Foundations:
Concurrency Concerns
Synchronization Basics

Chris Rossbach

CS378H

Today

- Questions?
- Administrivia
  - You've started Lab 1 right?
- Foundations
  - Parallelism
  - Basic Synchronization
  - Threads/Processes/Fibers, Oh my!
  - Cache coherence (maybe)

- Acknowledgments: some materials in this lecture borrowed from
  - Emmett Witchel (who borrowed them from: Kathryn McKinley, Ron Rockhold, Tom Anderson, John Carter, Mike Dahlin, Jim Kurose, Hank Levy, Harrick Vin, Thomas Narten, and Emery Berger)
  - Mark Silberstein (who borrowed them from: Blaise Barney, Kunle Olukoton, Gupta)
  - Andy Tannenbaum
  - Don Porter
  - me…
  - Photo source: https://img.devrant.com/devrant/rant/r_10875_uRYQF.jpg

Faux Quiz (answer any 2, 5 min)

- Who was Flynn? Why is her/his taxonomy important?
- How does domain decomposition differ from functional decomposition? Give examples of each.
- Can a SIMD parallel program use functional decomposition? Why/why not?
- What is an RMW instruction? How can they be used to construct synchronization primitives? How can sync primitives be constructed without them?

Who is Flynn?

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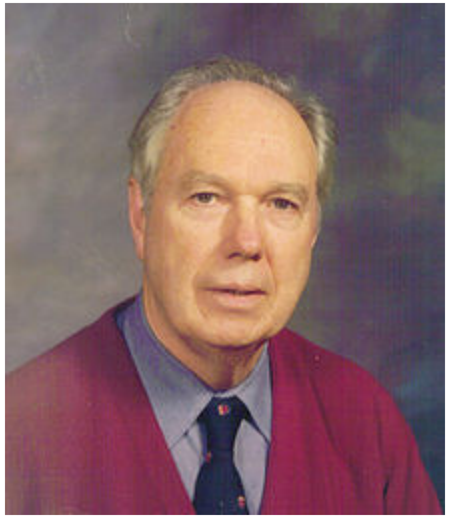

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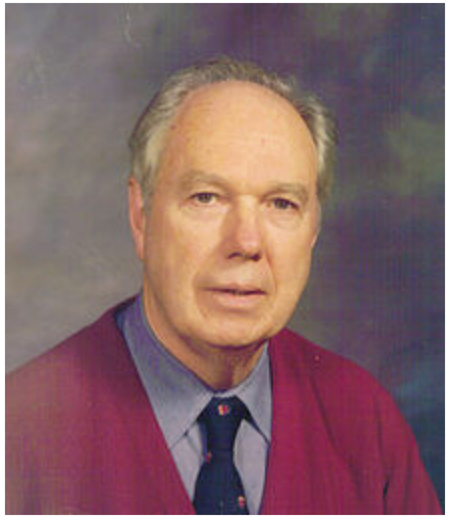

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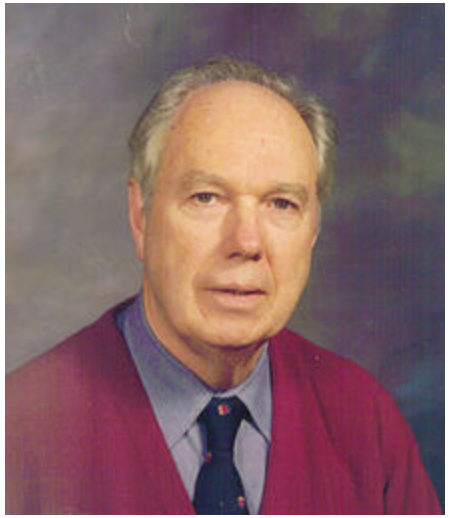

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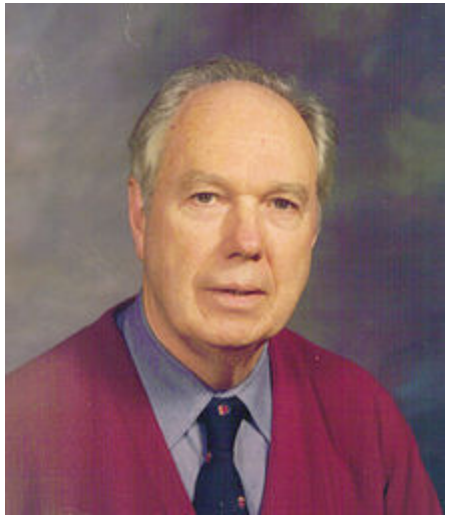

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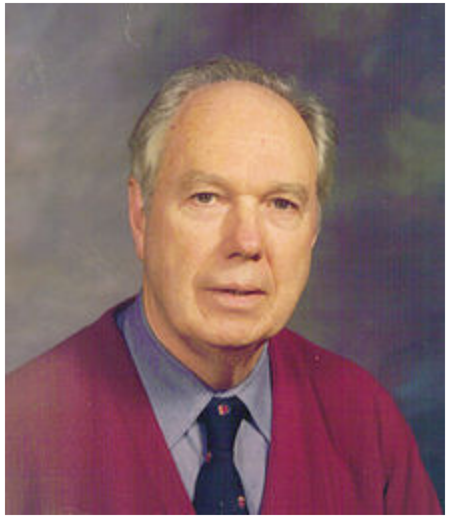

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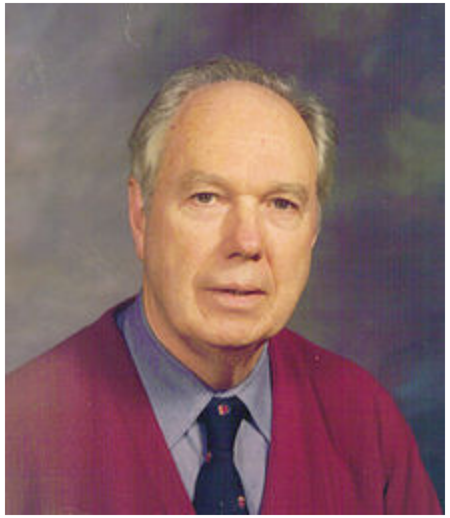

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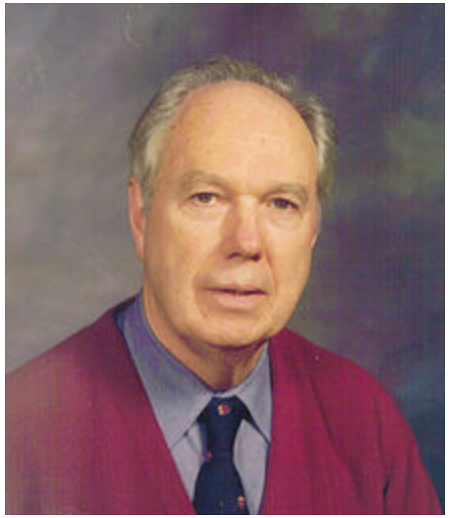

- (Thanks Wikipedia)

Review: Flynn’s Taxonomy

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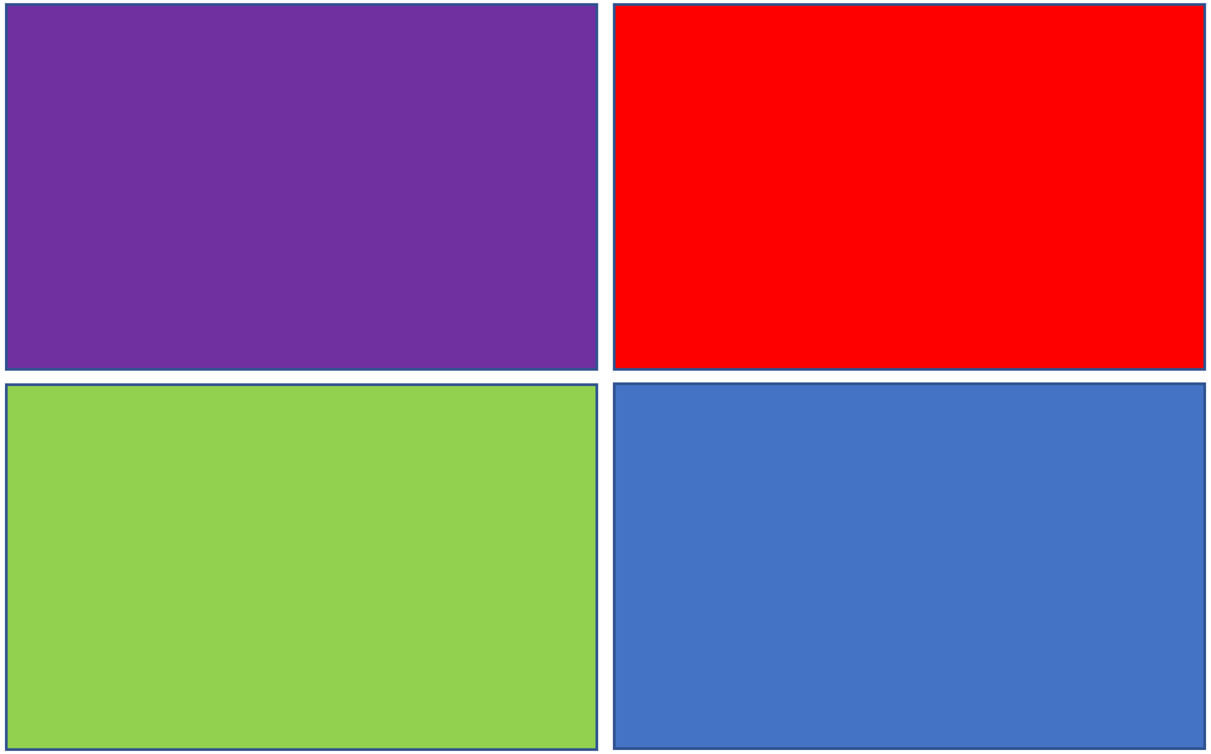

