

# **CSE 548: Analysis of Algorithms**

## **Lectures 27 – 30 ( Analyzing Parallel Algorithms )**

**Rezaul A. Chowdhury**

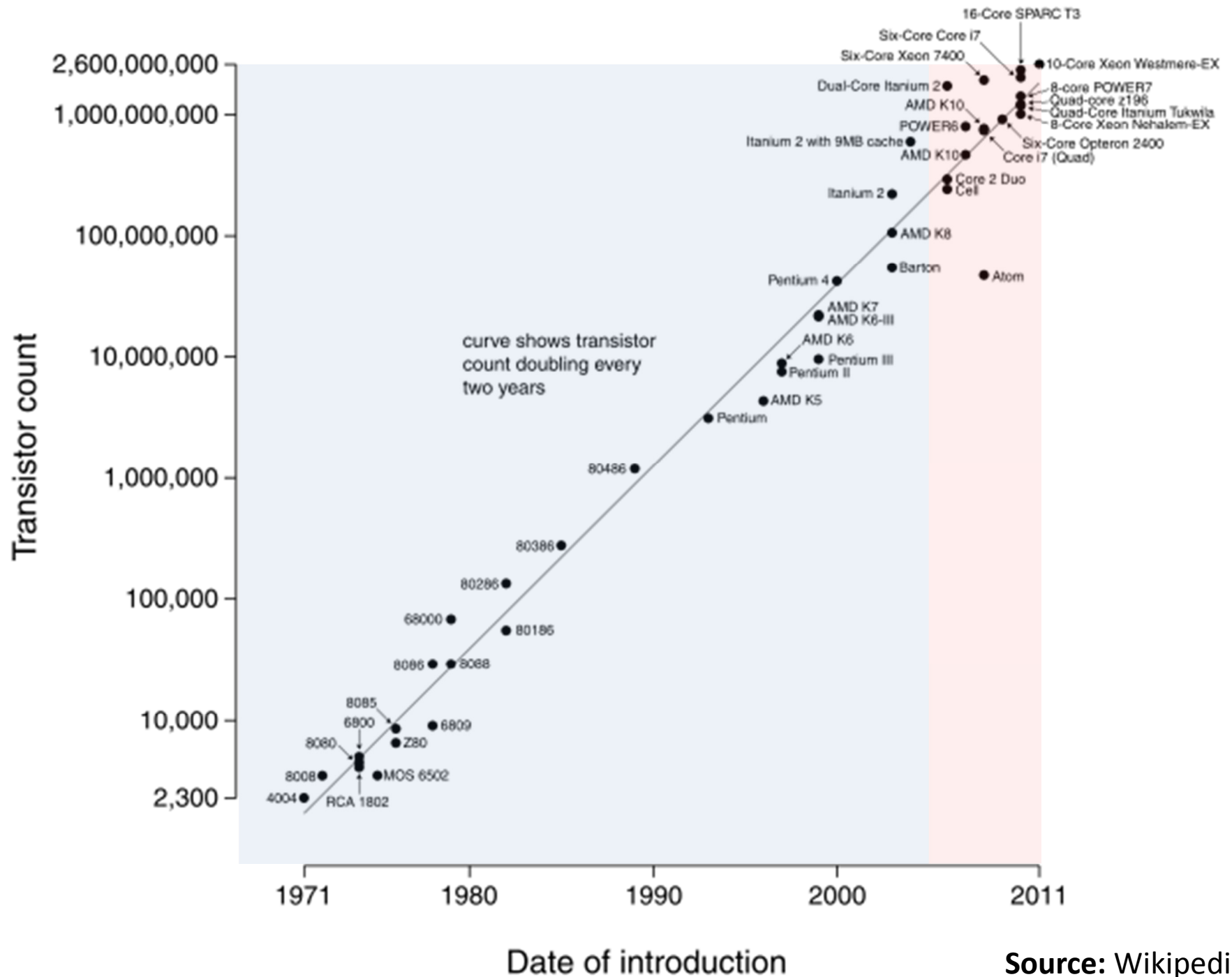
**Department of Computer Science**

**SUNY Stony Brook**

**Spring 2015**

# **Why Parallelism?**

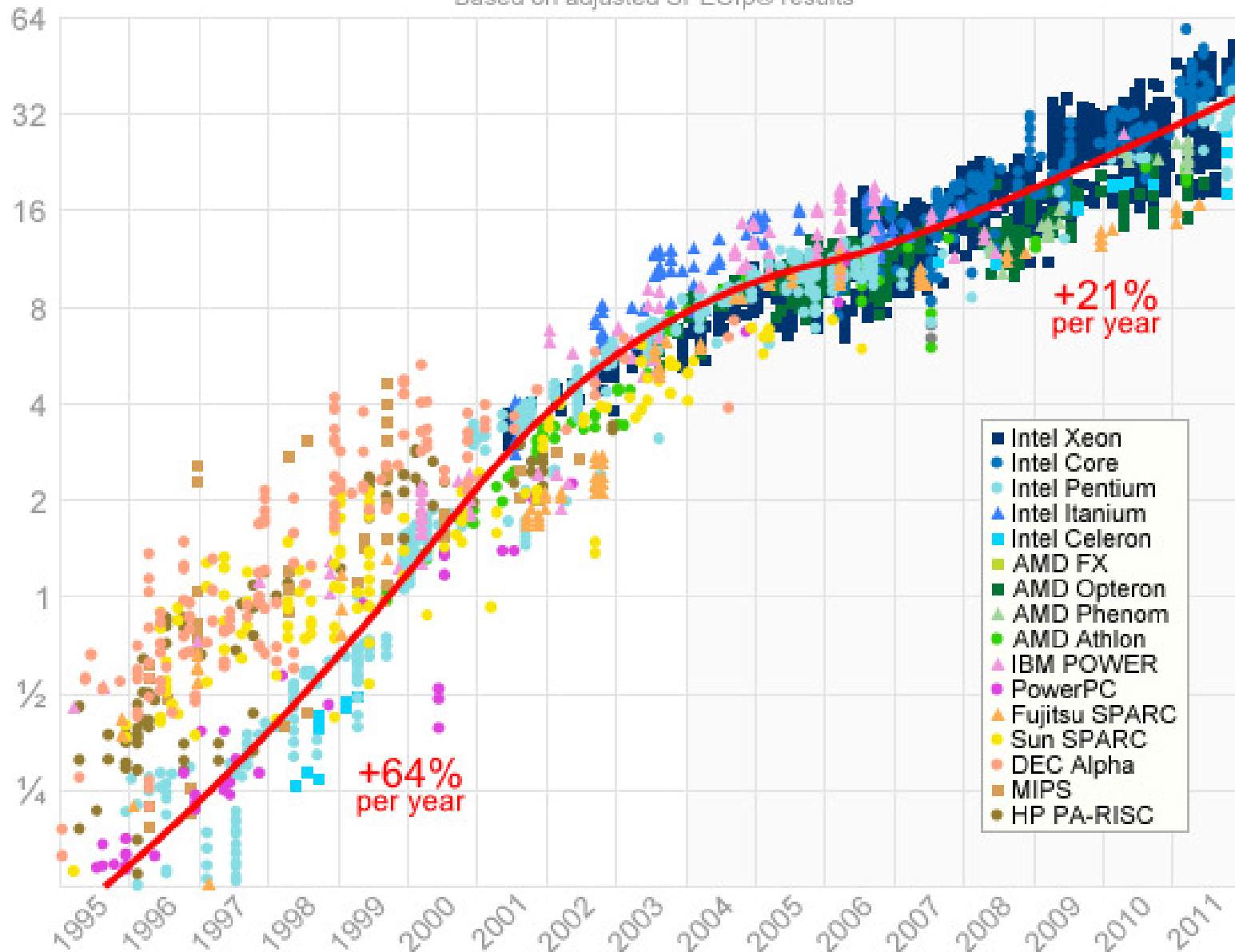
# Moore's Law



# Unicore Performance

## Single-Threaded Floating-Point Performance

Based on adjusted SPECfp® results



# Unicore Performance Has Hit a Wall!

## Some Reasons

- Lack of additional ILP  
( Instruction Level Hidden Parallelism )
- High power density
- Manufacturing issues
- Physical limits
- Memory speed

# Unicore Performance: No Additional ILP

*“Everything that can be invented has been invented.”*

*— Charles H. Duell*

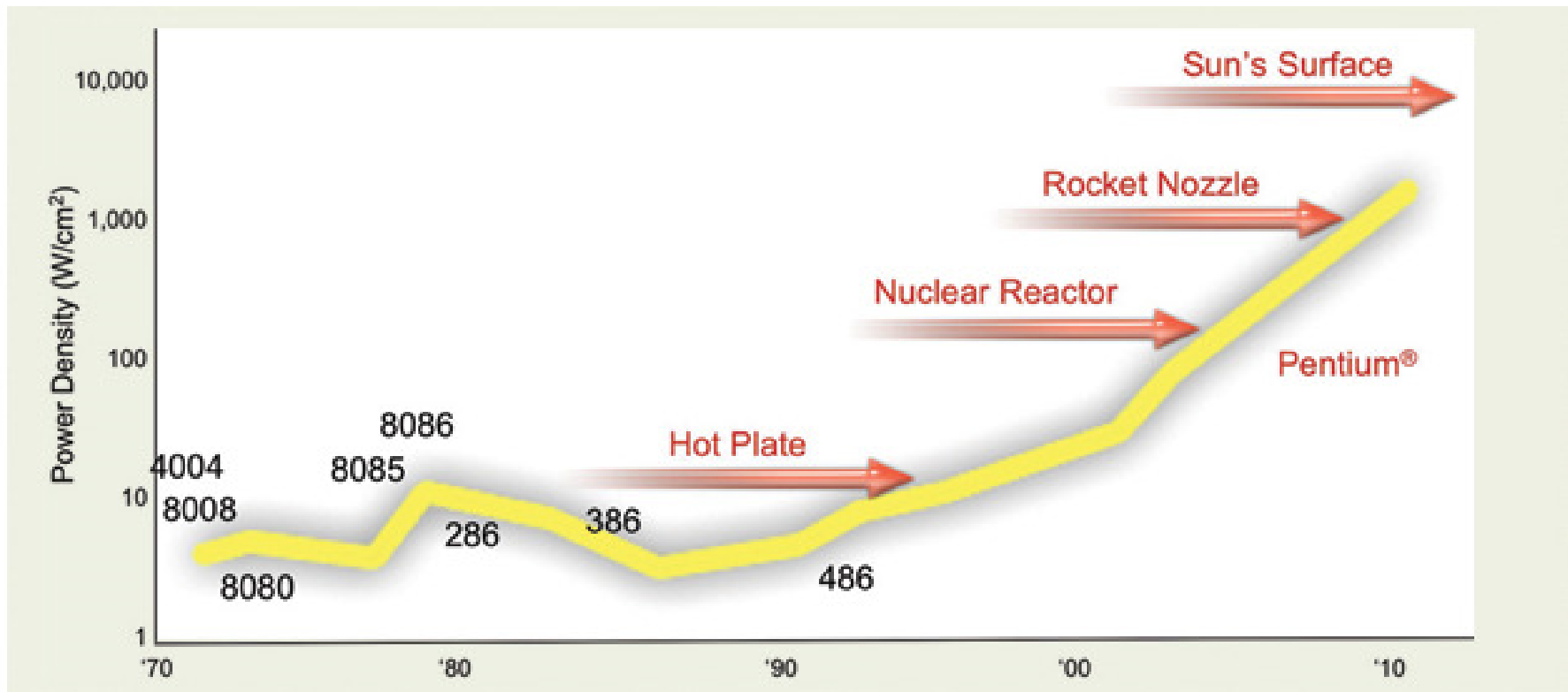
*Commissioner, U.S. patent office, 1899*

Exhausted all ideas to exploit hidden parallelism?

- Multiple simultaneous instructions
- Instruction Pipelining
- Out-of-order instructions
- Speculative execution
- Branch prediction
- Register renaming, etc.

# Unicore Performance: High Power Density

- Dynamic power,  $P_d \propto V^2 f C$ 
  - $V = \text{supply voltage}$
  - $f = \text{clock frequency}$
  - $C = \text{capacitance}$
- But  $V \propto f$
- Thus  $P_d \propto f^3$



Source: Patrick Gelsinger, Intel Developer Forum, Spring 2004 ( Simon Floyd )

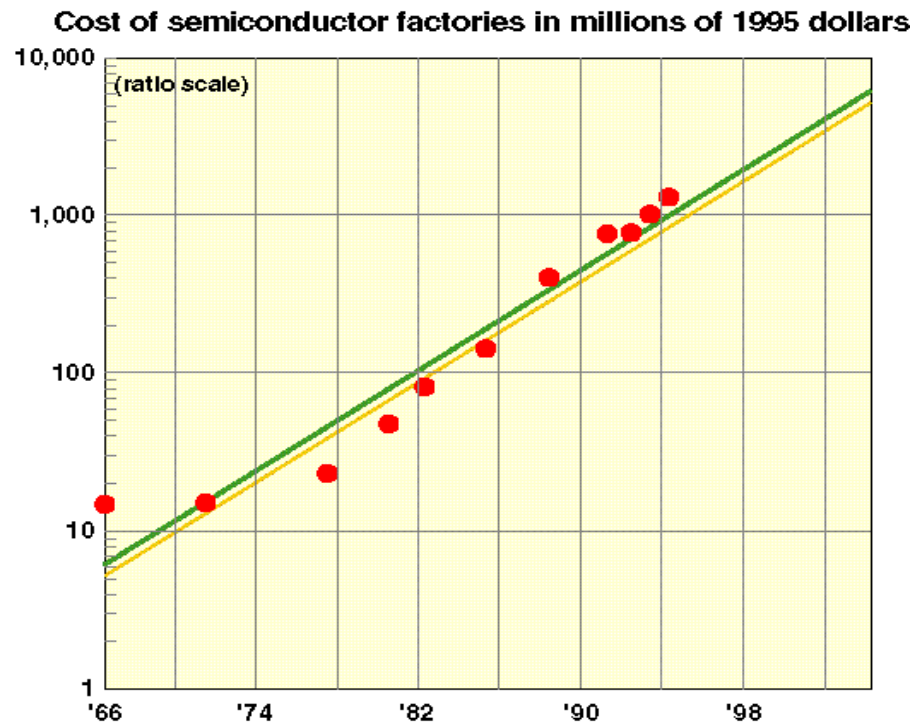
# Unicore Performance: Manufacturing Issues

- Frequency,  $f \propto 1 / s$ 
  - $s = \text{feature size ( transistor dimension )}$
- Transistors / unit area  $\propto 1 / s^2$
- Typically, die size  $\propto 1 / s$
- So, what happens if feature size goes down by a factor of  $x$ ?
  - Raw computing power goes up by a factor of  $x^4$  !
  - Typically most programs run faster by a factor of  $x^3$  without any change!



# Unicore Performance: Manufacturing Issues

- Manufacturing cost goes up as feature size decreases
  - Cost of a semiconductor fabrication plant doubles every 4 years ( Rock's Law )
- CMOS feature size is limited to 5 nm ( at least 10 atoms )



Source: Kathy Yelick and Jim Demmel, UC Berkeley

# Unicore Performance: Physical Limits

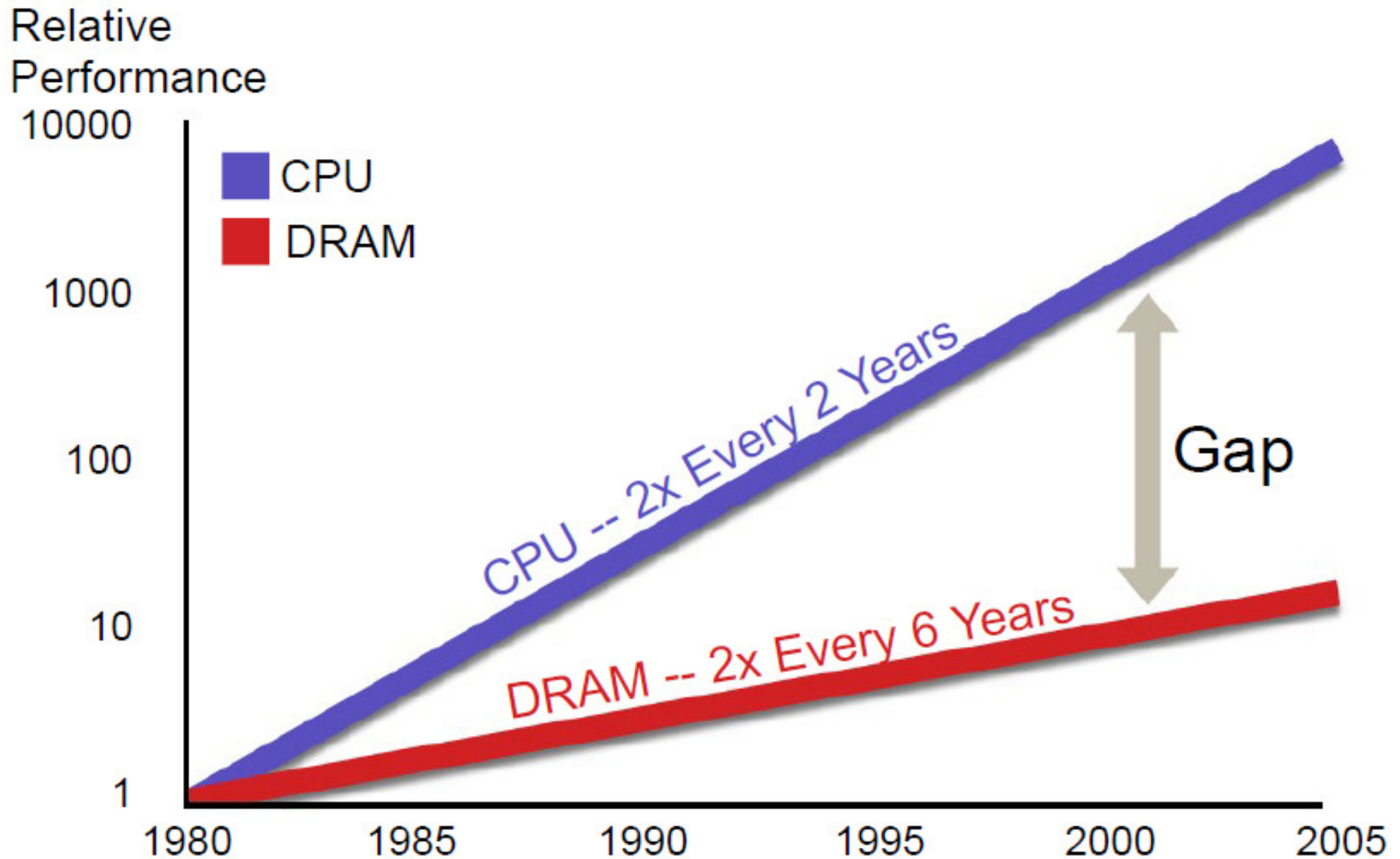
Execute the following loop on a serial machine in 1 second:

