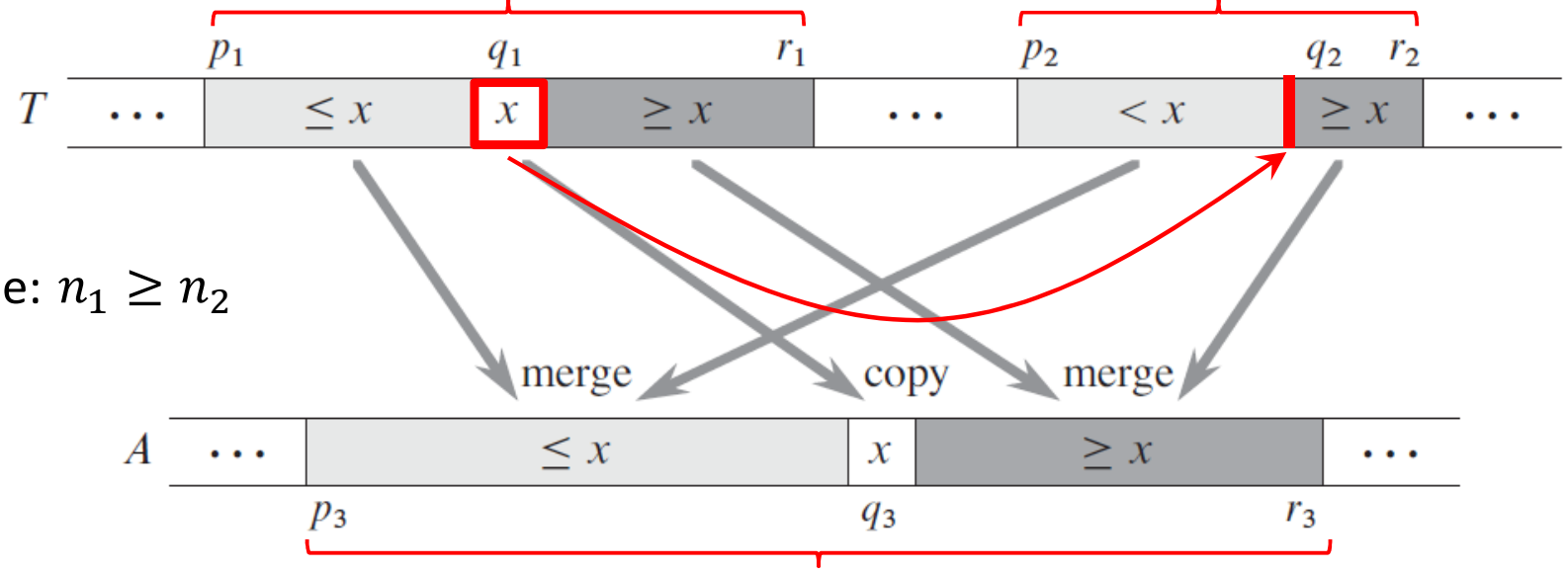
$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

Step 1: Find $x = T[q_1]$, where q_1 is the midpoint of $T[p_1..r_1]$

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

subarrays to merge: $T[p_1..r_1]$ $\quad$ $T[p_2..r_2]$



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suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

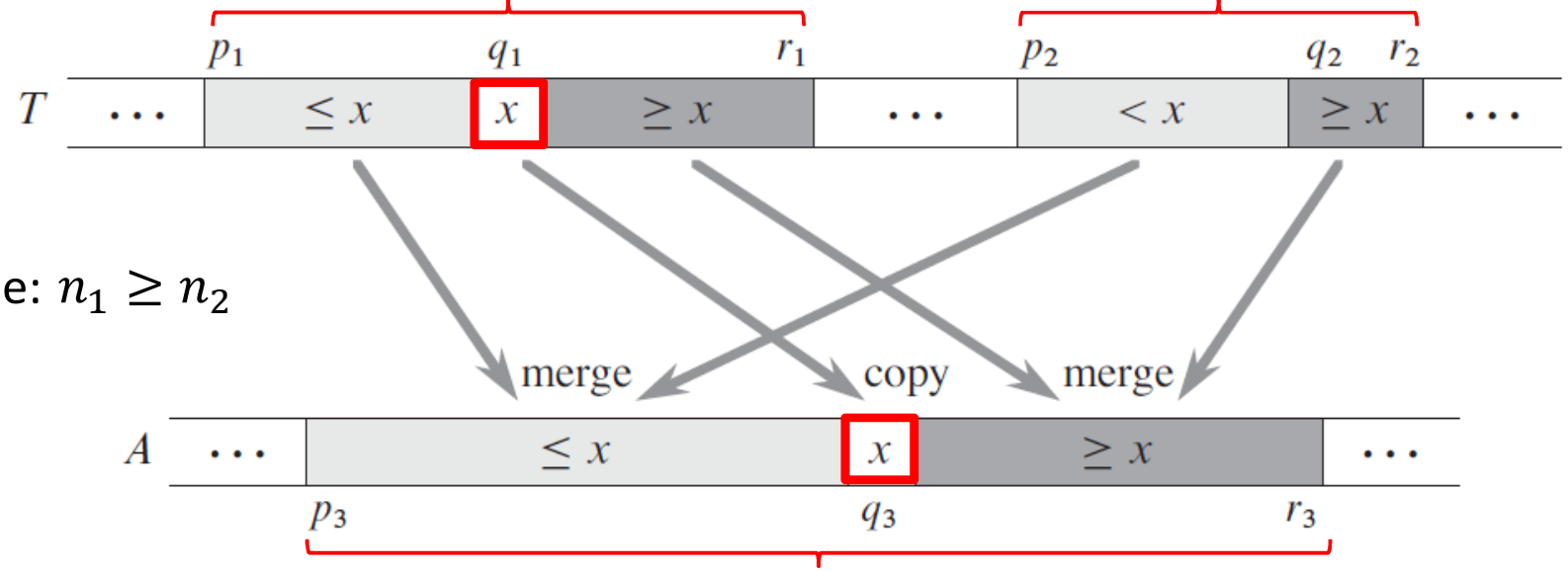
$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