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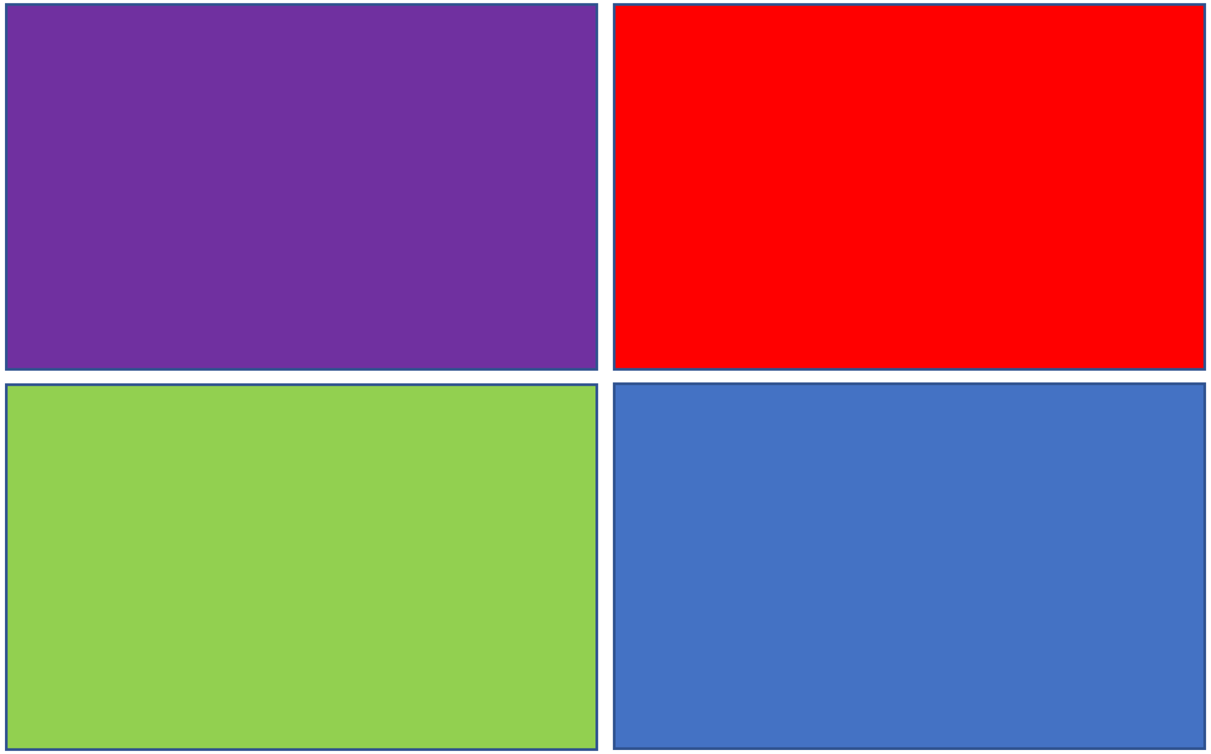

Y AXIS:

X AXIS:

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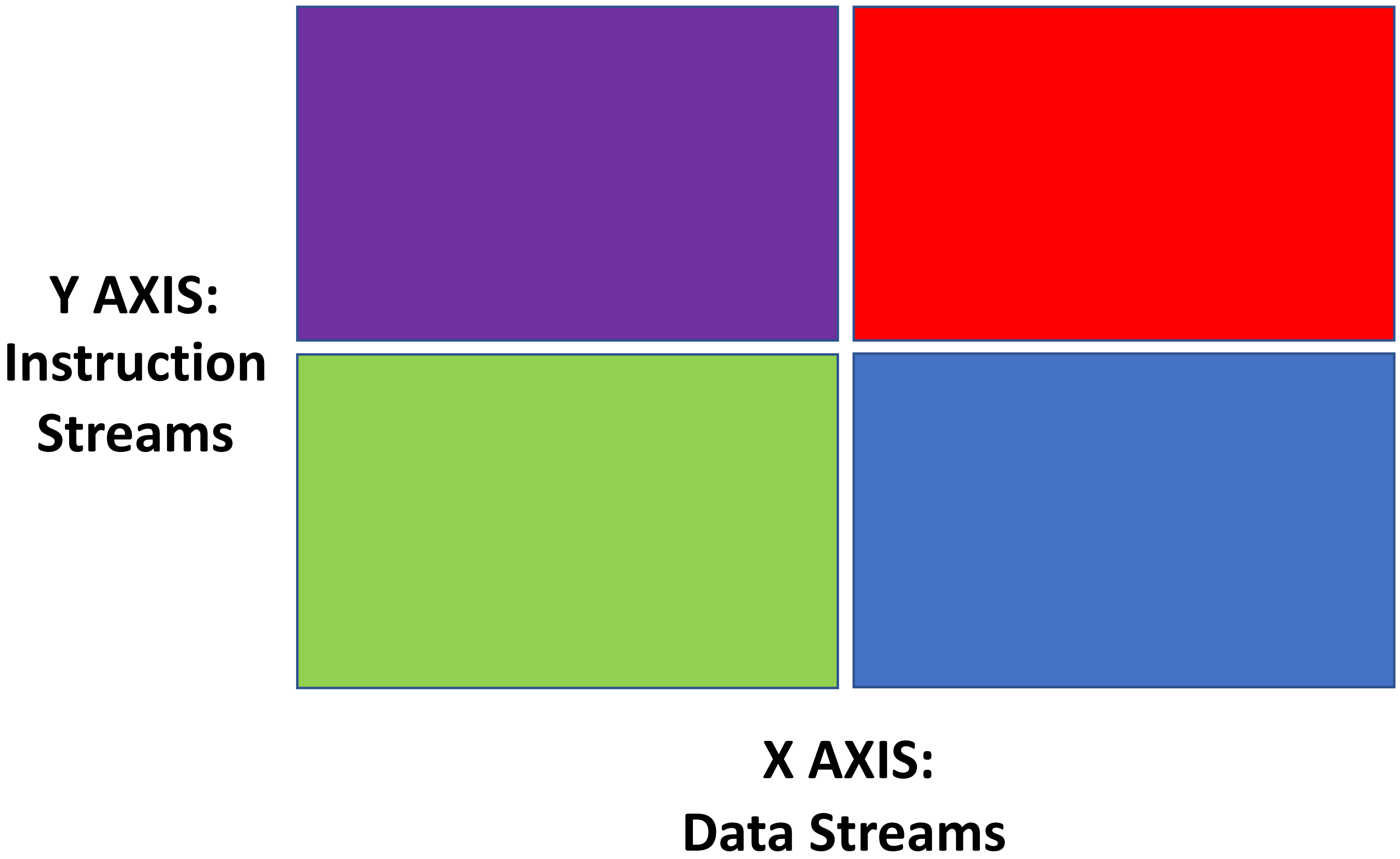
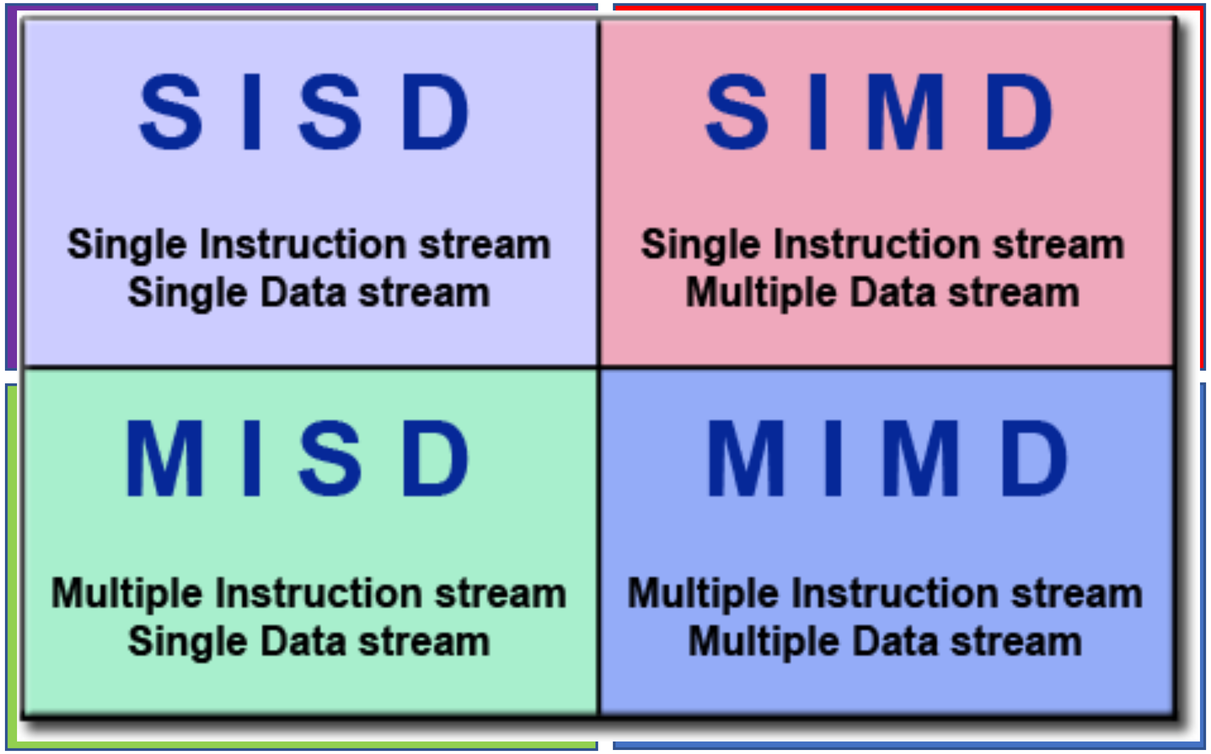