*for ( i = 0; i < 10<sup>12</sup>; ++i )*

*z[ i ] = x[ i ] + y[ i ];*

- We will have to access  $3 \times 10^{12}$  data items in one second
- Speed of light is,  $c \approx 3 \times 10^8$  m/s
- So each data item must be within  $c / 3 \times 10^{12} \approx 0.1$  mm from the CPU on the average
- All data must be put inside a 0.2 mm  $\times$  0.2 mm square
- Each data item ( $\geq 8$  bytes ) can occupy only  $1 \text{ \AA}^2$  space!  
( size of a small atom! )

# Unicore Performance: Memory Wall



Source: Sun World Wide Analyst Conference Feb. 25, 2003

Source: Rick Hetherington, Chief Technology Officer, Microelectronics, Sun Microsystems

# Unicore Performance Has Hit a Wall!

## Some Reasons

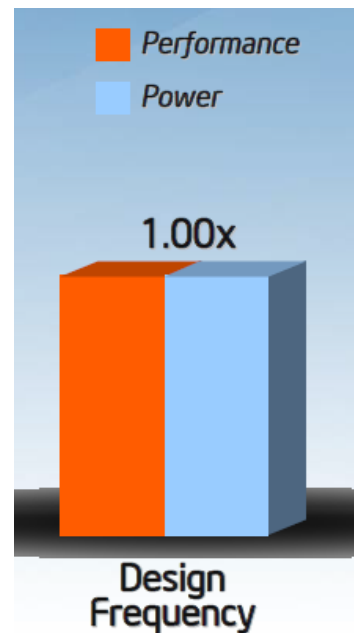
- Lack of additional ILP  
( Instruction Level Hidden Parallelism )
- High power density
- Manufacturing issues
- Physical limits
- Memory speed

*“Oh Sinnerman, where you gonna run to?”*

*— Sinnerman ( recorded by Nina Simone )*

# Where You Gonna Run To?

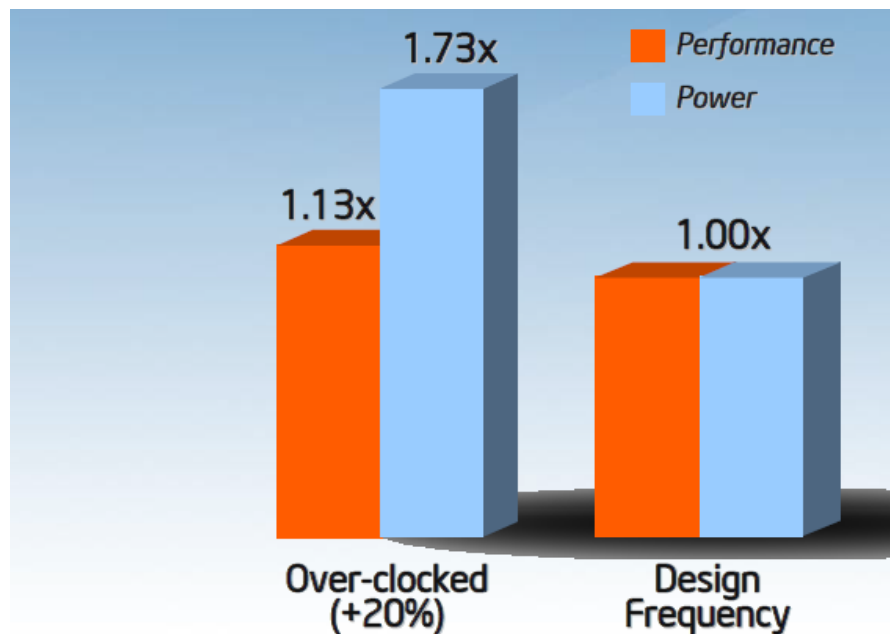
- Changing  $f$  by 20% changes performance by 13%
- So what happens if we overclock by 20%?



**Source:** Andrew A. Chien, Vice President of Research, Intel Corporation

# Where You Gonna Run To?

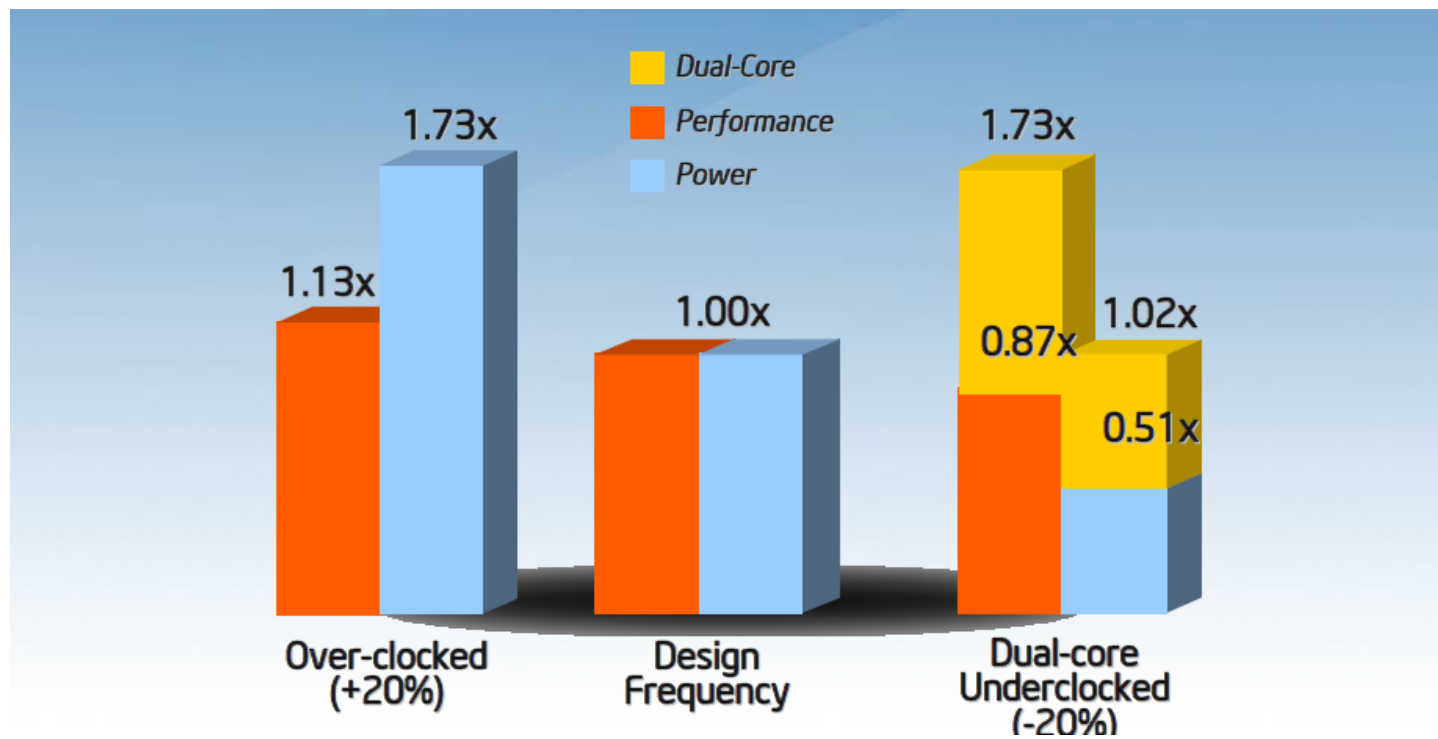
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- So what happens if we overclock by 20%?
- And underclock by 20%?



**Source:** Andrew A. Chien, Vice President of Research, Intel Corporation

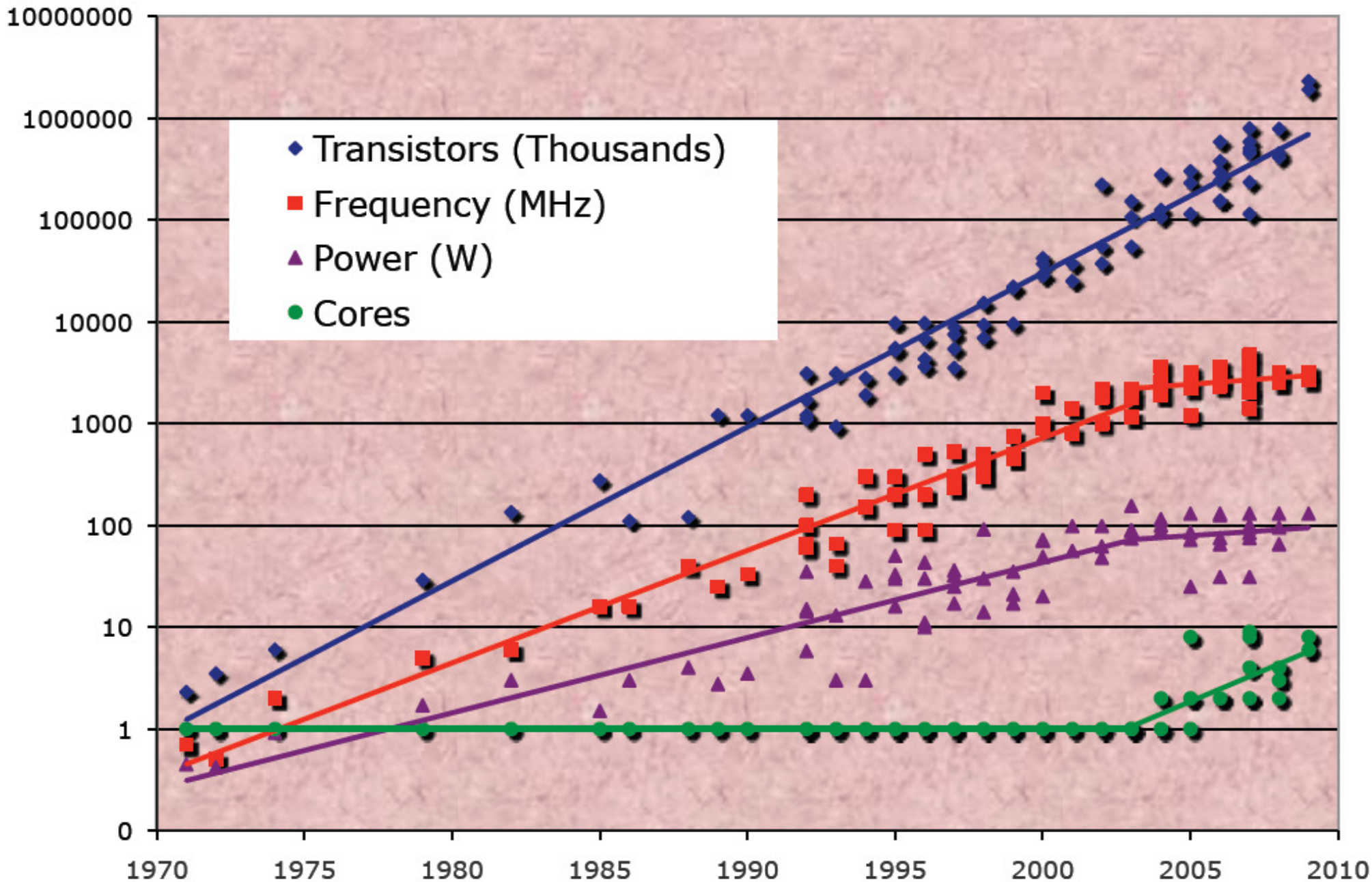
# Where You Gonna Run To?

- Changing  $f$  by 20% changes performance by 13%
- So what happens if we overclock by 20%?
- And underclock by 20%?



Source: Andrew A. Chien, Vice President of Research, Intel Corporation

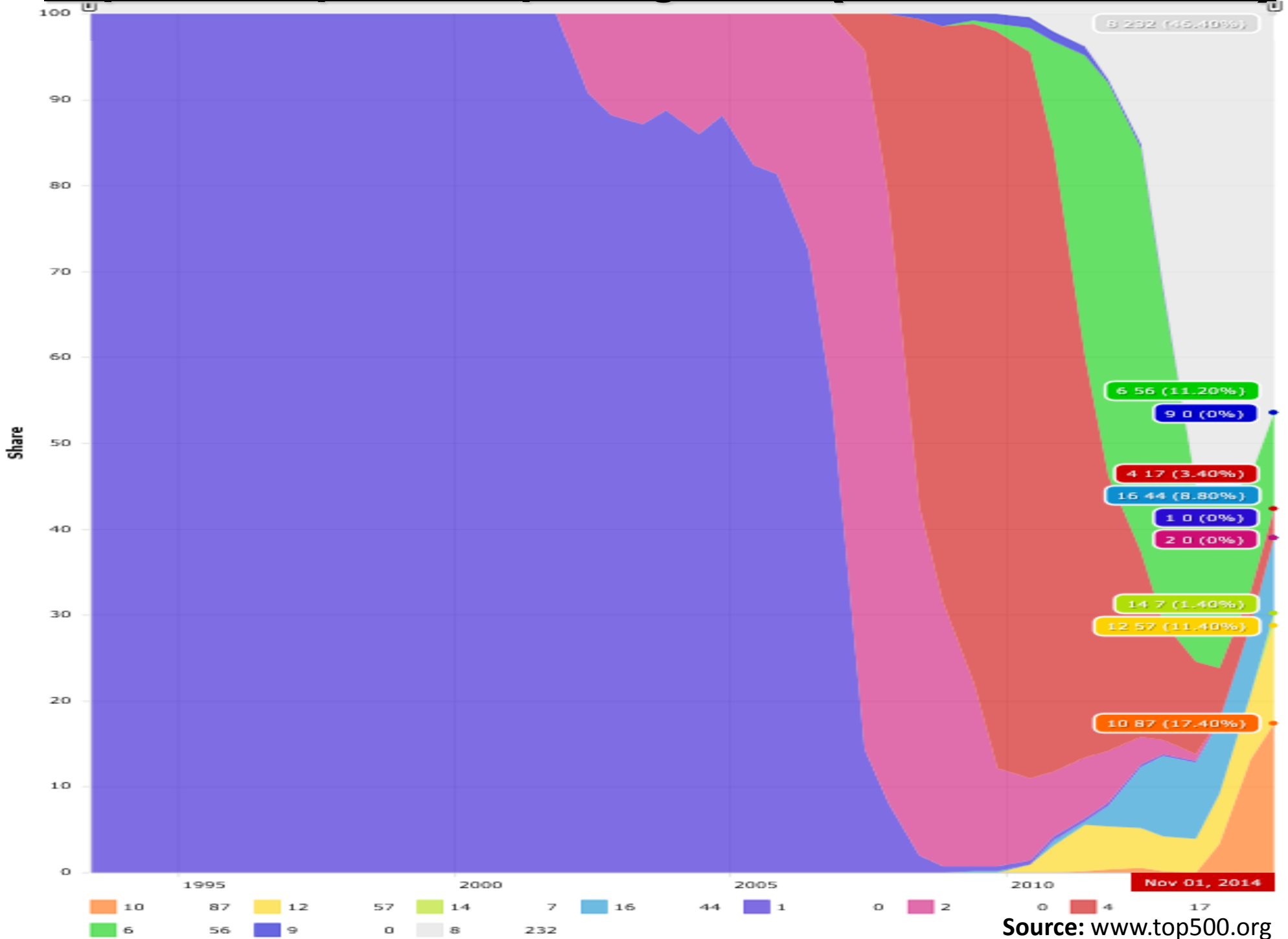
# Moore's Law Reinterpreted



Source: Report of the 2011 Workshop on Exascale Programming Challenges

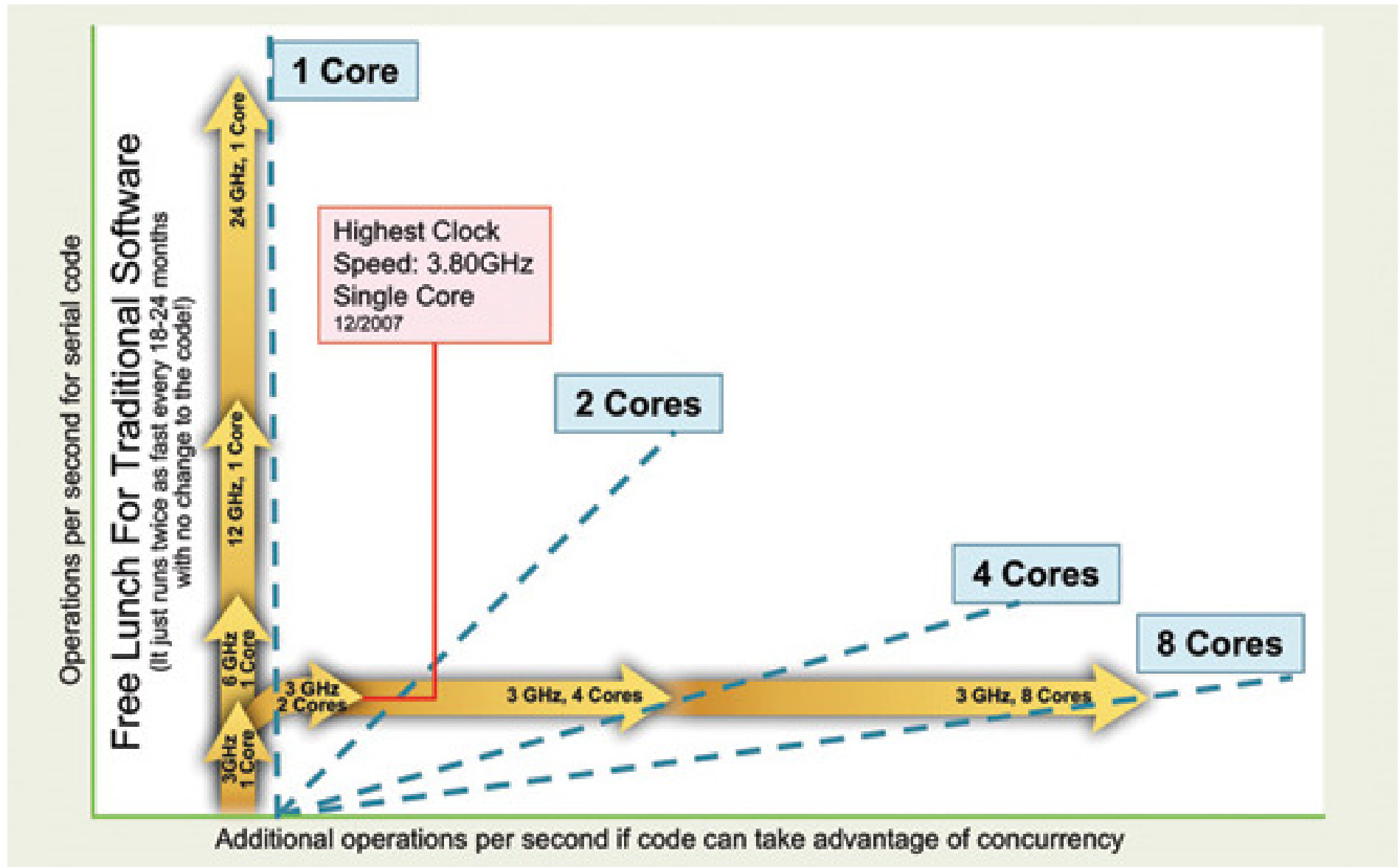


# Top 500 Supercomputing Sites ( Cores / Socket )



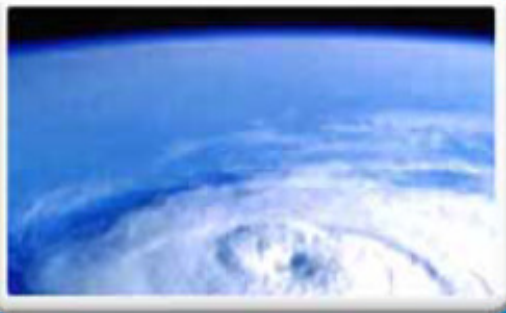
Source: [www.top500.org](http://www.top500.org)