Step 2: Use binary search to find the index q_2 in subarray $T[p_2..r_2]$ so that the subarray would still be sorted if we insert x between $T[q_2 - 1]$ and $T[q_2]$

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

subarrays to merge: $T[p_1..r_1]$ $\quad$ $T[p_2..r_2]$



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suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

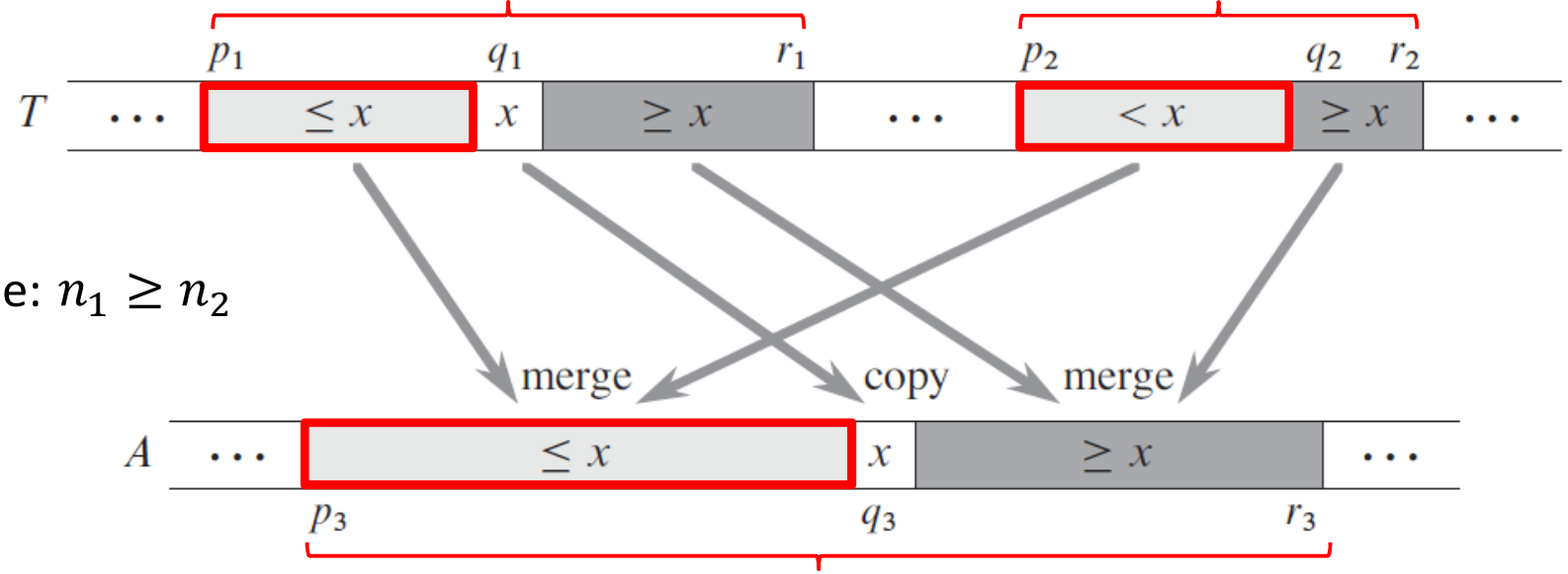
$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