Y AXIS:
Instruction
Streams

X AXIS:
Data Streams

Review: Flynn’s Taxonomy

Y AXIS:
Instruction Streams



SISD Single Instruction stream Single Data stream	**SIMD** Single Instruction stream Multiple Data stream
MISD Multiple Instruction stream Single Data stream	**MIMD** Multiple Instruction stream Multiple Data stream

X AXIS:
Data Streams

Review: Problem Partitioning

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- Domain Decomposition

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- Domain Decomposition
  - SPMD
  - Input domain
  - Output Domain
  - Both

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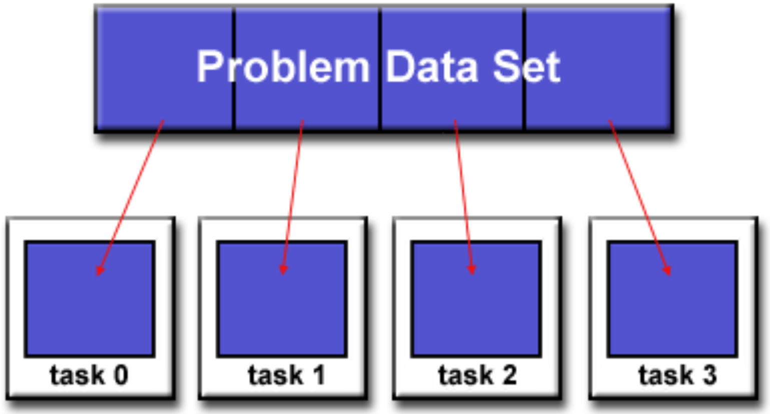

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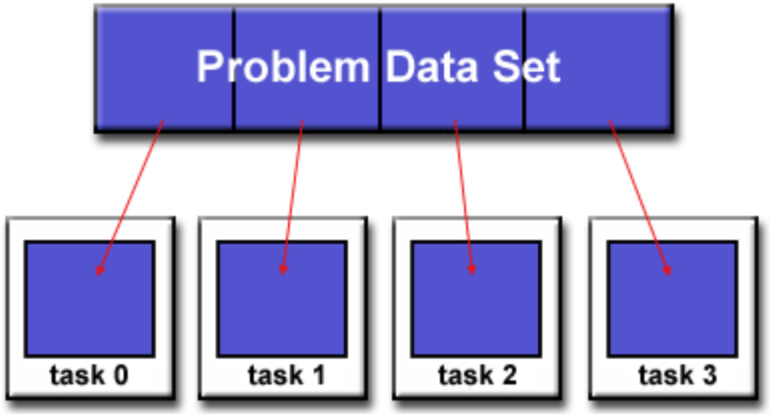

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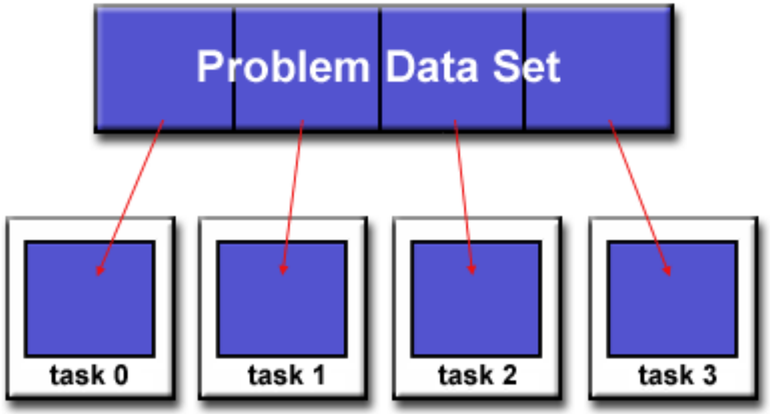
- Functional Decomposition
  - MPMD
  - Independent Tasks
  - Pipelining



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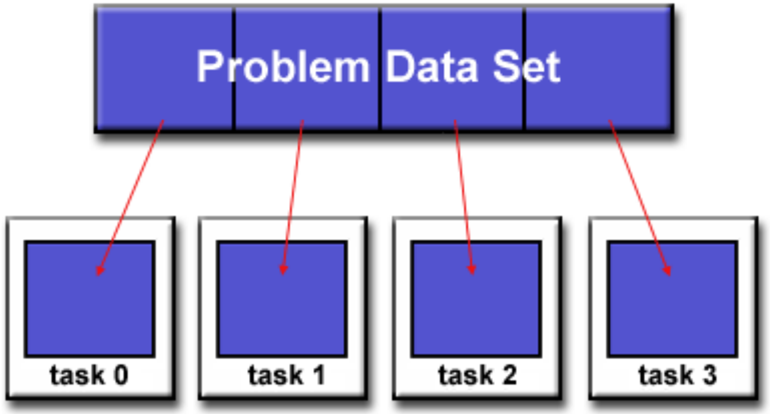

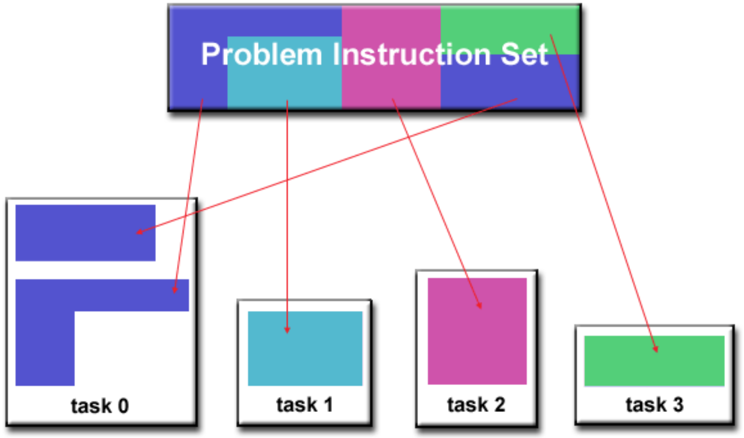

Domain decomposition

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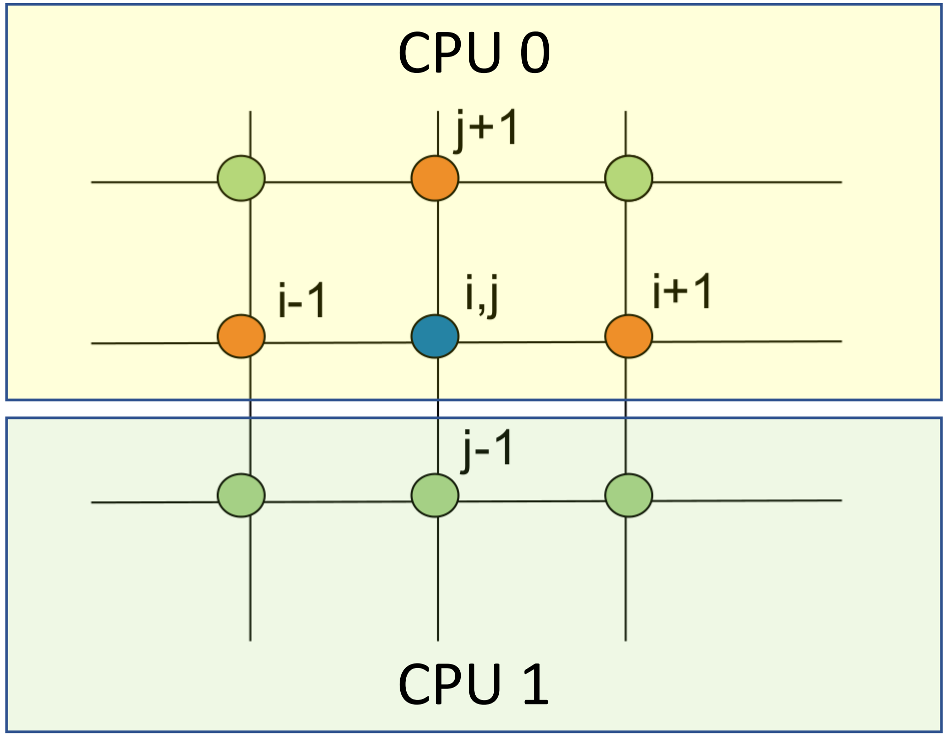

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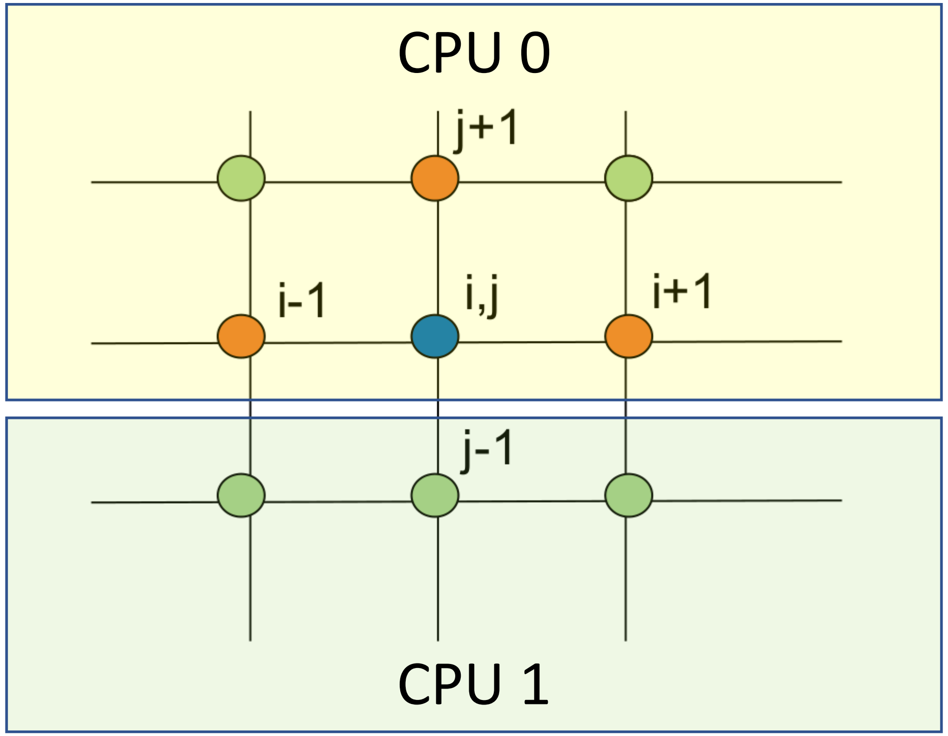