# No Free Lunch for Traditional Software

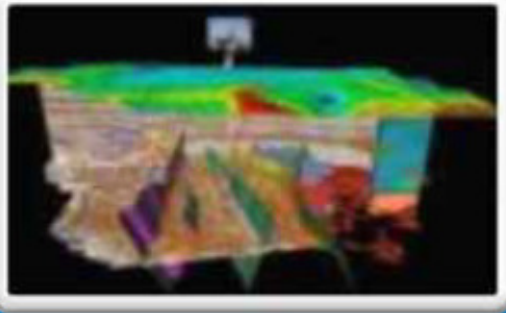


Source: Simon Floyd, Workstation Performance: Tomorrow's Possibilities (Viewpoint Column)

# Insatiable Demand for Performance



Weather Prediction



Oil Exploration



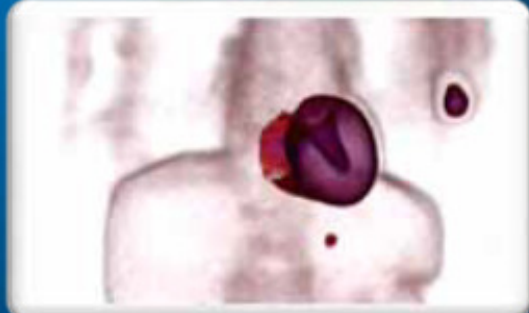
Design Simulation



Genomics Research



Financial Analysis

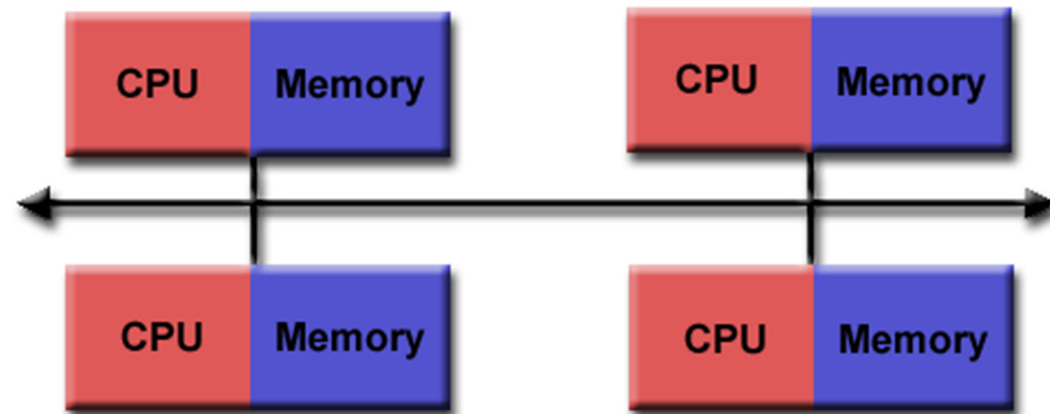


Medical Imaging

# **Some Useful Classifications of Parallel Computers**

# Parallel Computer Memory Architecture ( Distributed Memory )

- Each processor has its own local memory — no global address space
- Changes in local memory by one processor have no effect on memory of other processors

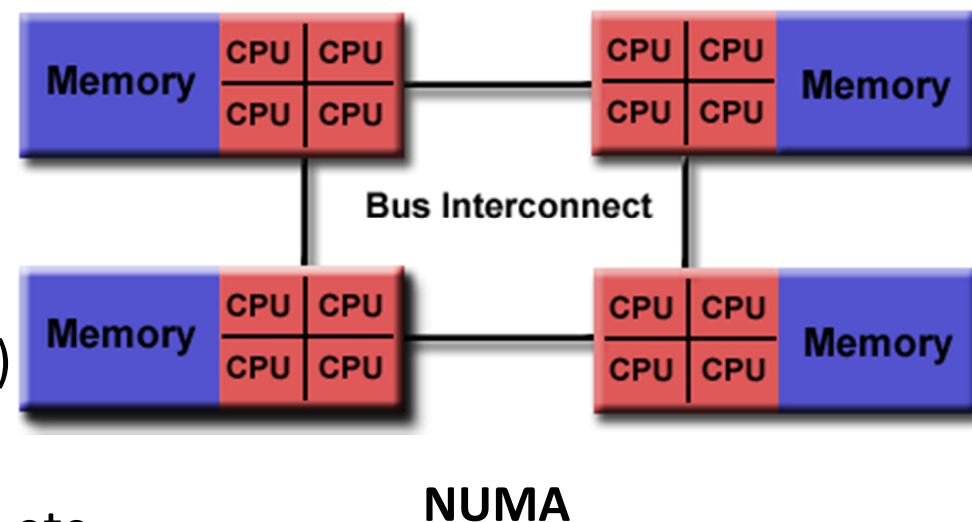
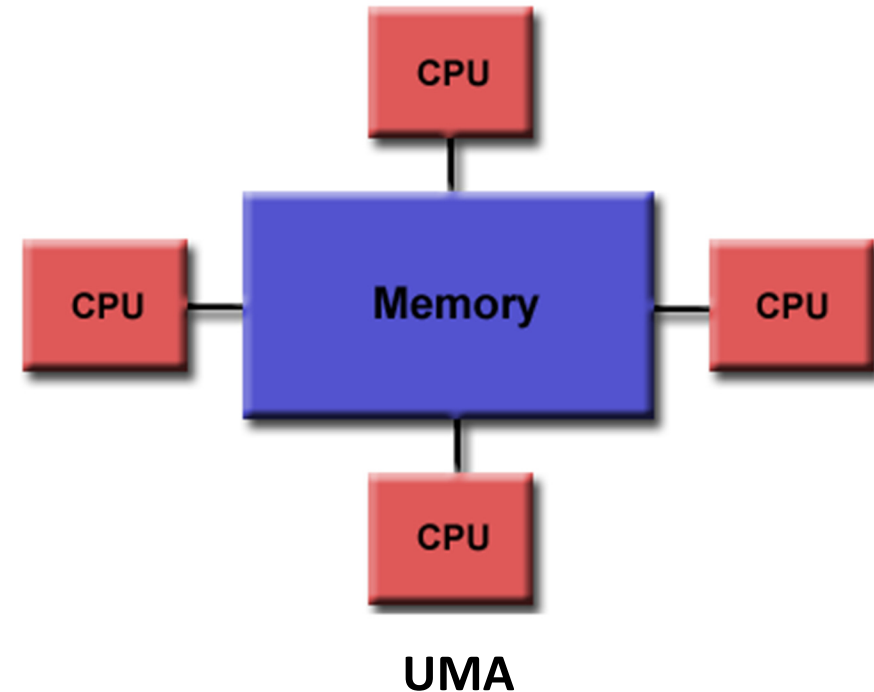


Source: Blaise Barney, LLNL

- Communication network to connect inter-processor memory
- Programming
  - Message Passing Interface ( MPI )
  - Many once available: PVM, Chameleon, MPL, NX, etc.

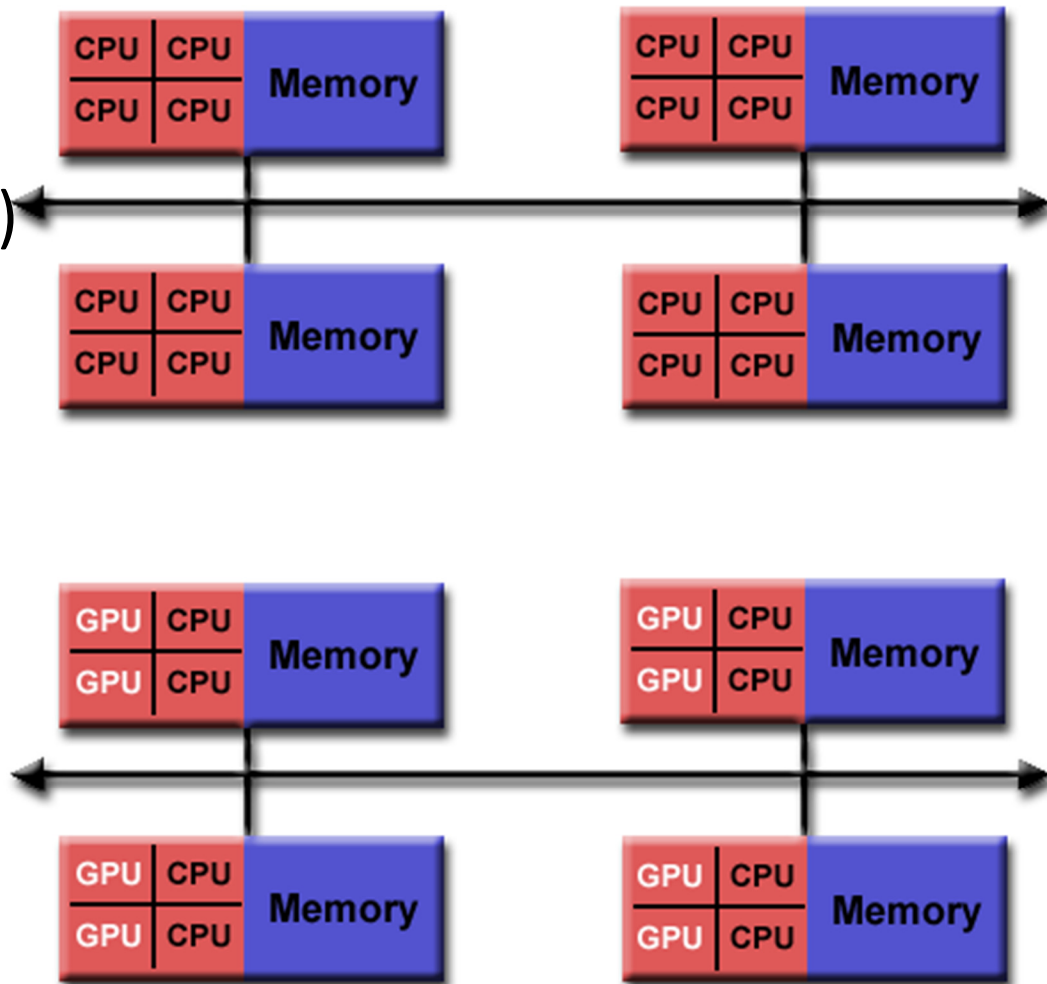
# Parallel Computer Memory Architecture ( Shared Memory )

- All processors access all memory as global address space
- Changes in memory by one processor are visible to all others
- Two types
  - Uniform Memory Access ( UMA )
  - Non-Uniform Memory Access ( NUMA )
- Programming
  - Open Multi-Processing ( OpenMP )
  - Cilk/Cilk++ and Intel Cilk Plus
  - Intel Thread Building Block ( TBB ), etc.



# Parallel Computer Memory Architecture ( Hybrid Distributed-Shared Memory )

- The share-memory component can be a cache-coherent SMP or a Graphics Processing Unit (GPU)
- The distributed-memory component is the networking of multiple SMP/GPU machines
- Most common architecture for the largest and fastest computers in the world today
- Programming
  - OpenMP / Cilk + CUDA / OpenCL + MPI, etc.



# **Types of Parallelism**



# Nested Parallelism

$${}^n C_r = {}^{n-1} C_{r-1} + {}^{n-1} C_r$$

```
int comb ( int n, int r )
{
    if ( r > n ) return 0;
    if ( r == 0 || r == n ) return 1;

    int x, y;

    x = comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    return ( x + y );
}
```

## Serial Code

Control cannot pass this point until all spawned children have returned.

Grant permission to execute the called ( spawned ) function in parallel with the caller.

```
int comb ( int n, int r )
{
    if ( r > n ) return 0;
    if ( r == 0 || r == n ) return 1;

    int x, y;

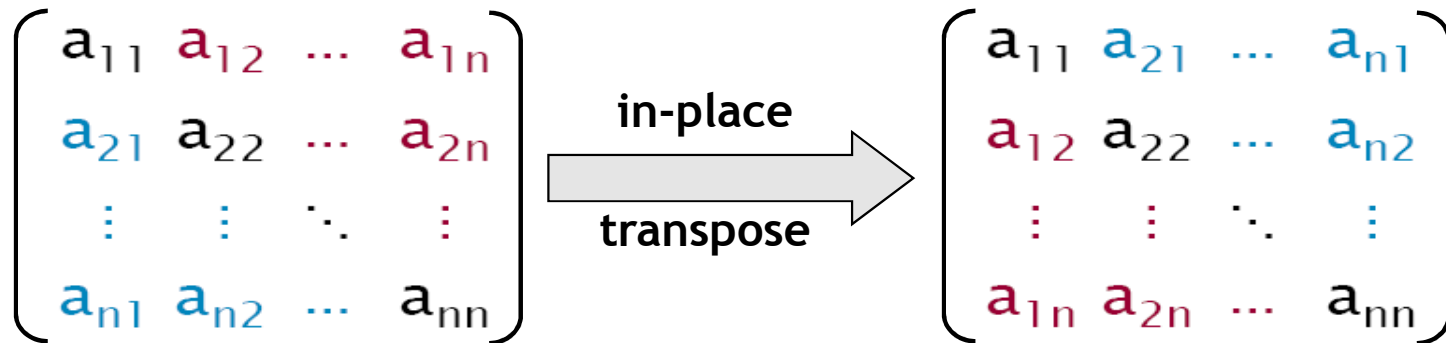
    x = spawn comb( n - 1, r - 1 );
    y = comb( n - 1, r );

    sync;

    return ( x + y );
}
```

## Parallel Code

# Loop Parallelism



```
for ( int i = 1; i < n; ++i )
  for ( int j = 0; j < i; ++j )
  {
    double t = A[ i ][ j ];
    A[ i ][ j ] = A[ j ][ i ];
    A[ j ][ i ] = t;
  }
```

Allows all iterations of the loop to be executed in parallel.

Can be converted to spawns and syncs using recursive divide-and-conquer.

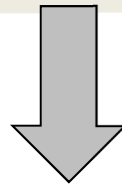
Serial Code

```
parallel for ( int i = 1; i < n; ++i )
  for ( int j = 0; j < i; ++j )
  {
    double t = A[ i ][ j ];
    A[ i ][ j ] = A[ j ][ i ];
    A[ j ][ i ] = t;
  }
```

Parallel Code

# Recursive D&C Implementation of Parallel Loops

```
parallel for ( int i = s; i < t; ++i )  
    BODY( i );
```



divide-and-conquer  
implementation

```
void recur( int lo, int hi )  
{  
    if ( hi - lo > GRAINSIZE )  
    {  
        int mid = lo + ( hi - lo ) / 2;  
        spawn recur( lo, mid );  
        recur( mid, hi );  
        sync;  
    }  
    else  
    {  
        for ( int i = lo; i < hi; ++i )  
            BODY( i );  
    }  
}  
  
recur( s, t );
```

# **Analyzing Parallel Algorithms**

# Speedup

Let  $T_p$  = running time using  $p$  identical processing elements

$$\text{Speedup, } S_p = \frac{T_1}{T_p}$$

Theoretically,  $S_p \leq p$

*Perfect or linear or ideal speedup if  $S_p = p$*

# Speedup

Consider adding  $n$  numbers using  $n$  identical processing elements.

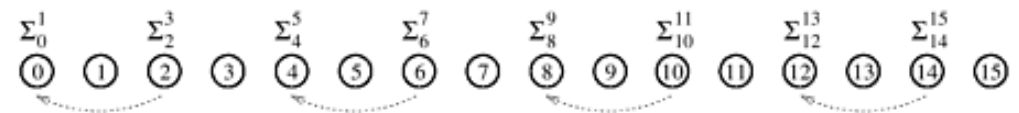
Serial runtime,  $T = \Theta(n)$

Parallel runtime,  $T_n = \Theta(\log n)$

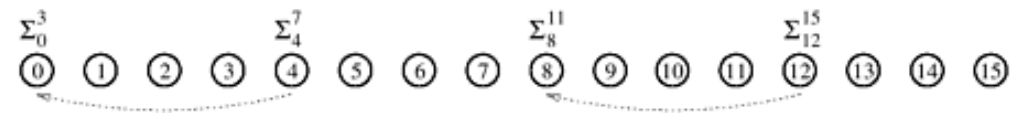
Speedup,  $S_n = \frac{T_1}{T_n} = \Theta\left(\frac{n}{\log n}\right)$



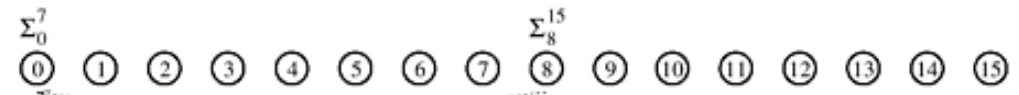
(a) Initial data distribution and the first communication step



(b) Second communication step



(c) Third communication step



(d) Fourth communication step



(e) Accumulation of the sum at processing element 0 after the final communication

# Superlinear Speedup

Theoretically,  $S_p \leq p$

But in practice *superlinear speedup* is sometimes observed, that is,  $S_p > p$  ( why? )

Reasons for superlinear speedup

- Cache effects
- Exploratory decomposition

# Parallelism & Span Law

We defined,  $T_p$  = runtime on  $p$  identical processing elements

Then span,  $T_\infty$  = runtime on an infinite number of identical processing elements

$$\text{Parallelism, } P = \frac{T_1}{T_\infty}$$

Parallelism is an upper bound on speedup, i.e.,  $S_p \leq P$

## Span Law

$$T_p \geq T_\infty$$



# Work Law

The cost of solving ( or work performed for solving ) a problem:

**On a Serial Computer:** is given by  $T_1$

**On a Parallel Computer:** is given by  $pT_p$

## Work Law

$$T_p \geq \frac{T_1}{p}$$

# Bounding Parallel Running Time ( $T_p$ )

A *runtime/online scheduler* maps tasks to processing elements dynamically at runtime.