Step 3: Copy x to $A[q_3]$, where $q_3 = p_3 + (q_1 - p_1) + (q_2 - p_2)$

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

subarrays to merge: $T[p_1..r_1]$ $\quad$ $T[p_2..r_2]$



Source: Cormen et al., "Introduction to Algorithms", 3rd Edition

suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

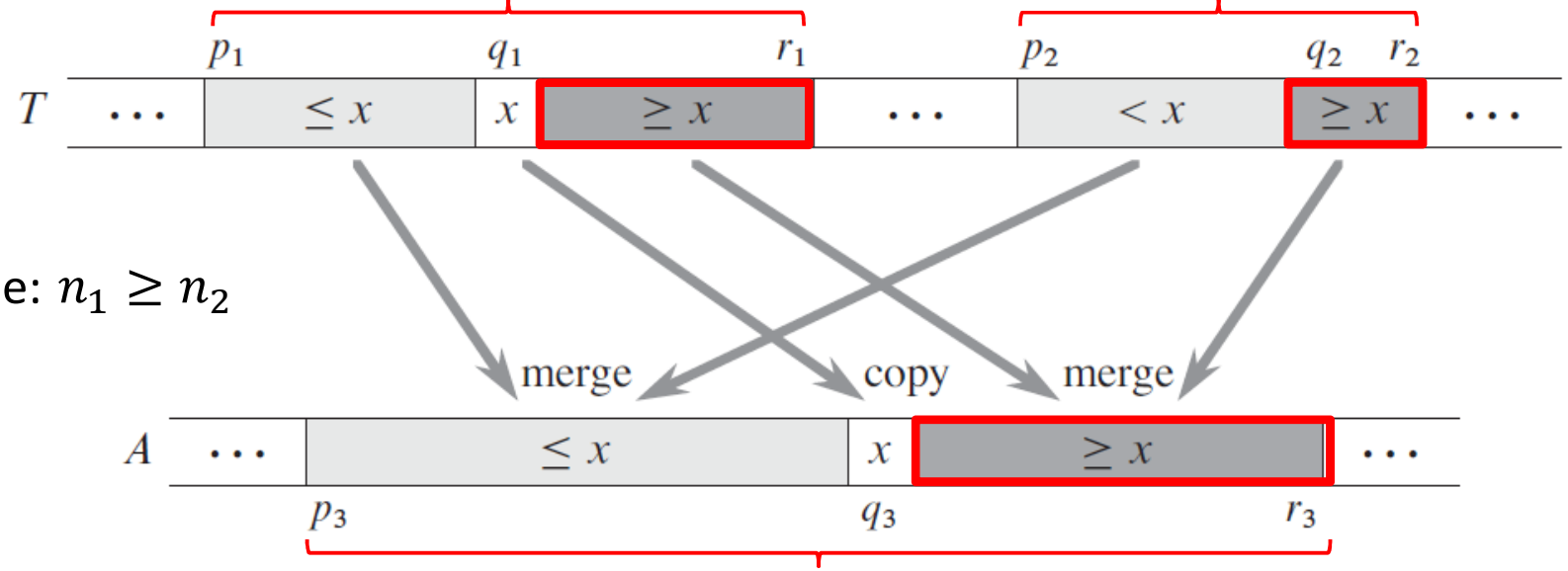
Perform the following two steps in parallel.

Step 4(a): Recursively merge $T[p_1..q_1 - 1]$ with $T[p_2..q_2 - 1]$, and place the result into $A[p_3..q_3 - 1]$

Parallel Merge

$n_1 = r_1 - p_1 + 1$ $\quad$ $n_2 = r_2 - p_2 + 1$

subarrays to merge: $T[p_1..r_1]$ $\quad$ $T[p_2..r_2]$



Source: Cormen et al., "Introduction to Algorithms", 3rd Edition

suppose: $n_1 \geq n_2$

merged output: $A[p_3..r_3]$

$n_3 = r_3 - p_3 + 1 = n_1 + n_2$

Perform the following two steps in parallel.

Step 4(a): Recursively merge $T[p_1..q_1 - 1]$ with $T[p_2..q_2 - 1]$, and place the result into $A[p_3..q_3 - 1]$

Step 4(b): Recursively merge $T[q_1 + 1..r_1]$ with $T[q_2 + 1..r_2]$, and place the result into $A[q_3 + 1..r_3]$

Parallel Merge

```
Par-Merge ( T, p1, r1, p2, r2, A, p3 )
 1. n1 ← r1 - p1 + 1,   n2 ← r2 - p2 + 1
 2. if n1 < n2 then
 3.     p1 ↔ p2,  r1 ↔ r2,  n1 ↔ n2
 4. if n1 = 0 then return
 5. else
 6.     q1 ← ⌊ ( p1 + r1 ) / 2 ⌋
 7.     q2 ← Binary-Search ( T[ q1 ],  T,  p2, r2 )
 8.     q3 ← p3 + ( q1 - p1 ) + ( q2 - p2 )
 9.     A[ q3 ] ← T[ q1 ]
10.     spawn Par-Merge ( T, p1, q1-1, p2, q2-1, A, p3 )
11.           Par-Merge ( T, q1+1, r1, q2+1, r2, A, q3+1 )
12.     sync
```