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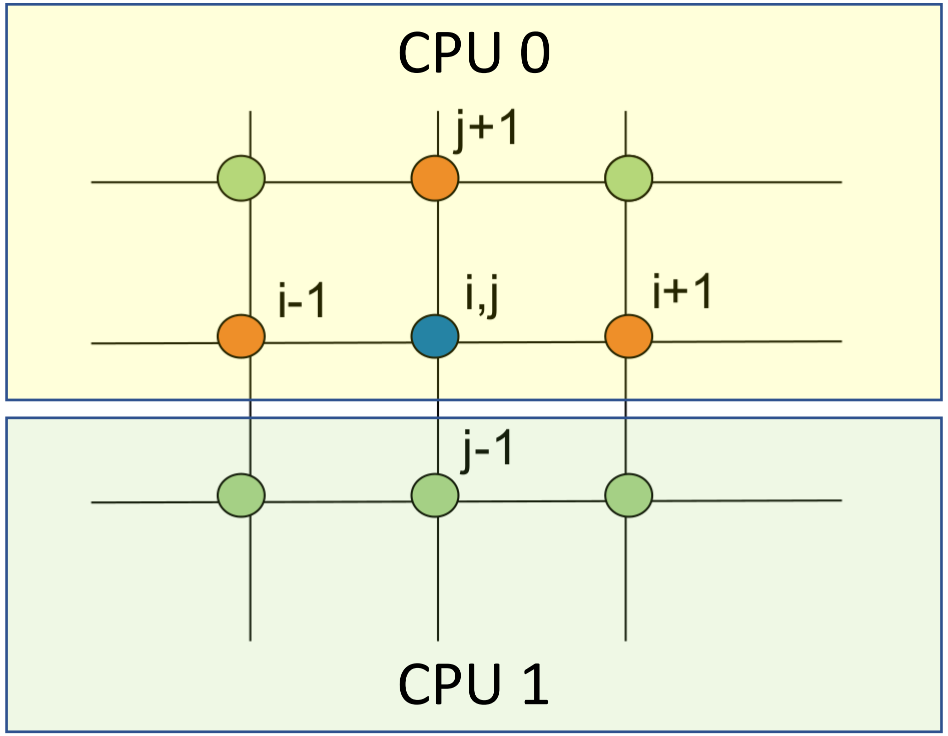

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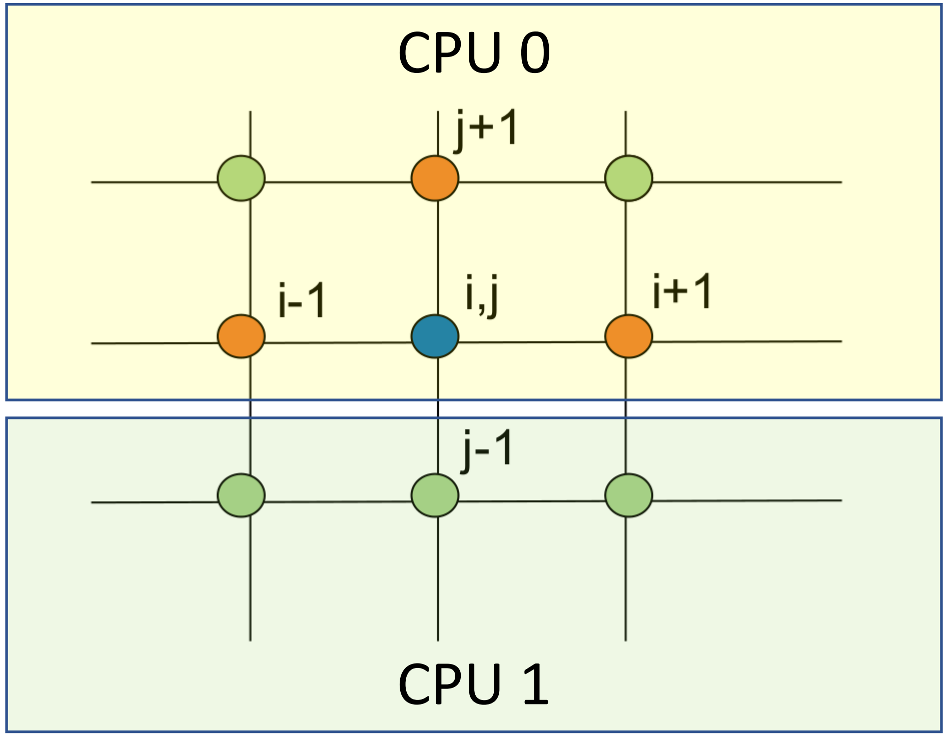

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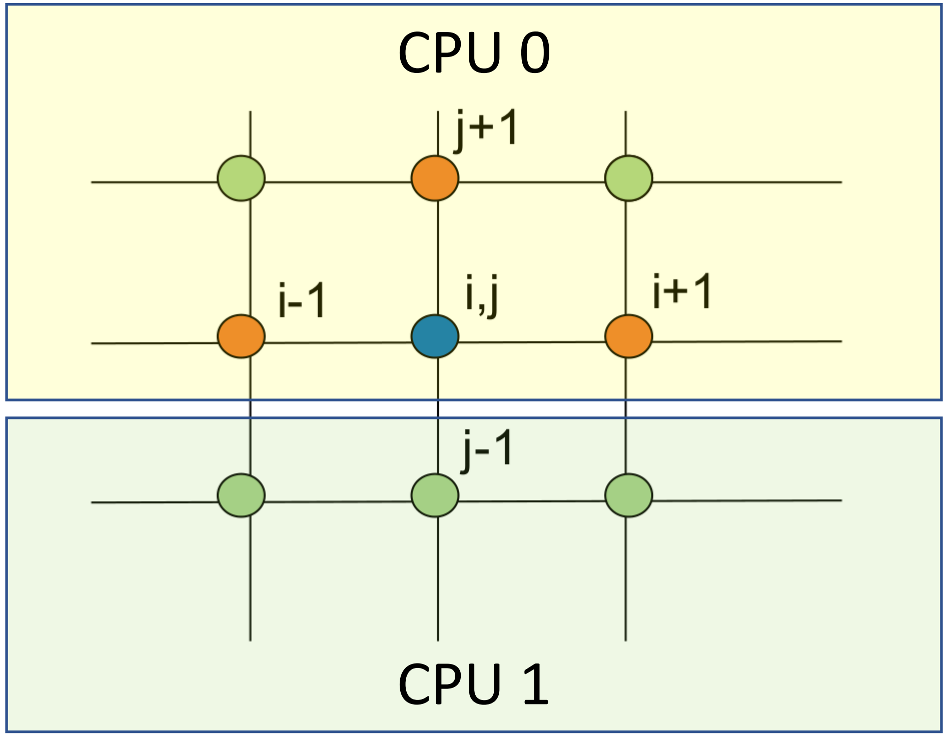

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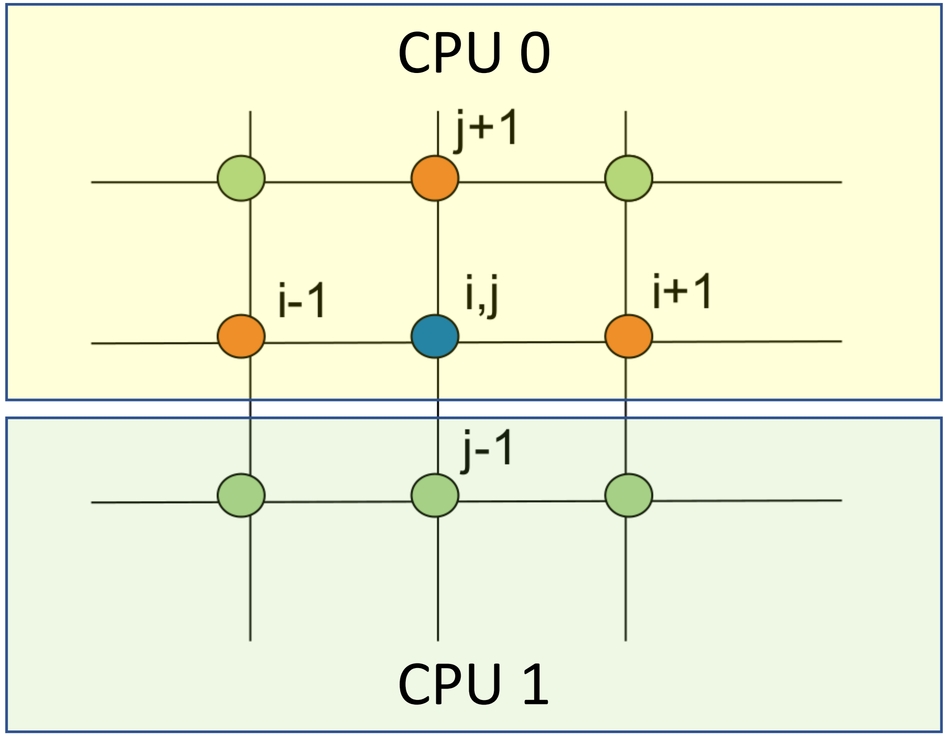