A *greedy scheduler* never leaves a processing element idle if it can map a task to it.

**Theorem [ Graham'68, Brent'74 ]:** For any greedy scheduler,

$$T_p \leq \frac{T_1}{p} + T_\infty$$

**Corollary:** For any greedy scheduler,

$$T_p \leq 2T_p^*,$$

where  $T_p^*$  is the running time due to optimal scheduling on  $p$  processing elements.

# Work Optimality

Let  $T_s$  = runtime of the optimal or the fastest known serial algorithm

A parallel algorithm is *cost-optimal* or *work-optimal* provided

$$pT_p = \Theta(T_s)$$

Our algorithm for adding  $n$  numbers using  $n$  identical processing elements is clearly not work optimal.

# Adding $n$ Numbers Work-Optimality

We reduce the number of processing elements which in turn increases the granularity of the subproblem assigned to each processing element.

Suppose we use  $p$  processing elements.

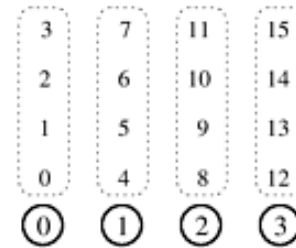
First each processing element locally

adds its  $\frac{n}{p}$  numbers in time  $\Theta\left(\frac{n}{p}\right)$ .

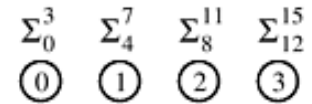
Then  $p$  processing elements adds these  $p$  partial sums in time  $\Theta(\log p)$ .

Thus  $T_p = \Theta\left(\frac{n}{p} + \log p\right)$ , and  $T_s = \Theta(n)$ .

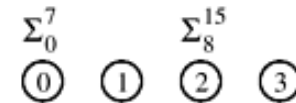
So the algorithm is work-optimal provided  $n = \Omega(p \log p)$ .



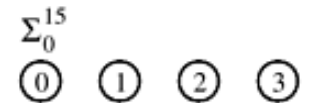
(a)



(b)



(c)

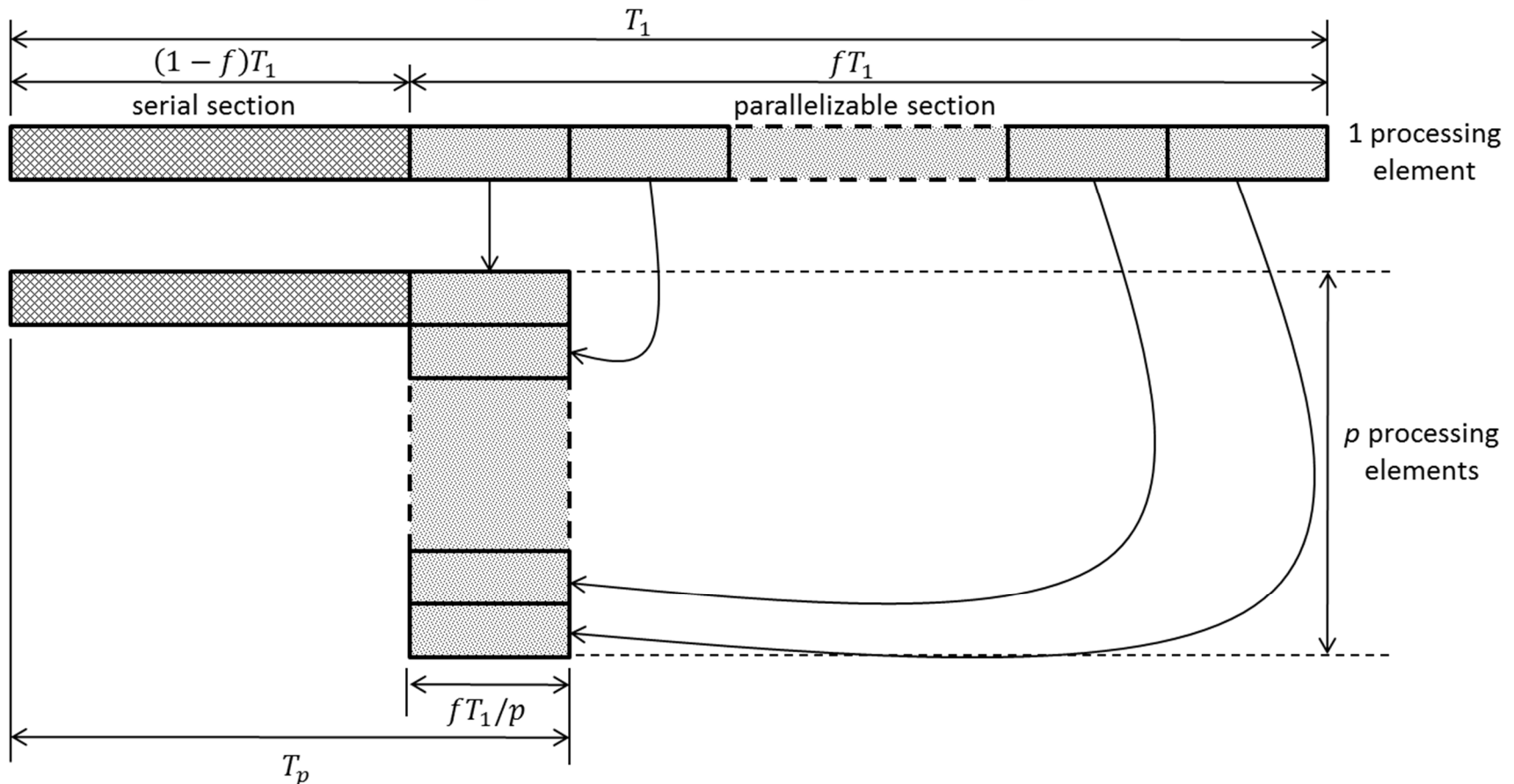


(d)

Source: Grama et al.,  
"Introduction to Parallel Computing", 2<sup>nd</sup> Edition

# **Scaling Law**

# Scaling of Parallel Algorithms ( Amdahl's Law )



Suppose only a fraction  $f$  of a computation can be parallelized.

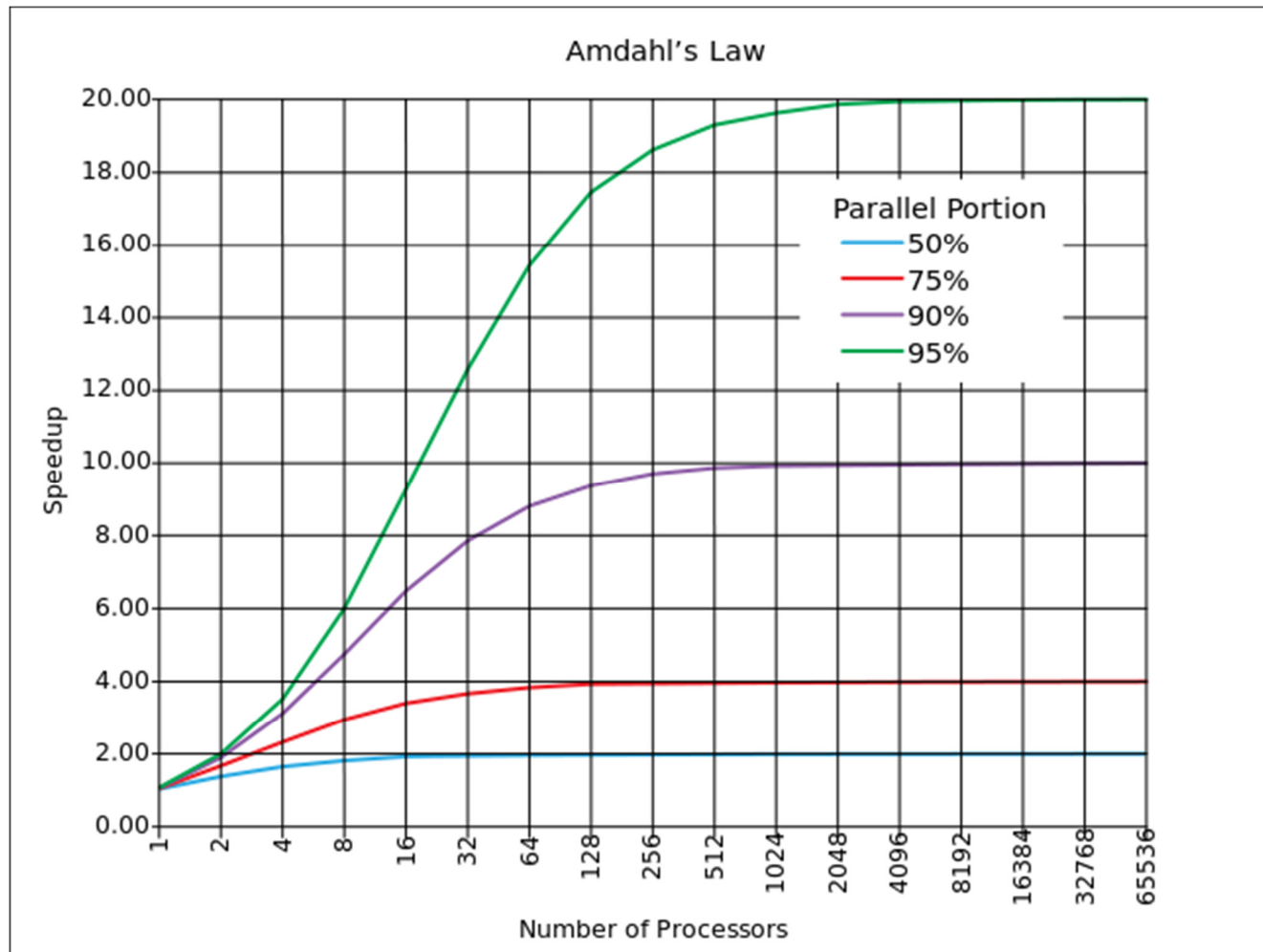
Then parallel running time,  $T_p \geq (1 - f)T_1 + f \frac{T_1}{p}$

$$\text{Speedup, } S_p = \frac{T_1}{T_p} \leq \frac{p}{f + (1-f)p} = \frac{1}{(1-f) + \frac{f}{p}} \leq \frac{1}{1-f}$$

# Scaling of Parallel Algorithms ( Amdahl's Law )

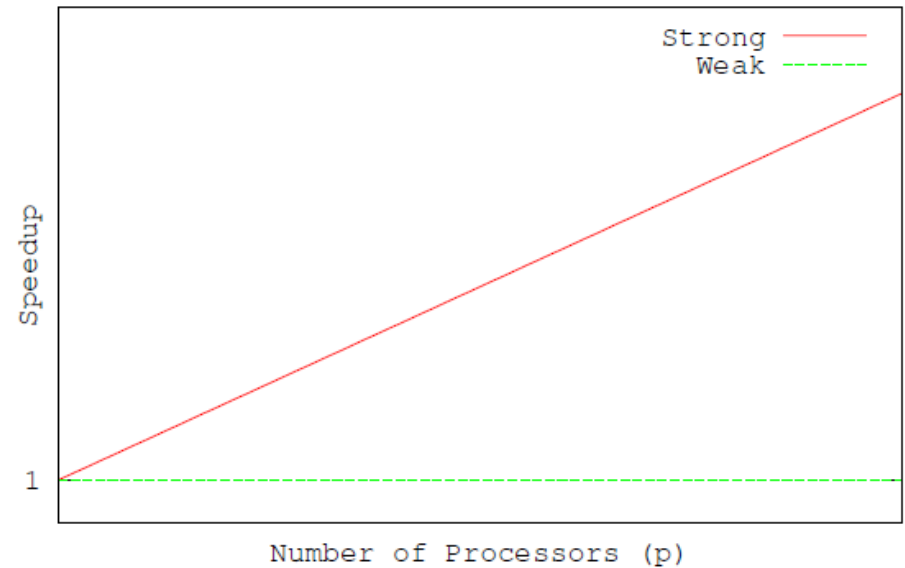
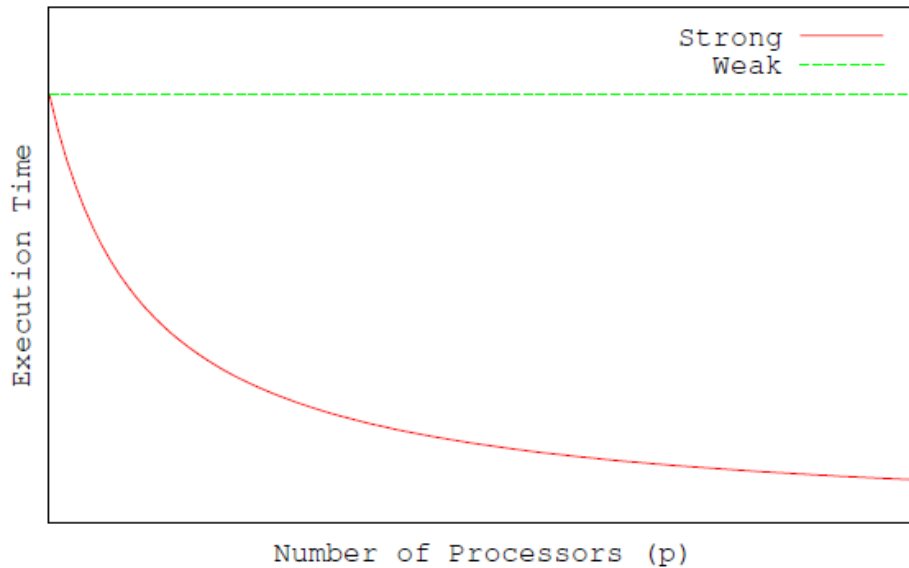
Suppose only a fraction  $f$  of a computation can be parallelized.

$$\text{Speedup, } S_p = \frac{T_1}{T_p} \leq \frac{1}{(1-f) + \frac{f}{p}} \leq \frac{1}{1-f}$$



Source: Wikipedia

# Strong Scaling vs. Weak Scaling



## Strong Scaling

How  $T_p$  ( or  $S_p$  ) varies with  $p$  when the problem size is fixed.

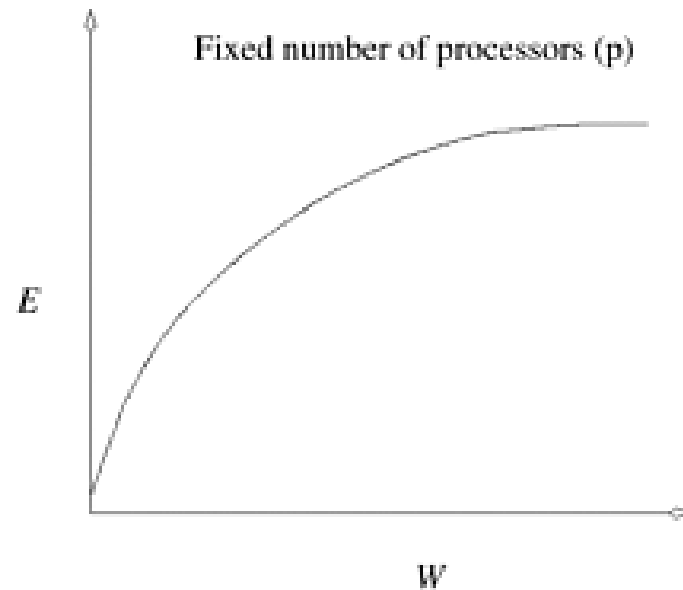
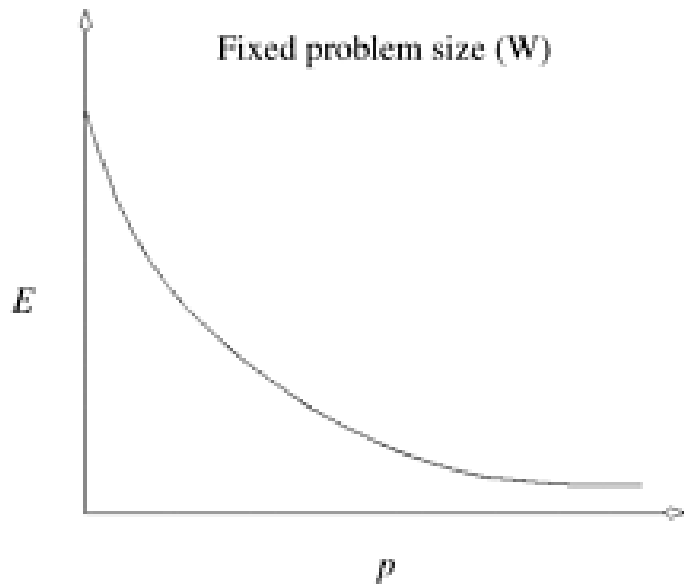
## Weak Scaling

How  $T_p$  ( or  $S_p$  ) varies with  $p$  when the problem size per processing element is fixed.



# Scalable Parallel Algorithms

Efficiency,  $E_p = \frac{S_p}{p} = \frac{T_1}{pT_p}$



Source: Grama et al.,  
"Introduction to Parallel Computing",  
2<sup>nd</sup> Edition

A parallel algorithm is called *scalable* if its efficiency can be maintained at a fixed value by simultaneously increasing the number of processing elements and the problem size.