Parallel Merge

```
Par-Merge ( T, p1, r1, p2, r2, A, p3 )
1.  n1 ← r1 - p1 + 1,   n2 ← r2 - p2 + 1
2.  if n1 < n2 then
3.      p1 ↔ p2,  r1 ↔ r2,  n1 ↔ n2
4.  if n1 = 0 then return
5.  else
6.      q1 ← ⌊ ( p1 + r1 ) / 2 ⌋
7.      q2 ← Binary-Search ( T[ q1 ],  T,  p2, r2 )
8.      q3 ← p3 + ( q1 - p1 ) + ( q2 - p2 )
9.      A[ q3 ] ← T[ q1 ]
10.     spawn Par-Merge ( T, p1, q1-1, p2, q2-1, A, p3 )
11.           Par-Merge ( T, q1+1, r1, q2+1, r2, A, q3+1 )
12.     sync
```

We have,

$$n_2 \leq n_1 \Rightarrow 2n_2 \leq n_1 + n_2 = n$$

In the worst case, a recursive call in lines 9-10 merges half the elements of $T[p_1..r_1]$ with all elements of $T[p_2..r_2]$.

Hence, #elements involved in such a call:

$$\left\lfloor \frac{n_1}{2} \right\rfloor + n_2 \leq \frac{n_1}{2} + \frac{n_2}{2} + \frac{n_2}{2} = \frac{n_1 + n_2}{2} + \frac{2n_2}{4} \leq \frac{n}{2} + \frac{n}{4} = \frac{3n}{4}$$

Parallel Merge

```
Par-Merge ( T, p1, r1, p2, r2, A, p3 )
1.  n1 ← r1 - p1 + 1,   n2 ← r2 - p2 + 1
2.  if n1 < n2 then
3.      p1 ↔ p2,  r1 ↔ r2,  n1 ↔ n2
4.  if n1 = 0 then return
5.  else
6.      q1 ← ⌊ ( p1 + r1 ) / 2 ⌋
7.      q2 ← Binary-Search ( T[ q1 ],  T,  p2, r2 )
8.      q3 ← p3 + ( q1 - p1 ) + ( q2 - p2 )
9.      A[ q3 ] ← T[ q1 ]
10.     spawn Par-Merge ( T, p1, q1-1, p2, q2-1, A, p3 )
11.           Par-Merge ( T, q1+1, r1, q2+1, r2, A, q3+1 )
12.     sync
```

Span:

$$T_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ T_\infty\left(\frac{3n}{4}\right) + \Theta(\log n), & otherwise. \end{cases}$$

$$= \Theta(\log^2 n) \qquad \text{[MT Case 2]}$$

Work:

Clearly, $T_1(n) = \Omega(n)$

We show below that, $T_1(n) = \mathrm{O}(n)$

For some $\alpha \in \left[\frac{1}{4}, \frac{3}{4}\right]$, we have the following recurrence,

$$T_1(n) = T_1(\alpha n) + T_1\big((1-\alpha)n\big) + \mathrm{O}(\log n)$$

Assuming $T_1(n) \le c_1 n - c_2 \log n$ for positive constants c_1 and c_2, and substituting on the right hand side of the above recurrence gives us: $T_1(n) \le c_1 n - c_2 \log n \ = \mathrm{O}(n)$.

Hence, $T_1(n) = \Theta(n)$.

Parallel Merge Sort with Parallel Merge

```
Par-Merge-Sort ( A, p, r )   { sort the elements in A[ p ... r ] }

1.  if p < r then
2.      q ← ⌊ ( p + r ) / 2 ⌋
3.      spawn Merge-Sort ( A, p, q )
4.            Merge-Sort ( A, q + 1, r )
5.      sync
6.      Par-Merge ( A, p, q, r )
```

Work: $$T_1(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ 2T_1\left(\frac{n}{2}\right) + \Theta(n), & otherwise. \end{cases}$$

$$= \Theta(n \log n) \qquad [\text{ MT Case 2 }]$$

Span: $$T_\infty(n) = \begin{cases} \Theta(1), & if\ n = 1, \\ T_\infty\left(\frac{n}{2}\right) + \Theta(\log^2 n), & otherwise. \end{cases}$$

$$= \Theta(\log^3 n) \qquad [\text{ MT Case 2 }]$$

Parallelism: $$\frac{T_1(n)}{T_\infty(n)} = \Theta\left(\frac{n}{\log^2 n}\right)$$