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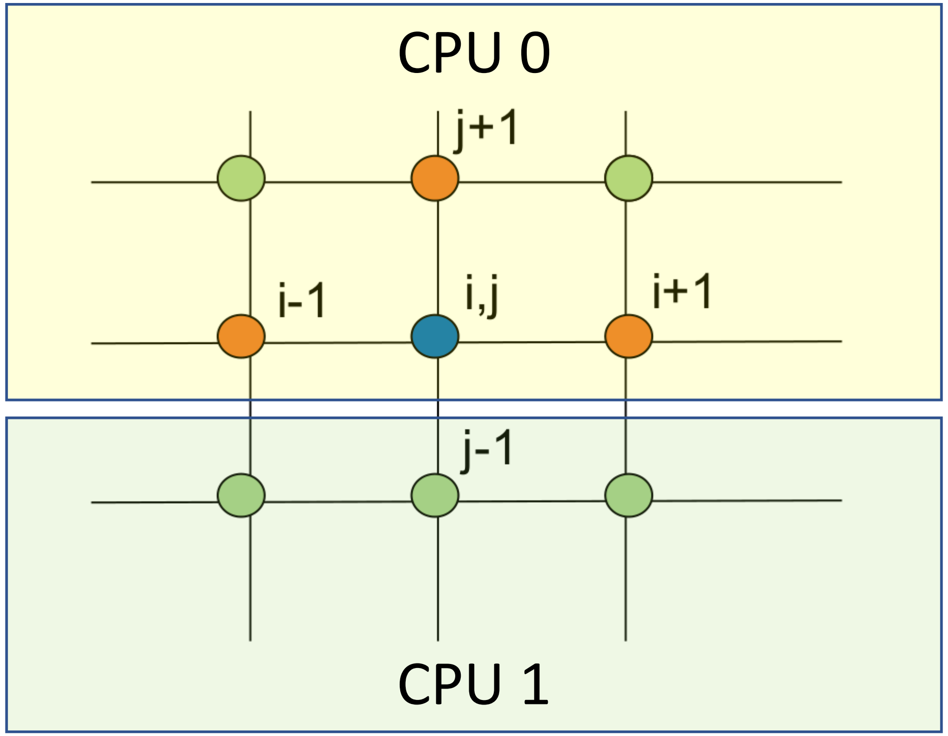

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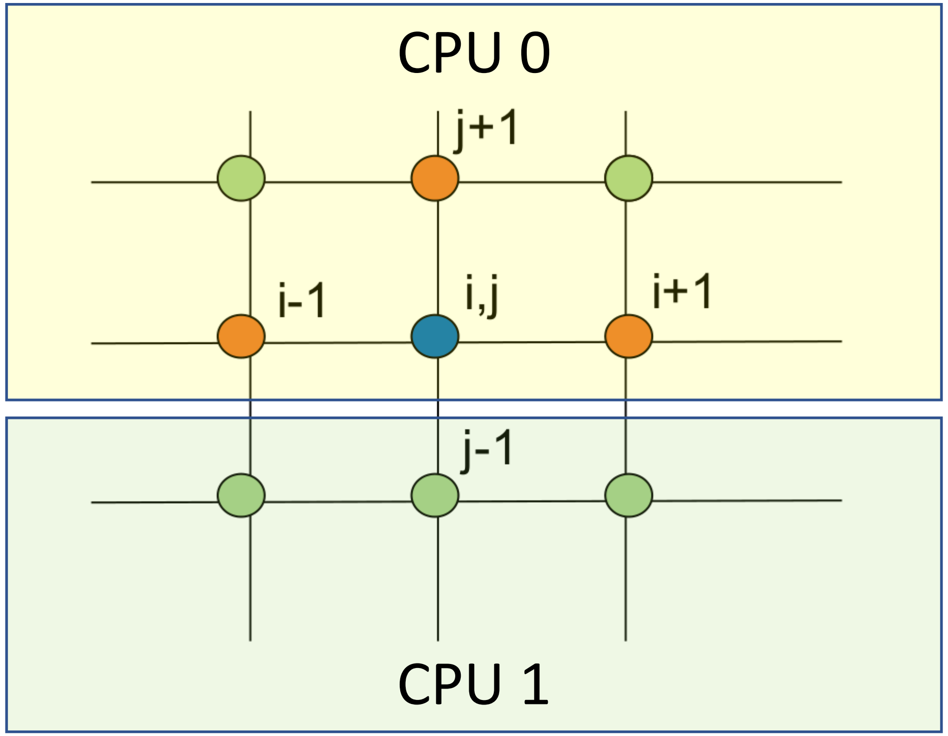

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- *Load Balance*
- Correctness
    - order of reads and writes is non-deterministic
    - synchronization is required to enforce the order
    - *locks, semaphores, barriers, conditionals….*

Load Balancing

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- Slowest task determines performance

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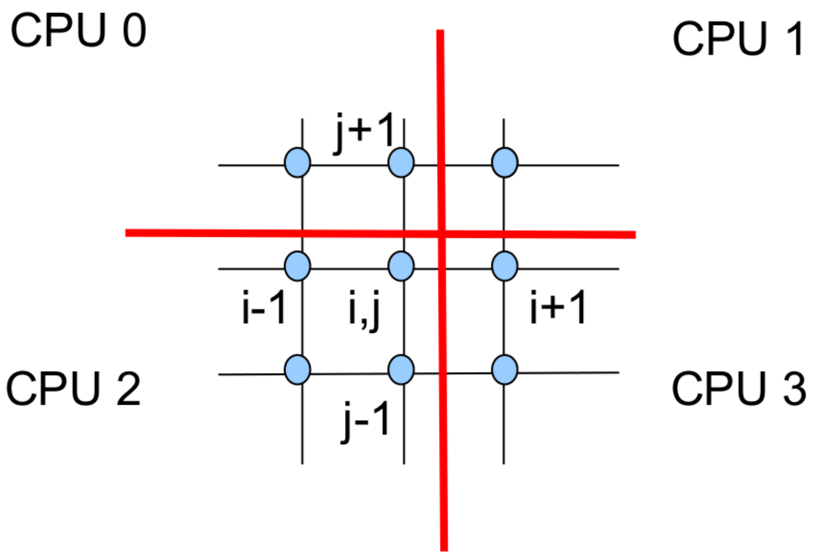

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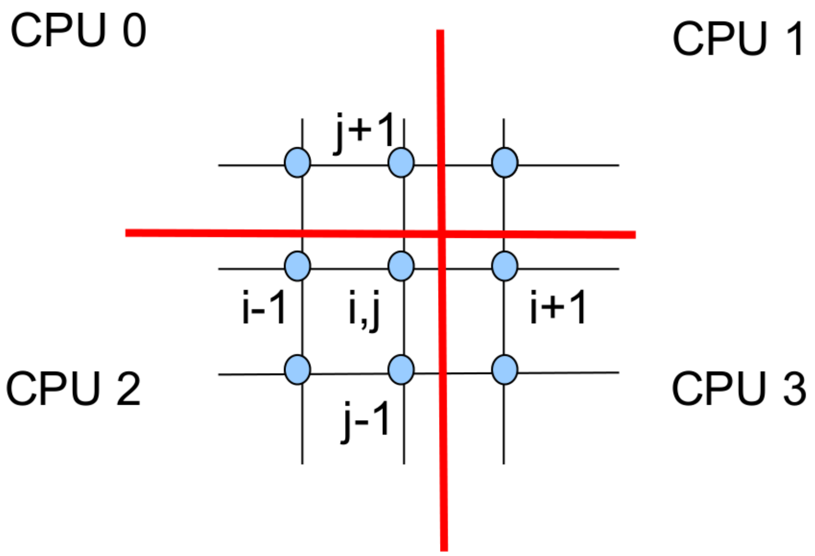

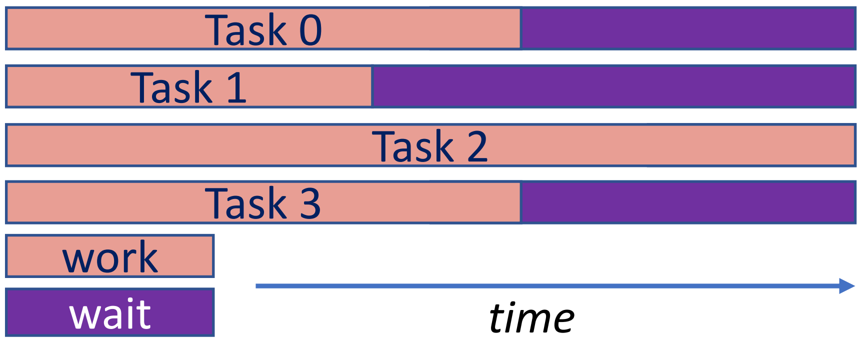

Granularity

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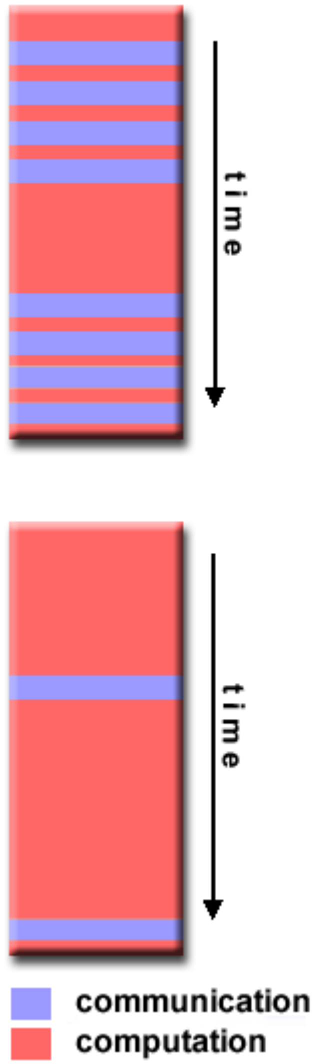
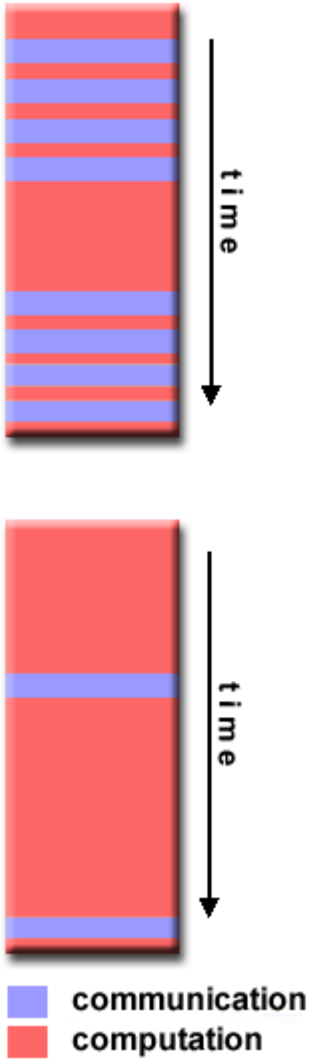