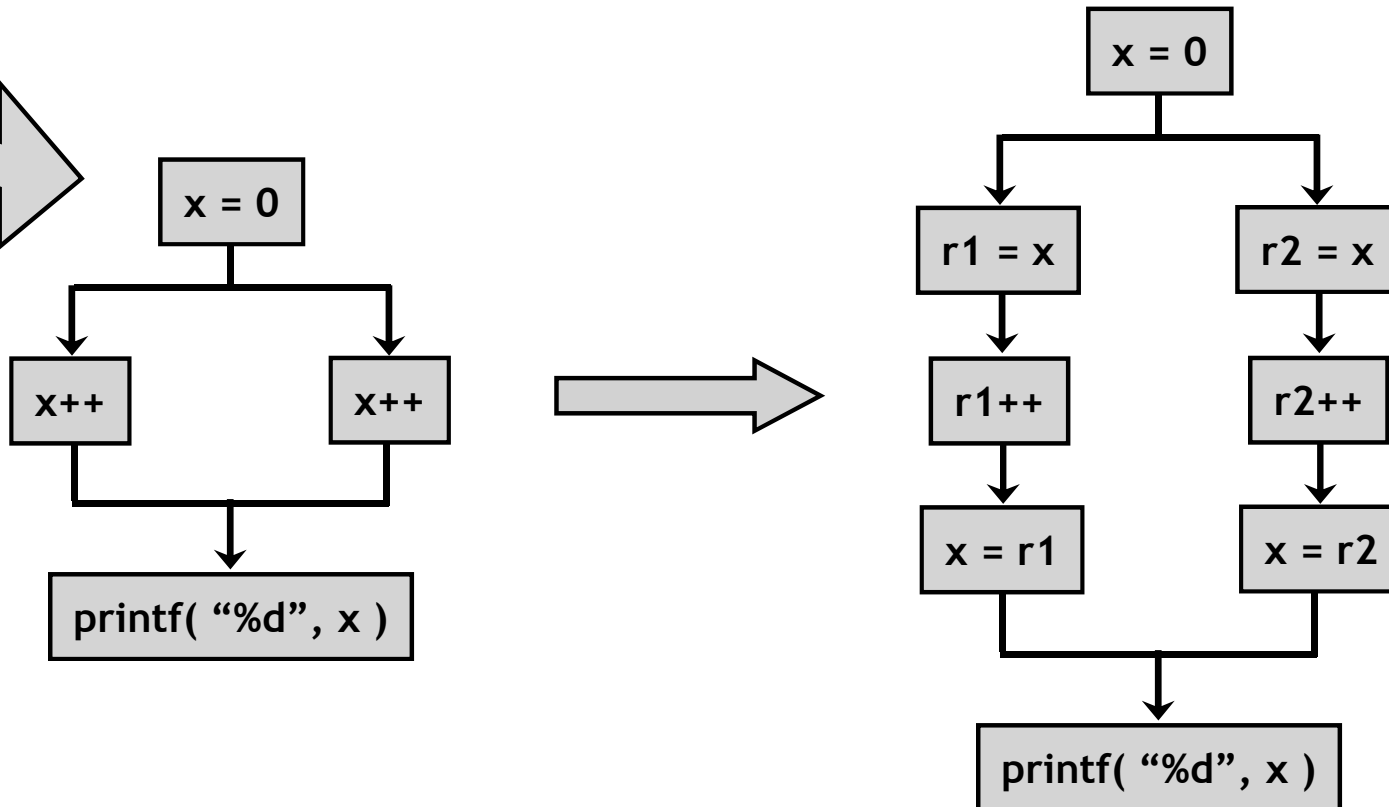
Scalability reflects a parallel algorithm's ability to utilize increasing processing elements effectively.

**Races**

# Race Bugs

A *determinacy race* occurs if two logically parallel instructions access the same memory location and at least one of them performs a write.

```
int x = 0;  
parallel for ( int i = 0; i < 2; i++ )  
    x++;  
printf( "%d", x );
```



# Critical Sections and Mutexes

```
int r = 0;
parallel for ( int i = 0; i < n; i++ )
    r += eval( x[ i ] );
```

race

critical section

two or more strands  
must not access  
at the same time

```
mutex mtx;
parallel for ( int i = 0; i < n; i++ )
    mtx.lock( );
    r += eval( x[ i ] );
    mtx.unlock( );
```

mutex ( mutual exclusion )

an attempt by a strand  
to lock an already locked mutex  
causes that strand to block (i.e., wait)  
until the mutex is unlocked

## Problems

- lock overhead
- lock contention

# Critical Sections and Mutexes

race

```
int r = 0;
parallel for ( int i = 0; i < n; i++ )
    r += eval( x[ i ] );
```

```
mutex mtx;

parallel for ( int i = 0; i < n; i++ )
    mtx.lock( );
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```
mutex mtx;

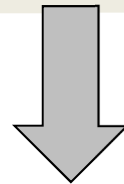
parallel for ( int i = 0; i < n; i++ )
    int y = eval( x[ i ] );
    mtx.lock( );
    r += y;
    mtx.unlock( );
```

- slightly better solution
- but lock contention can still destroy parallelism

# **Recursive D&C Implementation of Loops**

# Recursive D&C Implementation of Parallel Loops

```
parallel for ( int i = s; i < t; ++i )  
    BODY( i );
```



divide-and-conquer  
implementation

```
void recur( int lo, int hi )  
{  
    if ( hi - lo > GRAINSIZE )  
    {  
        int mid = lo + ( hi - lo ) / 2;  
        spawn recur( lo, mid );  
        recur( mid, hi );  
        sync;  
    }  
    else  
    {  
        for ( int i = lo; i < hi; ++i )  
            BODY( i );  
    }  
}  
  
recur( s, t );
```

Let  $n = t - s$

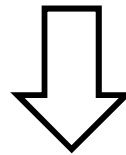
$m$  = running time of a single call to BODY

**Span:**  $T_{\infty}(n) = \Theta(\log n + \text{GRAINSIZE} \times m)$

# Parallel Iterative MM

*Iter-MM* (  $Z, X, Y$  )      {  $X, Y, Z$  are  $n \times n$  matrices,  
where  $n$  is a positive integer }

1. *for*  $i \leftarrow 1$  *to*  $n$  *do*
2.     *for*  $j \leftarrow 1$  *to*  $n$  *do*
3.          $Z[i][j] \leftarrow 0$
4.     *for*  $k \leftarrow 1$  *to*  $n$  *do*
5.          $Z[i][j] \leftarrow Z[i][j] + X[i][k] \cdot Y[k][j]$



*Par-Iter-MM* (  $Z, X, Y$  )      {  $X, Y, Z$  are  $n \times n$  matrices,  
where  $n$  is a positive integer }

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# Parallel Iterative MM

*Par-Iter-MM* (  $Z, X, Y$  )      {  $X, Y, Z$  are  $n \times n$  matrices,  
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3.          $Z[i][j] \leftarrow 0$
4.     *for*  $k \leftarrow 1$  to  $n$  *do*
5.          $Z[i][j] \leftarrow Z[i][j] + X[i][k] \cdot Y[k][j]$

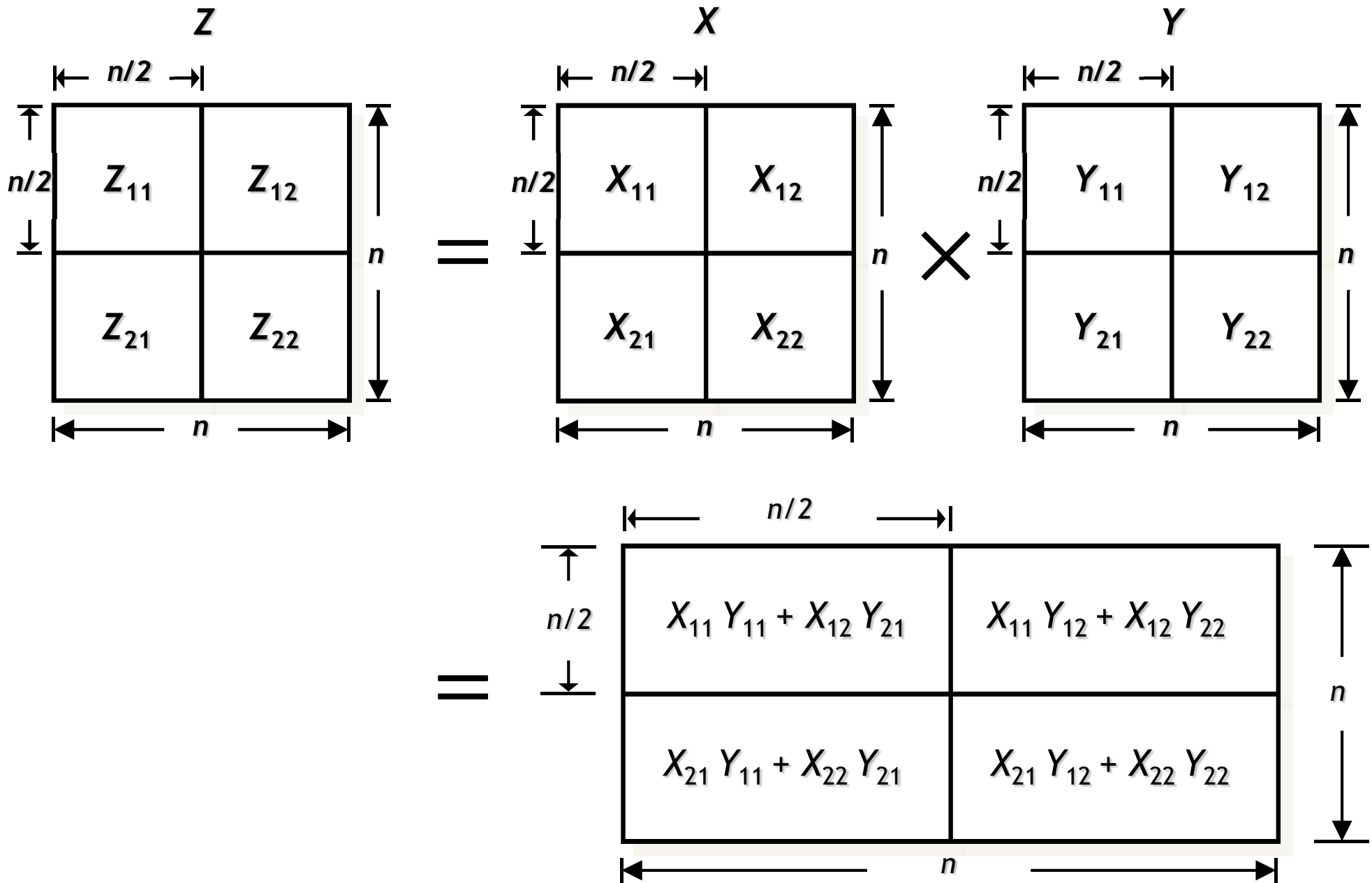
**Work:**  $T_1(n) = \Theta(n^3)$

**Span:**  $T_\infty(n) = \Theta(n)$

**Parallel Running Time:**  $T_p(n) = O\left(\frac{T_1(n)}{p} + T_\infty(n)\right) = O\left(\frac{n^3}{p} + n\right)$

**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  $n \times n$  matrices,  
where  $n = 2^k$  for integer  $k \geq 0$  }

1. *if*  $n = 1$  *then*
2.      $Z \leftarrow Z + X \cdot Y$
3. *else*
4.     *spawn* *Par-Rec-MM* (  $Z_{11}, X_{11}, Y_{11}$  )
5.     *spawn* *Par-Rec-MM* (  $Z_{12}, X_{11}, Y_{12}$  )
6.     *spawn* *Par-Rec-MM* (  $Z_{21}, X_{21}, Y_{11}$  )
7.         *Par-Rec-MM* (  $Z_{21}, X_{21}, Y_{12}$  )
8.     *sync*
9.     *spawn* *Par-Rec-MM* (  $Z_{11}, X_{12}, Y_{21}$  )
10.    *spawn* *Par-Rec-MM* (  $Z_{12}, X_{12}, Y_{22}$  )
11.    *spawn* *Par-Rec-MM* (  $Z_{21}, X_{22}, Y_{21}$  )
12.         *Par-Rec-MM* (  $Z_{22}, X_{22}, Y_{22}$  )
13.    *sync*
14. *endif*

# Parallel Recursive MM

*Par-Rec-MM* ( Z, X, Y ) { X, Y, Z are n × n matrices,  
where n = 2<sup>k</sup> for integer k ≥ 0 }

1. *if* n = 1 *then*
2.     Z ← Z + X · Y
3. *else*
4.     *spawn* *Par-Rec-MM* ( Z<sub>11</sub>, X<sub>11</sub>, Y<sub>11</sub> )
5.     *spawn* *Par-Rec-MM* ( Z<sub>12</sub>, X<sub>11</sub>, Y<sub>12</sub> )
6.     *spawn* *Par-Rec-MM* ( Z<sub>21</sub>, X<sub>21</sub>, Y<sub>11</sub> )
7.         *Par-Rec-MM* ( Z<sub>21</sub>, X<sub>21</sub>, Y<sub>12</sub> )
8.     *sync*
9.     *spawn* *Par-Rec-MM* ( Z<sub>11</sub>, X<sub>12</sub>, Y<sub>21</sub> )
10.    *spawn* *Par-Rec-MM* ( Z<sub>12</sub>, X<sub>12</sub>, Y<sub>22</sub> )
11.    *spawn* *Par-Rec-MM* ( Z<sub>21</sub>, X<sub>22</sub>, Y<sub>21</sub> )
12.         *Par-Rec-MM* ( Z<sub>22</sub>, X<sub>22</sub>, Y<sub>22</sub> )
13.    *sync*
14. *endif*

**Work:**

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

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

**Span:**

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

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

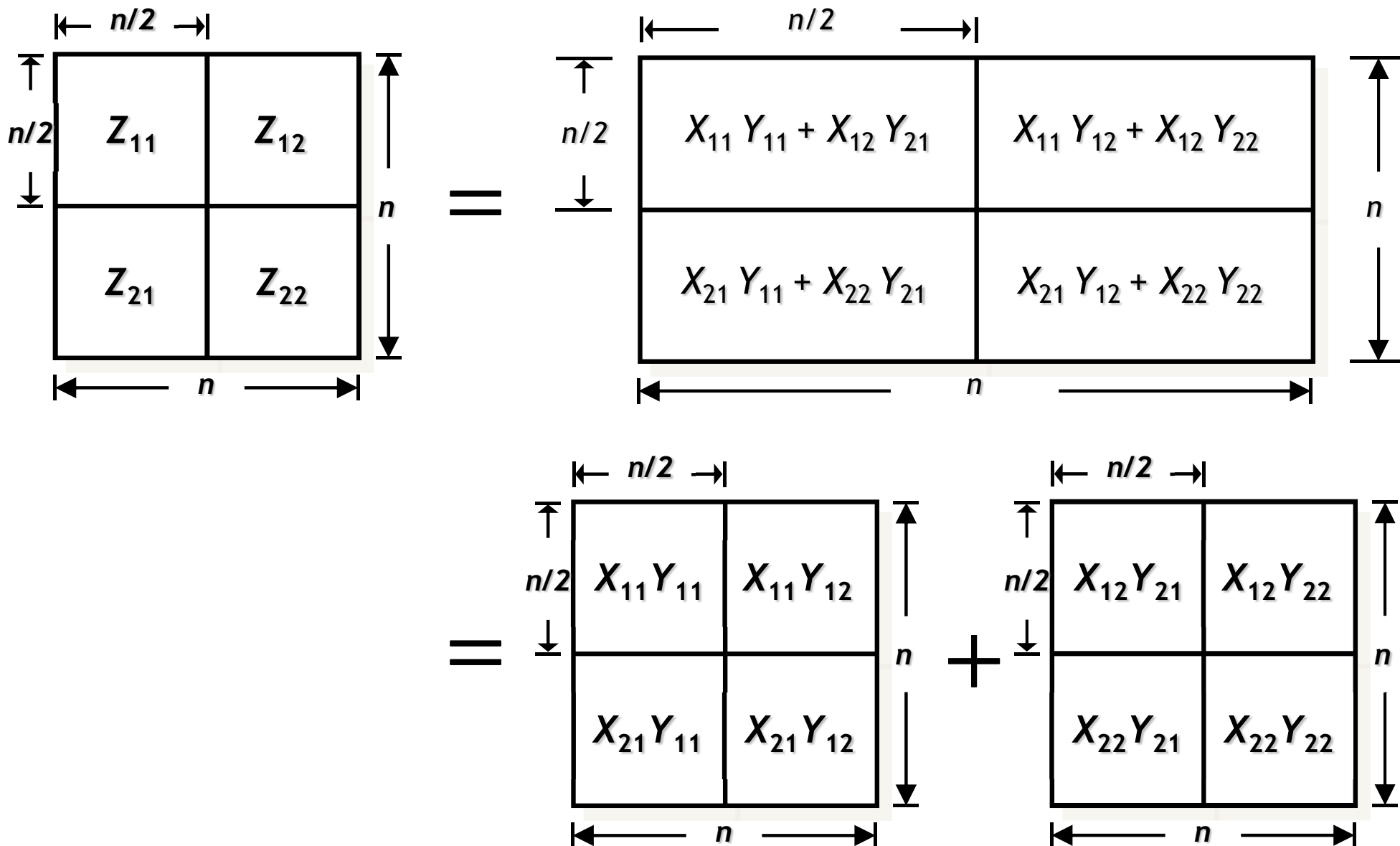
**Parallelism:**  $\frac{T_1(n)}{T_\infty(n)} = \Theta(n^2)$

**Additional Space:**

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

# Recursive MM with More Parallelism

Z



# Recursive MM with More Parallelism

```
Par-Rec-MM2 ( Z, X, Y )   { X, Y, Z are  $n \times n$  matrices,  
                           where  $n = 2^k$  for integer  $k \geq 0$  }  
  
1. if  $n = 1$  then  
2.    $Z \leftarrow Z + X \cdot Y$   
3. else           {  $T$  is a temporary  $n \times n$  matrix }  
  
4.   spawn Par-Rec-MM2 (  $Z_{11}$ ,  $X_{11}$ ,  $Y_{11}$  )  
5.   spawn Par-Rec-MM2 (  $Z_{12}$ ,  $X_{11}$ ,  $Y_{12}$  )  
6.   spawn Par-Rec-MM2 (  $Z_{21}$ ,  $X_{21}$ ,  $Y_{11}$  )  
7.   spawn Par-Rec-MM2 (  $Z_{21}$ ,  $X_{21}$ ,  $Y_{12}$  )  
8.   spawn Par-Rec-MM2 (  $T_{11}$ ,  $X_{12}$ ,  $Y_{21}$  )  
9.   spawn Par-Rec-MM2 (  $T_{12}$ ,  $X_{12}$ ,  $Y_{22}$  )  
10.  spawn Par-Rec-MM2 (  $T_{21}$ ,  $X_{22}$ ,  $Y_{21}$  )  
11.      Par-Rec-MM2 (  $T_{22}$ ,  $X_{22}$ ,  $Y_{22}$  )  
12.  sync  
13.  parallel for  $i \leftarrow 1$  to  $n$  do  
14.    parallel for  $j \leftarrow 1$  to  $n$  do  
15.       $Z[i][j] \leftarrow Z[i][j] + T[i][j]$   
16.  endif
```

# Recursive MM with More Parallelism

*Par-Rec-MM2* ( Z, X, Y )    { X, Y, Z are  $n \times n$  matrices,  
where  $n = 2^k$  for integer  $k \geq 0$  }

1. *if*  $n = 1$  *then*
2.      $Z \leftarrow Z + X \cdot Y$
3. *else*        { *T* is a temporary  $n \times n$  matrix }
4.     *spawn* *Par-Rec-MM2* (  $Z_{11}$ ,  $X_{11}$ ,  $Y_{11}$  )
5.     *spawn* *Par-Rec-MM2* (  $Z_{12}$ ,  $X_{11}$ ,  $Y_{12}$  )
6.     *spawn* *Par-Rec-MM2* (  $Z_{21}$ ,  $X_{21}$ ,  $Y_{11}$  )
7.     *spawn* *Par-Rec-MM2* (  $Z_{21}$ ,  $X_{21}$ ,  $Y_{12}$  )
8.     *spawn* *Par-Rec-MM2* (  $T_{11}$ ,  $X_{12}$ ,  $Y_{21}$  )
9.     *spawn* *Par-Rec-MM2* (  $T_{12}$ ,  $X_{12}$ ,  $Y_{22}$  )
10.    *spawn* *Par-Rec-MM2* (  $T_{21}$ ,  $X_{22}$ ,  $Y_{21}$  )
11.         *Par-Rec-MM2* (  $T_{22}$ ,  $X_{22}$ ,  $Y_{22}$  )
12.     *sync*
13.    *parallel for*  $i \leftarrow 1$  *to*  $n$  *do*
14.         *parallel for*  $j \leftarrow 1$  *to*  $n$  *do*
15.              $Z[i][j] \leftarrow Z[i][j] + T[i][j]$
16. *endif*

**Work:**

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

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

**Span:**

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

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

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

**Additional Space:**

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

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

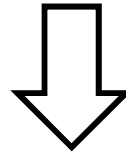
# Parallel Merge Sort



# Parallel Merge Sort

*Merge-Sort* (  $A, p, r$  )    { sort the elements in  $A[ p \dots r ]$  }

1. *if*  $p < r$  *then*
2.      $q \leftarrow \lfloor (p+r) / 2 \rfloor$
3.     *Merge-Sort* (  $A, p, q$  )
4.     *Merge-Sort* (  $A, q+1, r$  )
5.     *Merge* (  $A, p, q, r$  )



*Par-Merge-Sort* (  $A, p, r$  )    { sort the elements in  $A[ p \dots r ]$  }

1. *if*  $p < r$  *then*
2.      $q \leftarrow \lfloor (p+r) / 2 \rfloor$
3.     *spawn* *Merge-Sort* (  $A, p, q$  )
4.         *Merge-Sort* (  $A, q+1, r$  )
5.     *sync*
6.     *Merge* (  $A, p, q, r$  )

# Parallel Merge Sort

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

1. *if*  $p < r$  *then*
2.  $q \leftarrow \lfloor (p + r) / 2 \rfloor$
3. *spawn* *Merge-Sort* ( A, p, q )
4. *Merge-Sort* ( A, q + 1, r )
5. *sync*
6. *Merge* ( A, p, q, r )

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

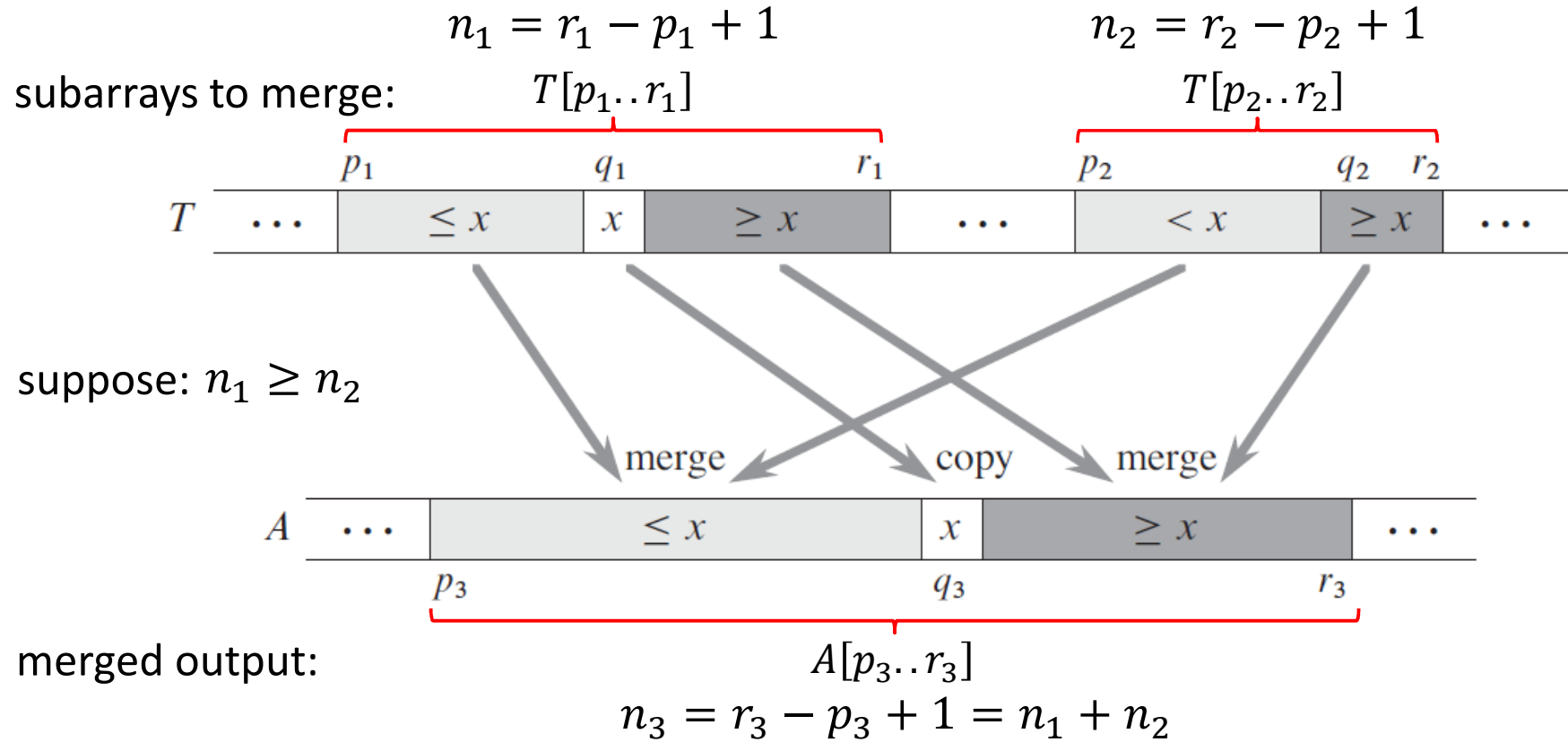
$$= \Theta(n \log n) \quad [ \text{MT Case 2} ]$$

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

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

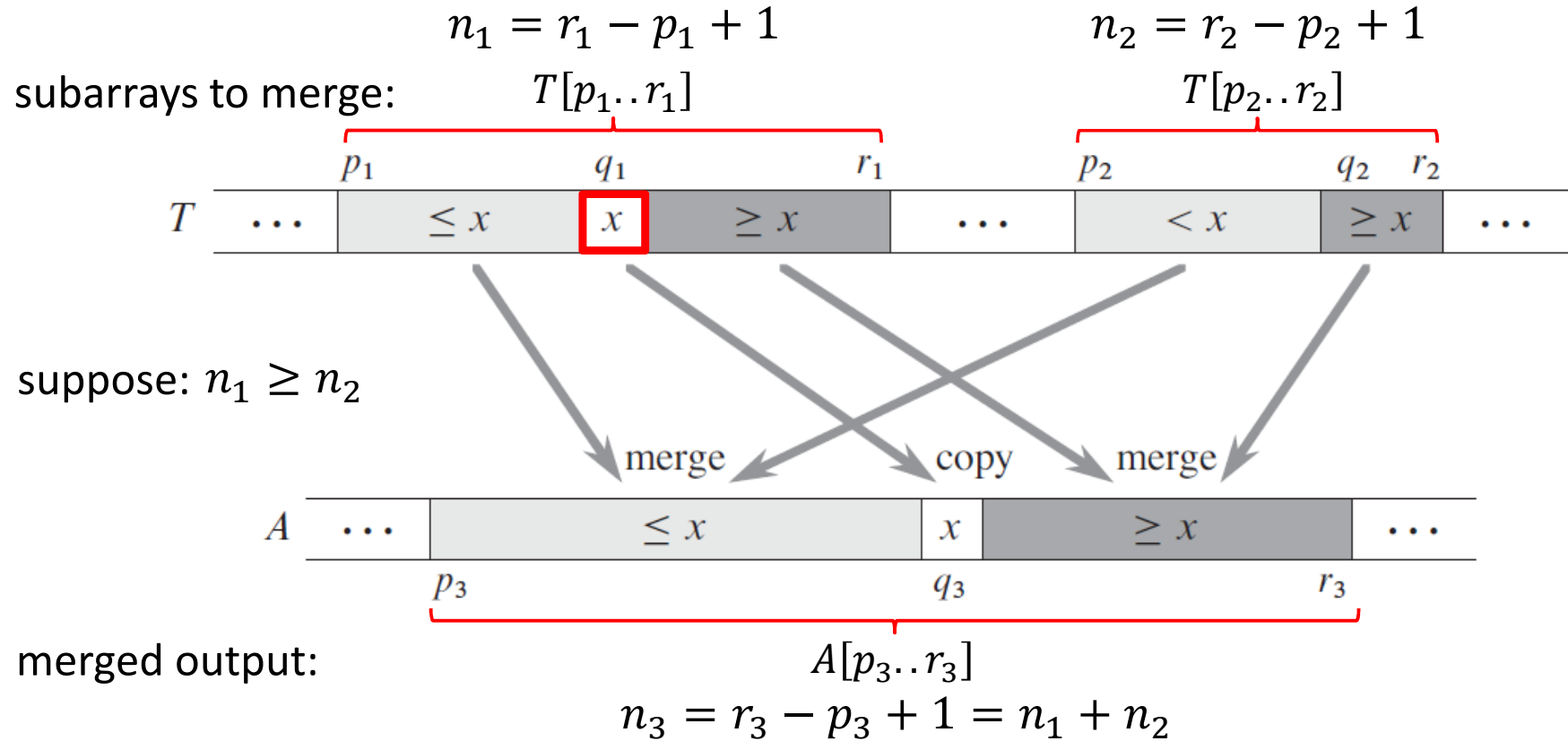
$$\text{Parallelism: } \frac{T_1(n)}{T_\infty(n)} = \Theta(\log n)$$

# Parallel Merge



Source: Cormen et al.,  
 "Introduction to Algorithms",  
 3<sup>rd</sup> Edition