Granularity

$$G = \frac{Computation}{Communication}$$

- Fine-grain parallelism
  - G is small
  - Good load balancing
  - Potentially high overhead
  - Hard to get correct
- Coarse-grain parallelism
  - G is large
  - Load balancing is tough
  - Low overhead
  - Easier to get correct



Performance: Amdahl’s law

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- Speedup is bound by serial component
- Split program serial time ($T_{serial} = 1$) into
  - Ideally parallelizable portion: A
    - assuming perfect load balancing, identical speed, no overheads
  - Cannot be parallelized (serial) portion : $1 - A$
  - Parallel time:

$$\mathrm{T}_{\mathrm{parallel}} = \frac{A}{\#CPUs} + (1 - A)$$

$$Speedup(\#CPUs) = \frac{T_{serial}}{T_{parallel}} = \frac{1}{\frac{A}{\#CPUs} + (1 - A)}$$

Performance: Amdahl’s law

- Speedup is bound by serial component
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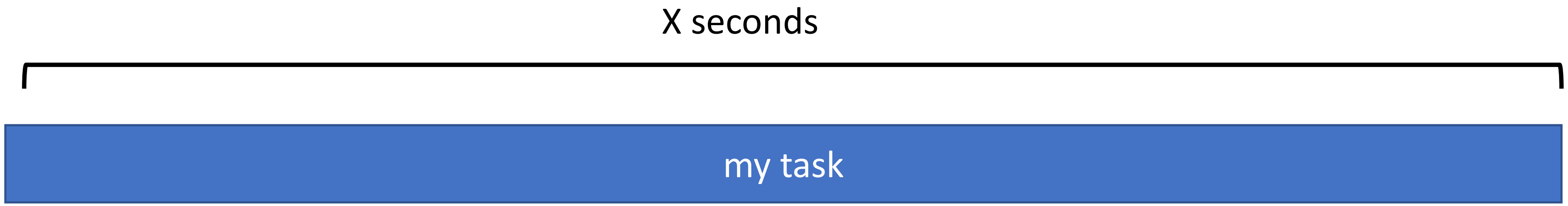
$$Speedup = \frac{\text{serial run time}}{\text{parallel run time}}$$

$_{parallel}$ $\#CPUs$

$$Speedup(\#CPUs) = \frac{T_{serial}}{T_{parallel}} = \frac{1}{\frac{A}{\#CPUs} + (1 - A)}$$

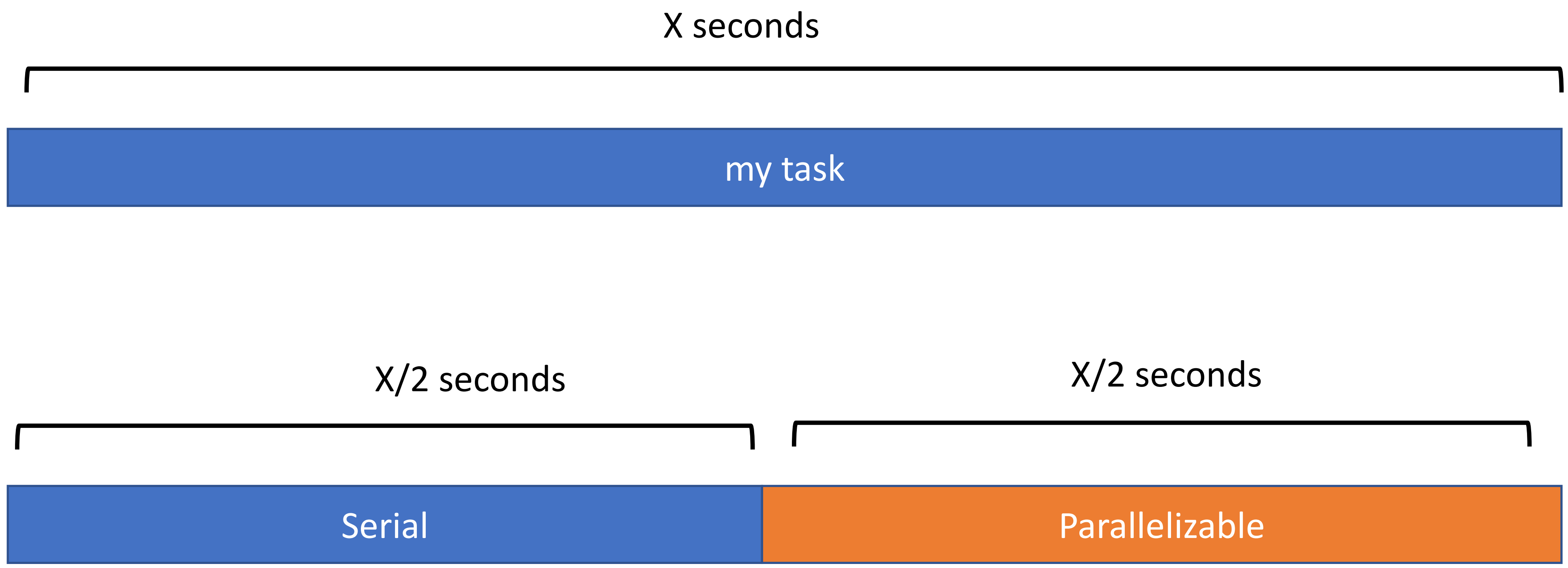
Amdahl’s law



X seconds

my task

Amdahl’s law



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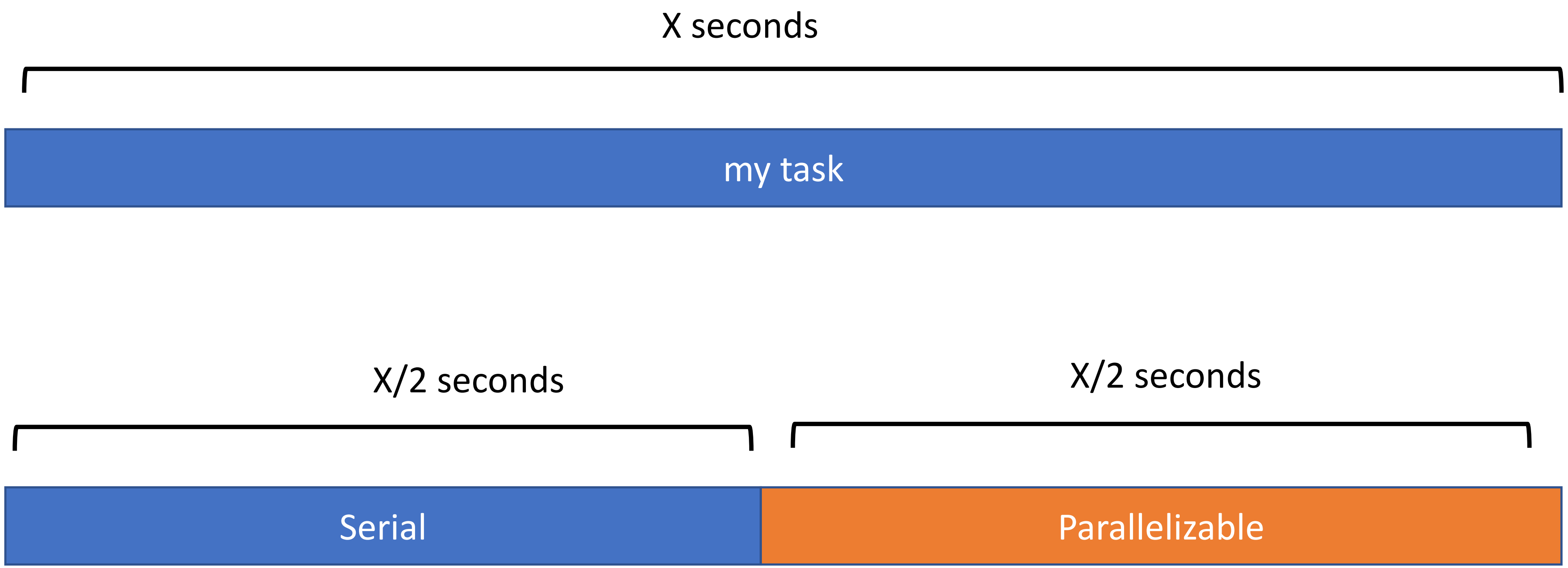
X/2 seconds

X/2 seconds

Serial

Parallelizable

Amdahl’s law



X seconds

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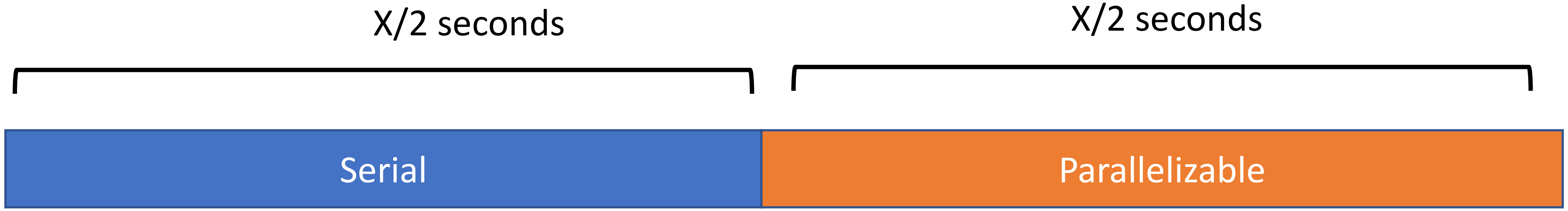
Serial

Parallelizable

What makes something “serial” vs. parallelizable?

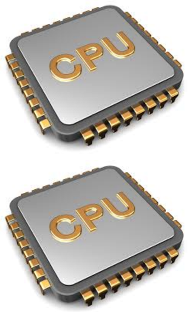
Amdahl’s law

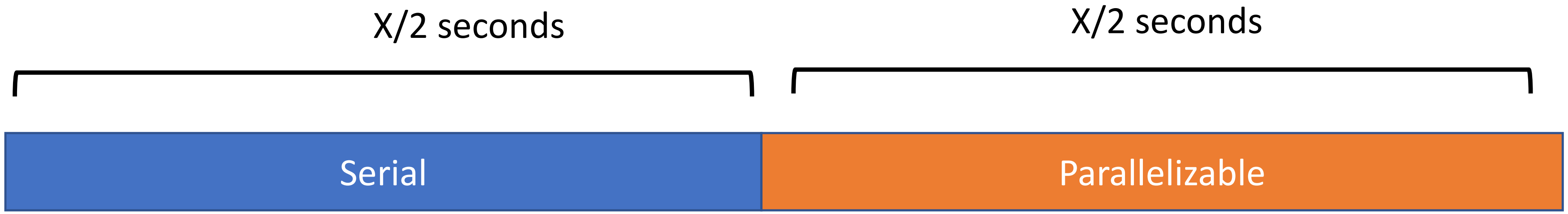


End to end time: X seconds

Amdahl’s law

2 CPUs





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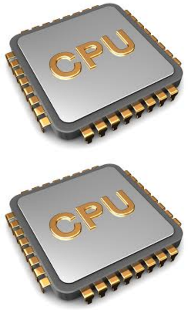

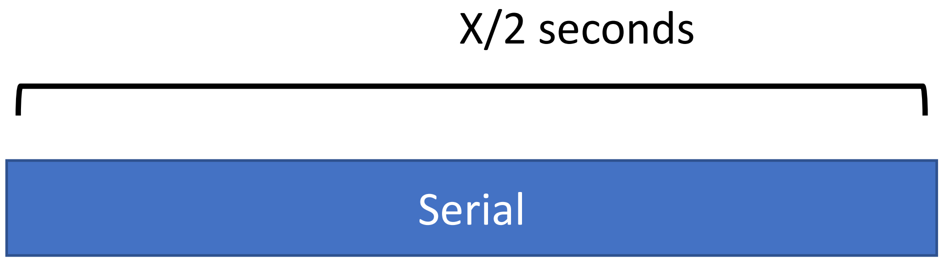

X/2 seconds

Serial

End to end time: X seconds

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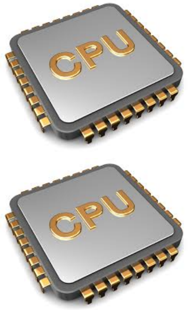

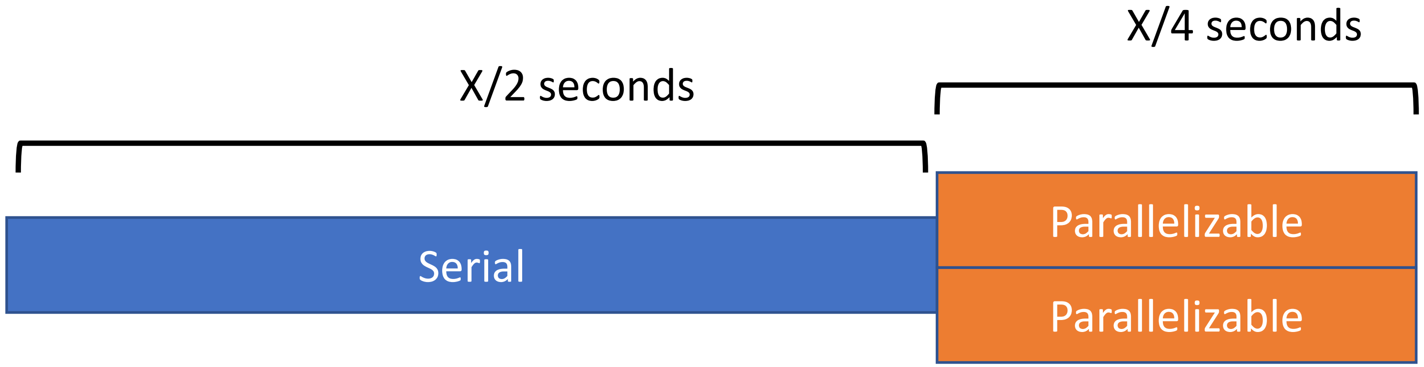

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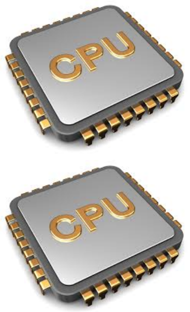

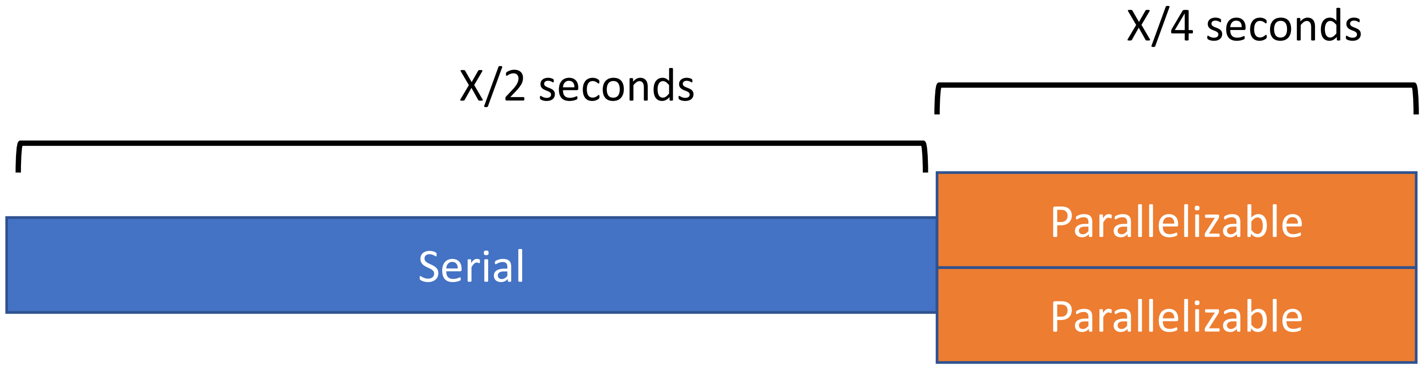

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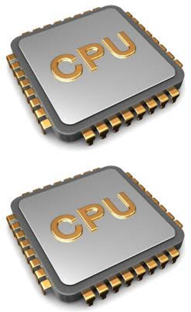
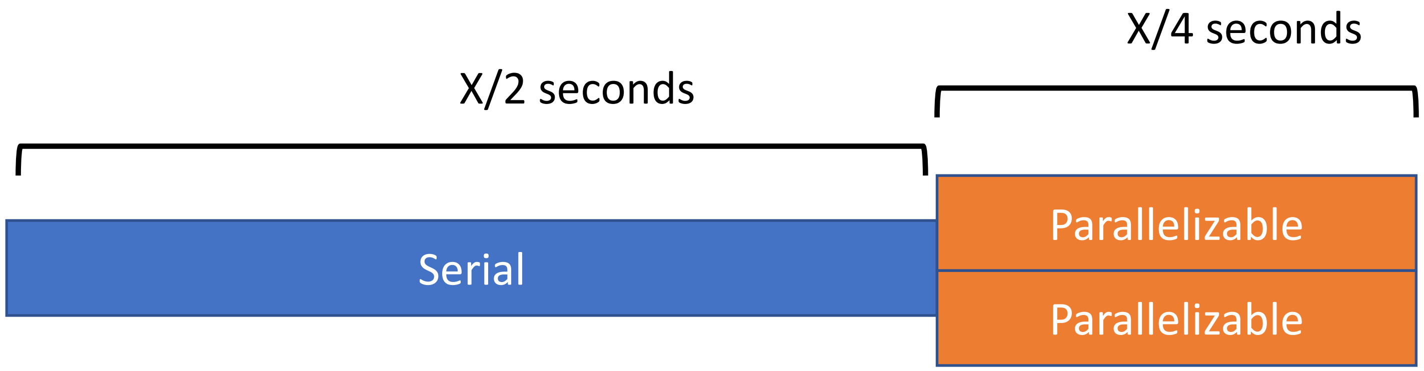