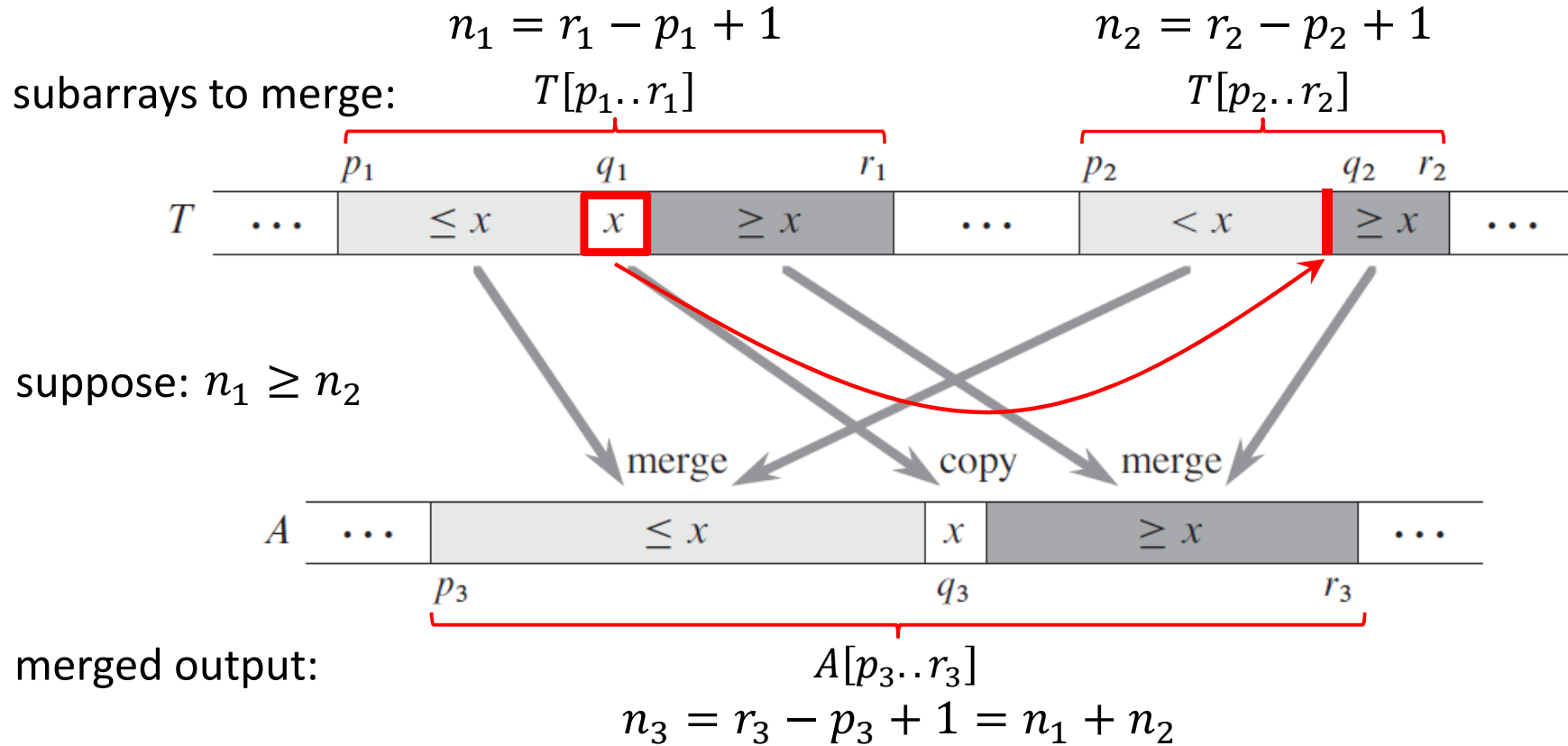
# Parallel Merge



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

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

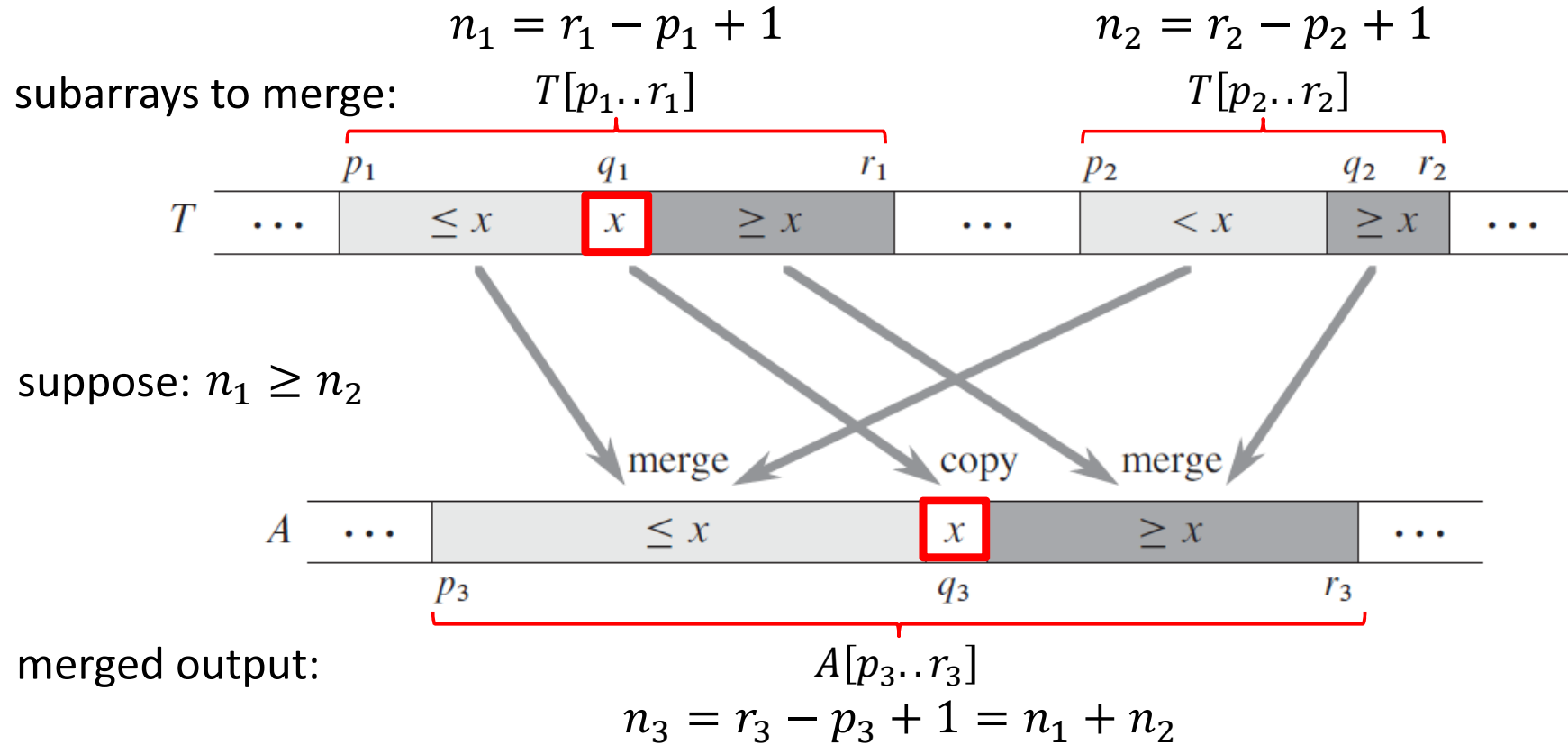
# Parallel Merge



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

**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  $T[q_2]$

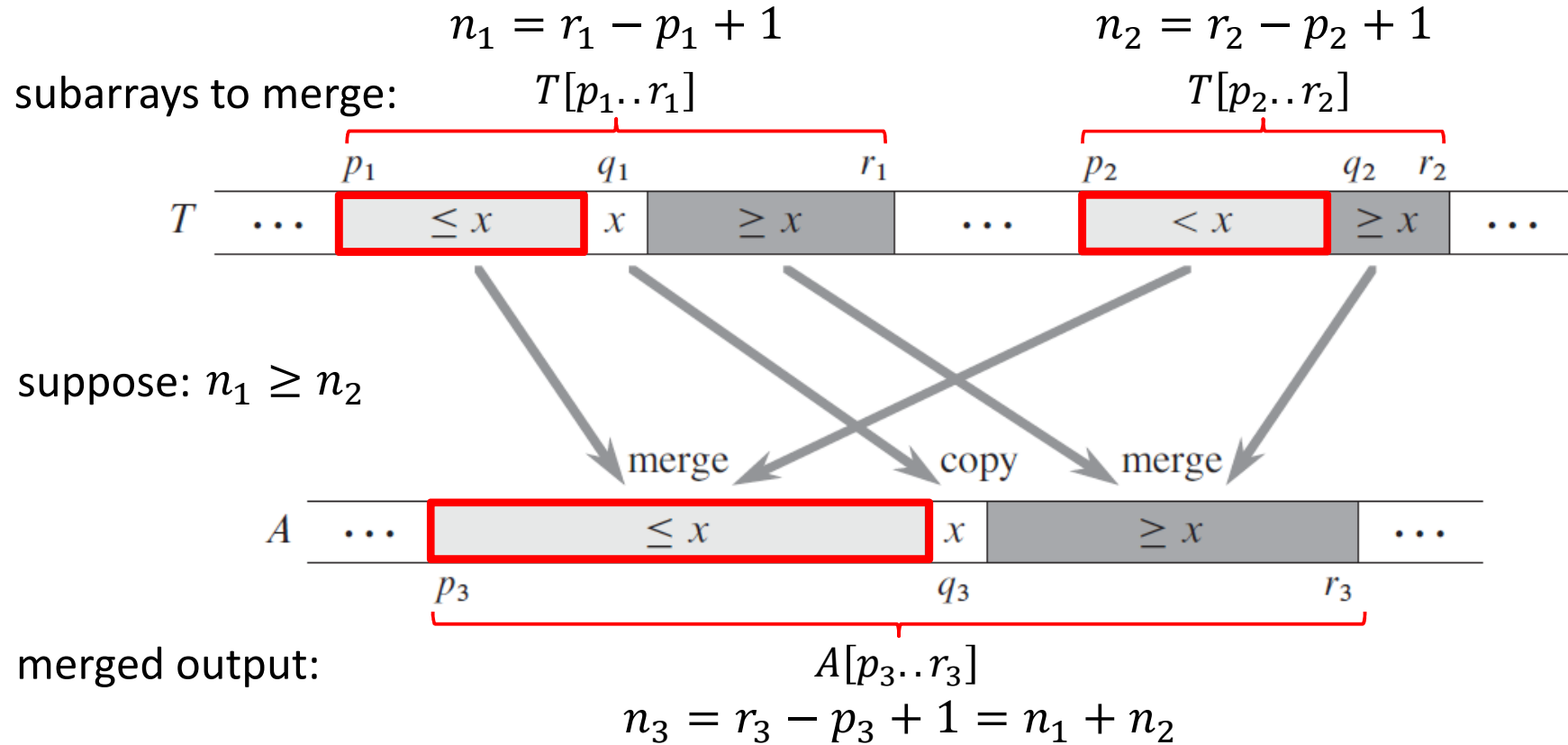
# Parallel Merge



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

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

# Parallel Merge

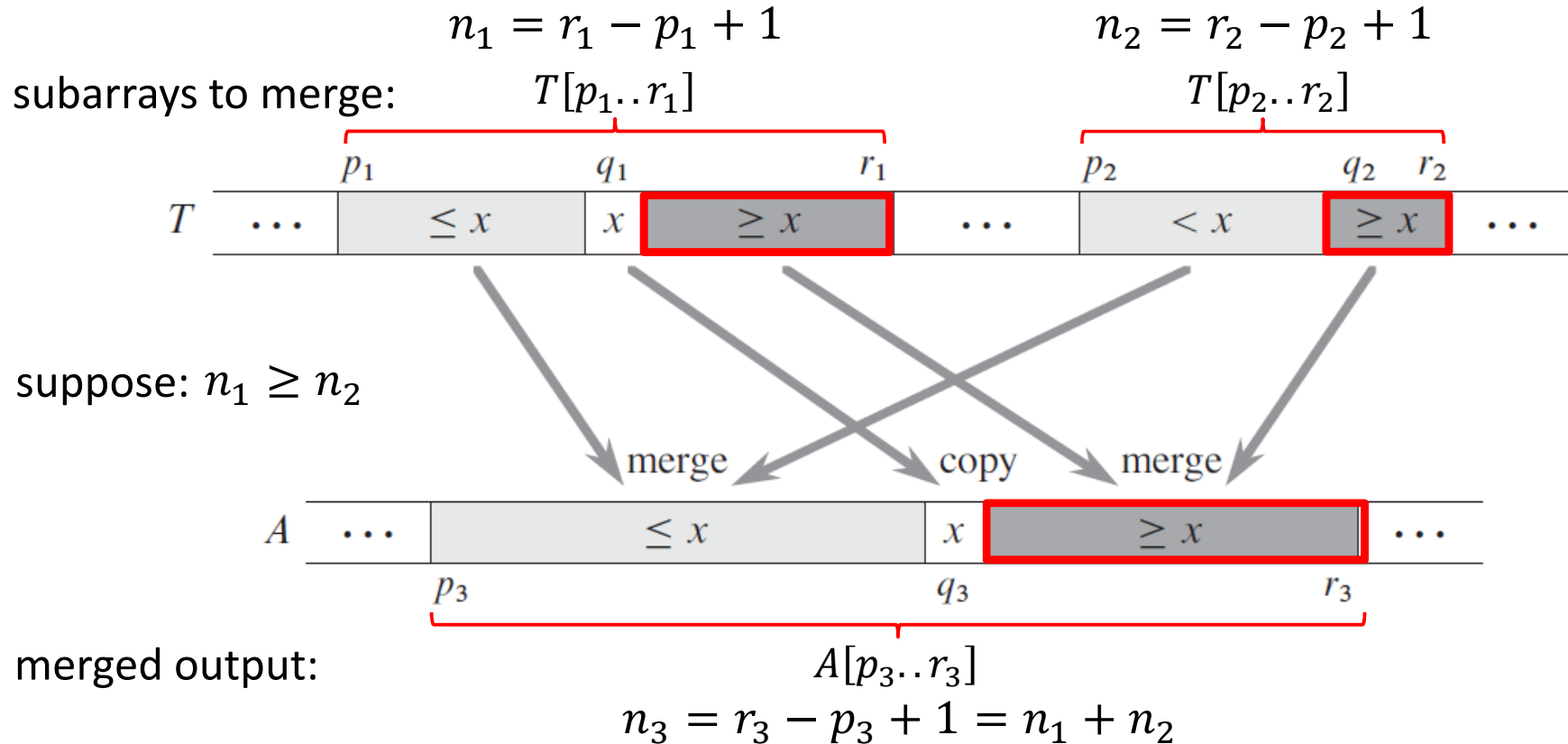


Source: Cormen et al.,  
 "Introduction to Algorithms",  
 3rd Edition

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



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

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* (  $T, p_1, r_1, p_2, r_2, A, p_3$  )

1.  $n_1 \leftarrow r_1 - p_1 + 1, n_2 \leftarrow r_2 - p_2 + 1$
2. *if*  $n_1 < n_2$  *then*
3.      $p_1 \leftrightarrow p_2, r_1 \leftrightarrow r_2, n_1 \leftrightarrow n_2$
4. *if*  $n_1 = 0$  *then return*
5. *else*
6.      $q_1 \leftarrow \lfloor (p_1 + r_1) / 2 \rfloor$
7.      $q_2 \leftarrow \text{Binary-Search} ( T[ q_1 ], T, p_2, r_2 )$
8.      $q_3 \leftarrow p_3 + ( q_1 - p_1 ) + ( q_2 - p_2 )$
9.      $A[ q_3 ] \leftarrow T[ q_1 ]$
10.     *spawn* *Par-Merge* (  $T, p_1, q_1-1, p_2, q_2-1, A, p_3$  )
11.     *Par-Merge* (  $T, q_1+1, r_1, q_2+1, r_2, A, q_3+1$  )
12.     *sync*

# Parallel Merge

*Par-Merge* (  $T, p_1, r_1, p_2, r_2, A, p_3$  )

1.  $n_1 \leftarrow r_1 - p_1 + 1, n_2 \leftarrow r_2 - p_2 + 1$
2. *if*  $n_1 < n_2$  *then*
3.      $p_1 \leftrightarrow p_2, r_1 \leftrightarrow r_2, n_1 \leftrightarrow n_2$
4. *if*  $n_1 = 0$  *then return*
5. *else*
6.      $q_1 \leftarrow \lfloor (p_1 + r_1) / 2 \rfloor$
7.      $q_2 \leftarrow \text{Binary-Search} ( T[q_1], T, p_2, r_2 )$
8.      $q_3 \leftarrow p_3 + (q_1 - p_1) + (q_2 - p_2)$
9.      $A[q_3] \leftarrow T[q_1]$
10.     *spawn* *Par-Merge* (  $T, p_1, q_1-1, p_2, q_2-1, A, p_3$  )
11.     *Par-Merge* (  $T, q_1+1, r_1, q_2+1, r_2, A, q_3+1$  )
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* (  $T, p_1, r_1, p_2, r_2, A, p_3$  )

1.  $n_1 \leftarrow r_1 - p_1 + 1, \quad n_2 \leftarrow r_2 - p_2 + 1$
2. *if*  $n_1 < n_2$  *then*
3.      $p_1 \leftrightarrow p_2, \quad r_1 \leftrightarrow r_2, \quad n_1 \leftrightarrow n_2$
4. *if*  $n_1 = 0$  *then return*
5. *else*
6.      $q_1 \leftarrow \lfloor (p_1 + r_1) / 2 \rfloor$
7.      $q_2 \leftarrow \text{Binary-Search} ( T[ q_1 ], T, p_2, r_2 )$
8.      $q_3 \leftarrow p_3 + (q_1 - p_1) + (q_2 - p_2)$
9.      $A[ q_3 ] \leftarrow T[ q_1 ]$
10.     *spawn* *Par-Merge* (  $T, p_1, q_1-1, p_2, q_2-1, A, p_3$  )
11.     *Par-Merge* (  $T, q_1+1, r_1, q_2+1, r_2, A, q_3+1$  )
12.     *sync*

**Span:**

$$T_{\infty}(n) = \begin{cases} \Theta(1), & \text{if } n = 1, \\ T_{\infty}\left(\frac{3n}{4}\right) + \Theta(\log n), & \text{otherwise.} \end{cases}$$
$$= \Theta(\log^2 n) \quad [ \text{MT Case 2} ]$$

**Work:**

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

We show below that,  $T_1(n) = O(n)$

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

$$T_1(n) = T_1(\alpha n) + T_1((1 - \alpha)n) + O(\log n)$$

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

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

# Parallel Merge Sort with Parallel Merge

*Par-Merge-Sort* (  $A, p, r$  ) { sort the elements in  $A[ p \dots r ]$  }

1. *if*  $p < r$  *then*
2.      $q \leftarrow \lfloor (p+r) / 2 \rfloor$
3.     *spawn* *Merge-Sort* (  $A, p, q$  )
4.     *Merge-Sort* (  $A, q+1, r$  )
5.     *sync*
6.     *Par-Merge* (  $A, p, q, r$  )

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

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

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

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

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

# Parallel Prefix Sums

# Parallel Prefix Sums

**Input:** A sequence of  $n$  elements  $\{x_1, x_2, \dots, x_n\}$  drawn from a set  $S$  with a binary associative operation, denoted by  $\oplus$ .

**Output:** A sequence of  $n$  partial sums  $\{s_1, s_2, \dots, s_n\}$ , where  $s_i = x_1 \oplus x_2 \oplus \dots \oplus x_i$  for  $1 \leq i \leq n$ .

$x_1$	$x_2$	$x_3$	$x_4$	$x_5$	$x_6$	$x_7$	$x_8$
5	3	7	1	3	6	2	4

$\oplus$  = binary addition

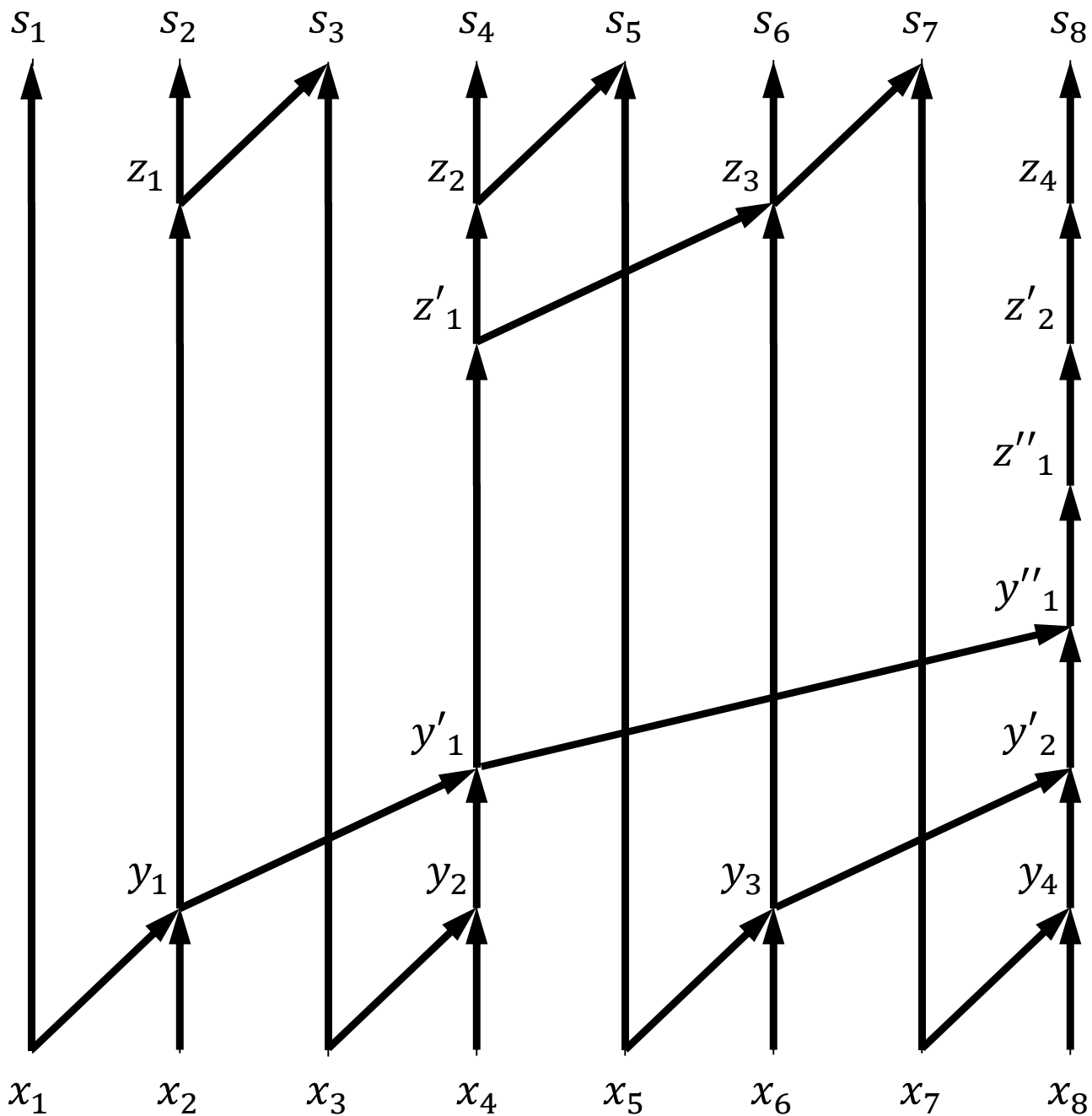
5	8	15	16	19	25	27	31
$s_1$	$s_2$	$s_3$	$s_4$	$s_5$	$s_6$	$s_7$	$s_8$

# Parallel Prefix Sums

*Prefix-Sum* (  $\langle x_1, x_2, \dots, x_n \rangle, \oplus$  )  $\{ n = 2^k \text{ for some } k \geq 0. \}$   
Return prefix sums  
 $\langle s_1, s_2, \dots, s_n \rangle$  }

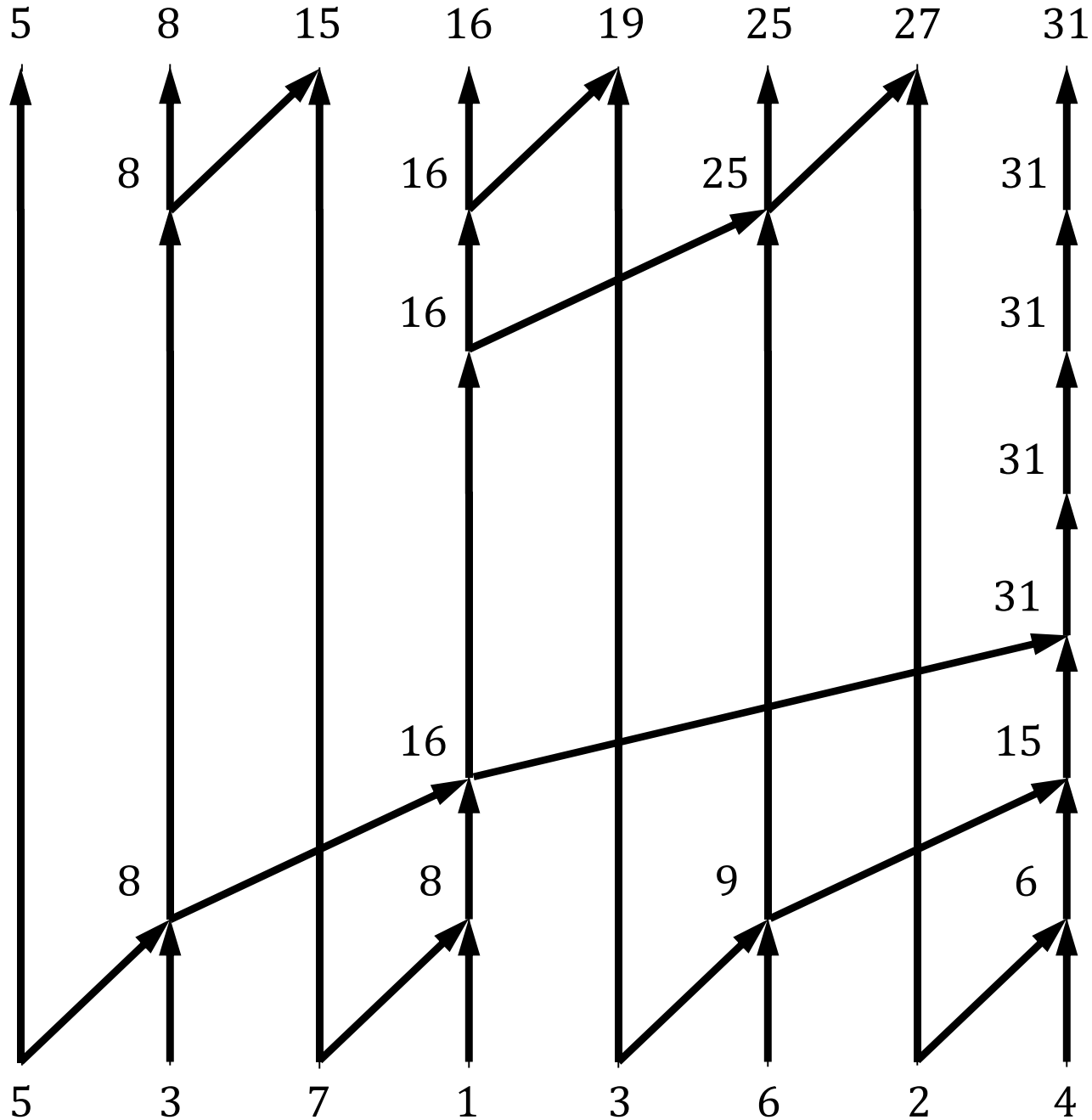
1. *if*  $n = 1$  *then*
2.      $s_1 \leftarrow x_1$
3. *else*
4.     *parallel for*  $i \leftarrow 1$  *to*  $n/2$  *do*
5.          $y_i \leftarrow x_{2i-1} \oplus x_{2i}$
6.      $\langle z_1, z_2, \dots, z_{n/2} \rangle \leftarrow \text{Prefix-Sum}(\langle y_1, y_2, \dots, y_{n/2} \rangle, \oplus)$
7.     *parallel for*  $i \leftarrow 1$  *to*  $n$  *do*
8.         *if*  $i = 1$  *then*  $s_1 \leftarrow x_1$
9.         *else if*  $i = \text{even}$  *then*  $s_i \leftarrow z_{i/2}$
10.         *else*  $s_i \leftarrow z_{(i-1)/2} \oplus x_i$
11. *return*  $\langle s_1, s_2, \dots, s_n \rangle$

# Parallel Prefix Sums





# Parallel Prefix Sums



# Parallel Prefix Sums

*Prefix-Sum* (  $\langle x_1, x_2, \dots, x_n \rangle, \oplus$  )  $\{ n = 2^k \text{ for some } k \geq 0. \}$   
 Return prefix sums  
 $\langle s_1, s_2, \dots, s_n \rangle \}$

1. *if*  $n = 1$  *then*
2.      $s_1 \leftarrow x_1$
3. *else*
4.     *parallel for*  $i \leftarrow 1$  *to*  $n/2$  *do*
5.          $y_i \leftarrow x_{2i-1} \oplus x_{2i}$
6.      $\langle z_1, z_2, \dots, z_{n/2} \rangle \leftarrow \text{Prefix-Sum}(\langle y_1, y_2, \dots, y_{n/2} \rangle, \oplus)$
7.     *parallel for*  $i \leftarrow 1$  *to*  $n$  *do*
8.         *if*  $i = 1$  *then*  $s_1 \leftarrow x_1$
9.         *else if*  $i = \text{even}$  *then*  $s_i \leftarrow z_{i/2}$
10.         *else*  $s_i \leftarrow z_{(i-1)/2} \oplus x_i$
11. *return*  $\langle s_1, s_2, \dots, s_n \rangle$

**Work:**

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

$$= \Theta(n)$$

**Span:**

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

$$= \Theta(\log n)$$

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

Observe that we have assumed here that a *parallel for loop* can be executed in  $\Theta(1)$  time. But recall that *cilk\_for* is implemented using divide-and-conquer, and so in practice, it will take  $\Theta(\log n)$  time. In that case, we will have  $T_\infty(n) = \Theta(\log^2 n)$ , and parallelism =  $\Theta\left(\frac{n}{\log^2 n}\right)$ .

# Parallel Partition

# Parallel Partition

**Input:** An array  $A[ q : r ]$  of distinct elements, and an element  $x$  from  $A[ q : r ]$ .

**Output:** Rearrange the elements of  $A[ q : r ]$ , and return an index  $k \in [ q, r ]$ , such that all elements in  $A[ q : k - 1 ]$  are smaller than  $x$ , all elements in  $A[ k + 1 : r ]$  are larger than  $x$ , and  $A[ k ] = x$ .

```
Par-Partition (  $A[ q : r ], x$  )
1.  $n \leftarrow r - q + 1$ 
2. if  $n = 1$  then return  $q$ 
3. array  $B[ 0 : n - 1 ], lt[ 0 : n - 1 ], gt[ 0 : n - 1 ]$ 
4. parallel for  $i \leftarrow 0$  to  $n - 1$  do
5.    $B[ i ] \leftarrow A[ q + i ]$ 
6.   if  $B[ i ] < x$  then  $lt[ i ] \leftarrow 1$  else  $lt[ i ] \leftarrow 0$ 
7.   if  $B[ i ] > x$  then  $gt[ i ] \leftarrow 1$  else  $gt[ i ] \leftarrow 0$ 
8.  $lt[ 0 : n - 1 ] \leftarrow$  Par-Prefix-Sum (  $lt[ 0 : n - 1 ], +$  )
9.  $gt[ 0 : n - 1 ] \leftarrow$  Par-Prefix-Sum (  $gt[ 0 : n - 1 ], +$  )
10.  $k \leftarrow q + lt[ n - 1 ], A[ k ] \leftarrow x$ 
11. parallel for  $i \leftarrow 0$  to  $n - 1$  do
12.   if  $B[ i ] < x$  then  $A[ q + lt[ i ] - 1 ] \leftarrow B[ i ]$ 
13.   else if  $B[ i ] > x$  then  $A[ k + gt[ i ] ] \leftarrow B[ i ]$ 
14. return  $k$ 
```

# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

**B:**

0	1	2	3	4	5	6	7	8	9
9	5	7	11	1	3	8	14	4	21

**lt:**

0	1	2	3	4	5	6	7	8	9
0	1	1	0	1	1	0	0	1	0

**gt:**

0	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	1	0	1

# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

**B:**

0	1	2	3	4	5	6	7	8	9
9	5	7	11	1	3	8	14	4	21

**lt:**

0	1	2	3	4	5	6	7	8	9
0	1	1	0	1	1	0	0	1	0

**lt:**

0	1	2	2	3	4	4	4	5	5
---	---	---	---	---	---	---	---	---	---

*prefix sum*

**gt:**

0	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	1	0	1

**gt:**

1	1	1	2	2	2	2	3	3	4
---	---	---	---	---	---	---	---	---	---

*prefix sum*





# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

**B:**

0	1	2	3	4	5	6	7	8	9
9	5	7	11	1	3	8	14	4	21

**lt:**

0	1	2	3	4	5	6	7	8	9
0	1	1	0	1	1	0	0	1	0

**gt:**

0	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	1	0	1

**lt:**

0	1	2	2	3	4	4	4	5	5
---	---	---	---	---	---	---	---	---	---

**gt:**

1	1	1	2	2	2	2	3	3	4
---	---	---	---	---	---	---	---	---	---

*prefix sum*

$k = 5$

*prefix sum*

**A:**

0	1	2	3	4	5	6	7	8	9
5	7	1	3	4	<b>8</b>				

# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

**B:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**lt:**

0	1	1	0	1	1	0	0	1	0
---	---	---	---	---	---	---	---	---	---

**gt:**

1	0	0	1	0	0	0	1	0	1
---	---	---	---	---	---	---	---	---	---

**lt:**

0	1	2	2	3	4	4	4	5	5
---	---	---	---	---	---	---	---	---	---

  
*prefix sum*

**gt:**

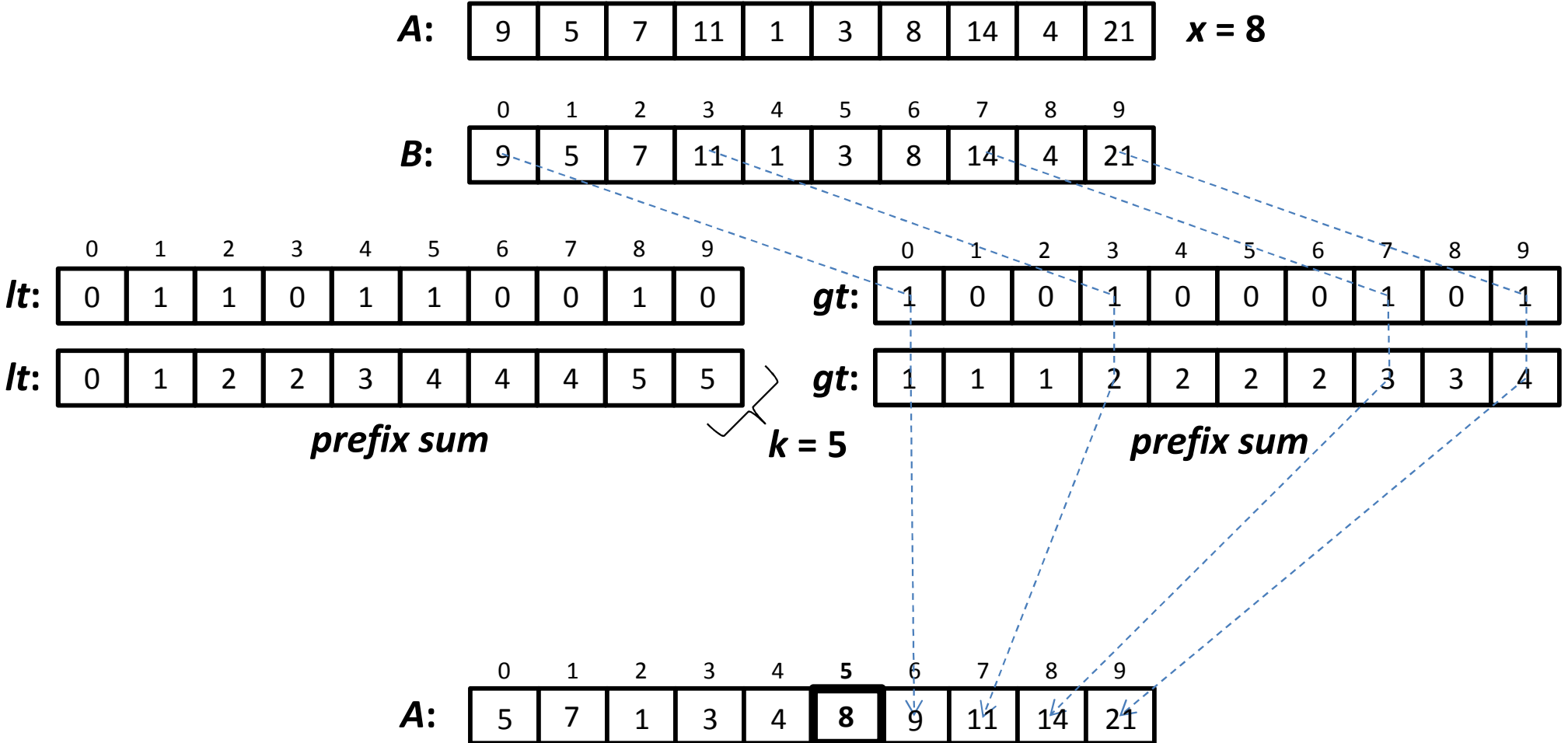
1	1	1	2	2	2	2	3	3	4
---	---	---	---	---	---	---	---	---	---

  
*prefix sum*

$k = 5$

**A:**

5	7	1	3	4	<b>8</b>	9	11	14	21
---	---	---	---	---	----------	---	----	----	----



# Parallel Partition

**A:**

9	5	7	11	1	3	8	14	4	21
---	---	---	----	---	---	---	----	---	----

**x = 8**

**B:**

0	1	2	3	4	5	6	7	8	9
9	5	7	11	1	3	8	14	4	21

**lt:**

0	1	2	3	4	5	6	7	8	9
0	1	1	0	1	1	0	0	1	0

**gt:**

0	1	2	3	4	5	6	7	8	9
1	0	0	1	0	0	0	1	0	1

**lt:**

0	1	2	2	3	4	4	4	5	5
---	---	---	---	---	---	---	---	---	---

  
*prefix sum*

**gt:**

1	1	1	2	2	2	2	3	3	4
---	---	---	---	---	---	---	---	---	---

  
*prefix sum*

} **k = 5**

**A:**

0	1	2	3	4	5	6	7	8	9
5	7	1	3	4	<b>8</b>	9	11	14	21

# Parallel Partition: Analysis

*Par-Partition* (  $A[ q : r ]$ ,  $x$  )

1.  $n \leftarrow r - q + 1$
2. *if*  $n = 1$  *then return*  $q$
3. *array*  $B[ 0 : n - 1 ]$ ,  $lt[ 0 : n - 1 ]$ ,  $gt[ 0 : n - 1 ]$
4. *parallel for*  $i \leftarrow 0$  *to*  $n - 1$  *do*
5.      $B[ i ] \leftarrow A[ q + i ]$
6.     *if*  $B[ i ] < x$  *then*  $lt[ i ] \leftarrow 1$  *else*  $lt[ i ] \leftarrow 0$
7.     *if*  $B[ i ] > x$  *then*  $gt[ i ] \leftarrow 1$  *else*  $gt[ i ] \leftarrow 0$
8.  $lt[ 0 : n - 1 ] \leftarrow$  *Par-Prefix-Sum* (  $lt[ 0 : n - 1 ]$ ,  $+$  )
9.  $gt[ 0 : n - 1 ] \leftarrow$  *Par-Prefix-Sum* (  $gt[ 0 : n - 1 ]$ ,  $+$  )
10.  $k \leftarrow q + lt[ n - 1 ]$ ,  $A[ k ] \leftarrow x$
11. *parallel for*  $i \leftarrow 0$  *to*  $n - 1$  *do*
12.     *if*  $B[ i ] < x$  *then*  $A[ q + lt[ i ] - 1 ] \leftarrow B[ i ]$
13.     *else if*  $B[ i ] > x$  *then*  $A[ k + gt[ i ] ] \leftarrow B[ i ]$
14. *return*  $k$

**Work:**

$$\begin{aligned} T_1(n) &= \Theta(n) && [ \text{lines } 1 - 7 ] \\ &+ \Theta(n) && [ \text{lines } 8 - 9 ] \\ &+ \Theta(n) && [ \text{lines } 10 - 14 ] \\ &= \Theta(n) \end{aligned}$$

**Span:**

Assuming  $\log n$  depth for *parallel for* loops:

$$\begin{aligned} T_\infty(n) &= \Theta(\log n) && [ \text{lines } 1 - 7 ] \\ &+ \Theta(\log^2 n) && [ \text{lines } 8 - 9 ] \\ &+ \Theta(\log n) && [ \text{lines } 10 - 14 ] \\ &= \Theta(\log^2 n) \end{aligned}$$

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

# Parallel Quicksort

# Randomized Parallel QuickSort

**Input:** An array  $A[ q : r ]$  of distinct elements.

**Output:** Elements of  $A[ q : r ]$  sorted in increasing order of value.

*Par-Randomized-QuickSort* (  $A[ q : r ]$  )

1.  $n \leftarrow r - q + 1$
2. *if*  $n \leq 30$  *then*
3.     sort  $A[ q : r ]$  using any sorting algorithm
4. *else*
5.     select a random element  $x$  from  $A[ q : r ]$
6.      $k \leftarrow$  *Par-Partition* (  $A[ q : r ], x$  )
7.     *spawn* *Par-Randomized-QuickSort* (  $A[ q : k - 1 ]$  )
8.     *Par-Randomized-QuickSort* (  $A[ k + 1 : r ]$  )
9.     *sync*

# Randomized Parallel QuickSort: Analysis

```
Par-Randomized-QuickSort (  $A[ q : r ]$  )  
1.  $n \leftarrow r - q + 1$   
2. if  $n \leq 30$  then  
3.   sort  $A[ q : r ]$  using any sorting algorithm  
4. else  
5.   select a random element  $x$  from  $A[ q : r ]$   
6.    $k \leftarrow \text{Par-Partition} ( A[ q : r ], x )$   
7.   spawn Par-Randomized-QuickSort (  $A[ q : k - 1 ]$  )  
8.   Par-Randomized-QuickSort (  $A[ k + 1 : r ]$  )  
9.   sync
```

Lines 1—6 take  $\Theta(\log^2 n)$  parallel time and perform  $\Theta(n)$  work.

Also the recursive spawns in lines 7—8 work on disjoint parts of  $A[ q : r ]$ . So the upper bounds on the parallel time and the total work in each level of recursion are  $\Theta(\log^2 n)$  and  $\Theta(n)$ , respectively.

Hence, if  $D$  is the *recursion depth* of the algorithm, then

$$T_1(n) = O(nD) \text{ and } T_\infty(n) = O(D \log^2 n)$$

# Randomized Parallel QuickSort: Analysis

```
Par-Randomized-QuickSort (  $A[ q : r ]$  )  
1.  $n \leftarrow r - q + 1$   
2. if  $n \leq 30$  then  
3.   sort  $A[ q : r ]$  using any sorting algorithm  
4. else  
5.   select a random element  $x$  from  $A[ q : r ]$   
6.    $k \leftarrow$  Par-Partition (  $A[ q : r ]$ ,  $x$  )  
7.   spawn Par-Randomized-QuickSort (  $A[ q : k - 1 ]$  )  
8.   Par-Randomized-QuickSort (  $A[ k + 1 : r ]$  )  
9.   sync
```

We already proved that w.h.p. recursion depth,  $D = O(\log n)$ .

Hence, with high probability,

$$T_1(n) = O(n \log n) \text{ and } T_\infty(n) = O(\log^3 n)$$