X/4 seconds

X/2 seconds

Serial

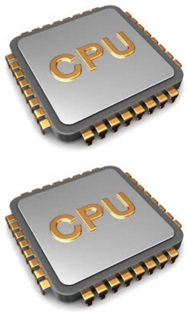
Parallelizable

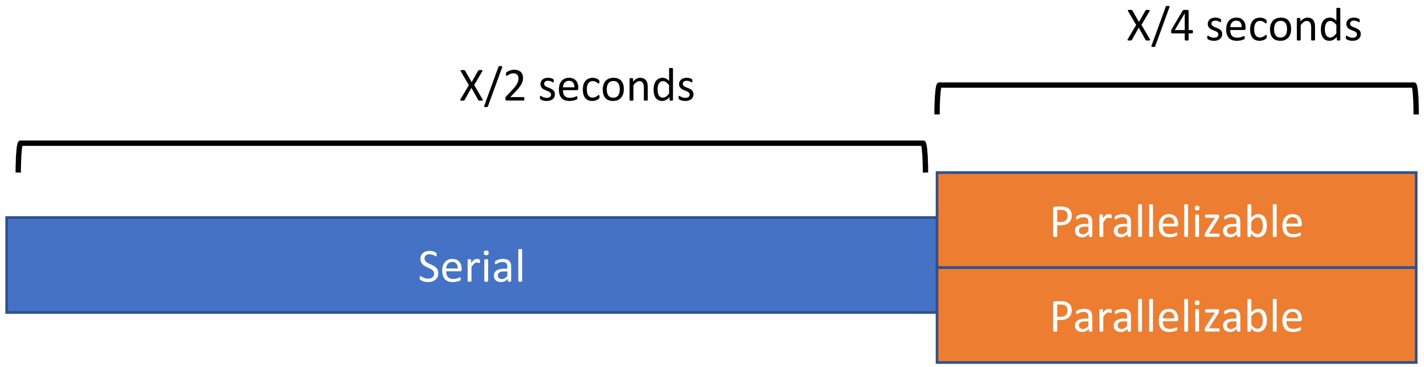
Parallelizable

End to end time: (X/2 + X/4) = (3/4)X seconds

Amdahl’s law

2 CPUs





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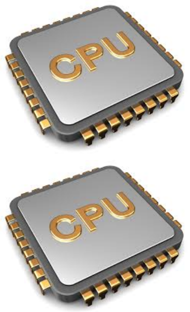
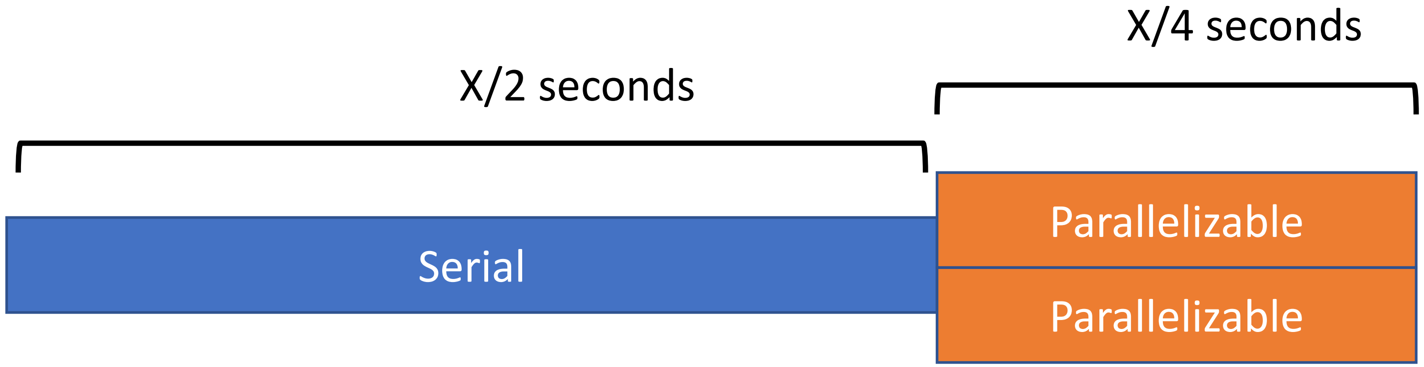
What is the “speedup” in this case?

Amdahl’s law

2 CPUs





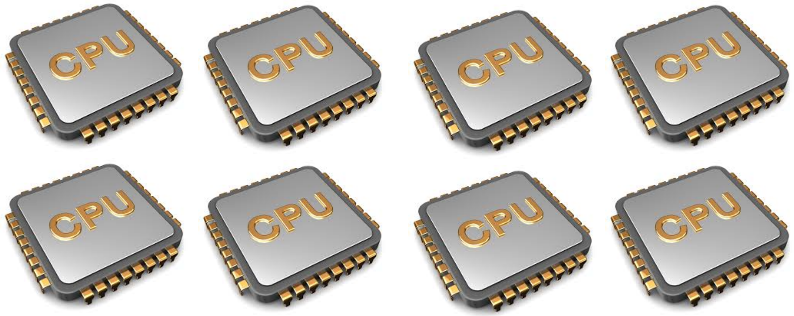
End to end time: (X/2 + X/4) = (3/4)X seconds

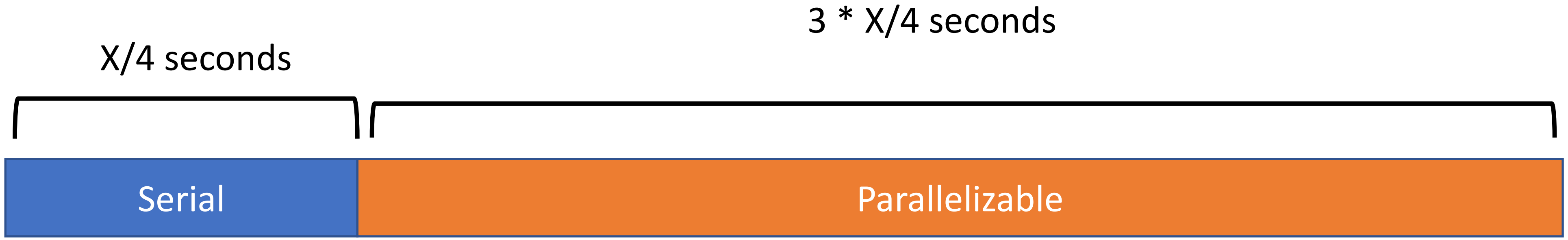
What is the “speedup” in this case?

$$Speedup = \frac{\text{serial run time}}{\text{parallel run time}} = \frac{1}{\frac{A}{\#CPUs} + (1 - A)} = \frac{1}{\frac{.5}{2\text{ cpus}} + (1\text{-}.5)} = 1.333$$

Speedup exercise

8 CPUs





3 * X/4 seconds

X/4 seconds

Serial

Parallelizable

End to end time: X seconds

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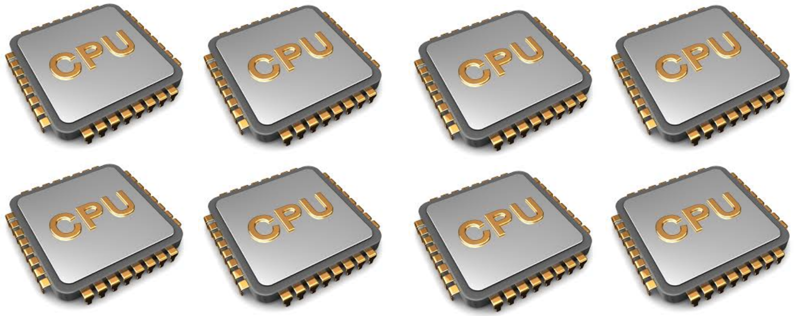

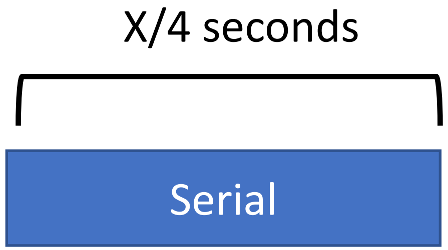

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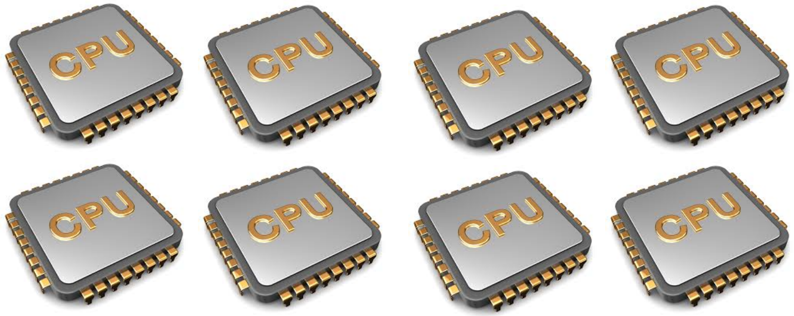
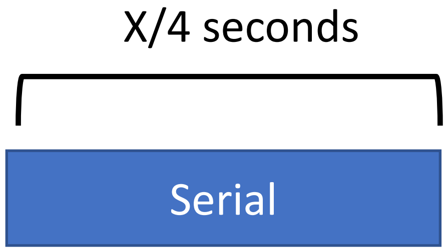
Speedup exercise

8 CPUs

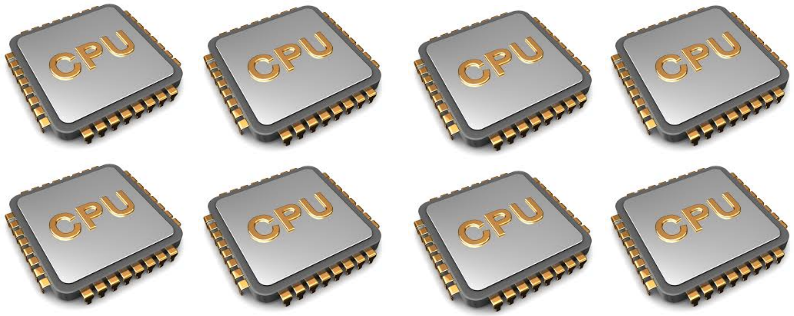




X/4 seconds

Serial

Speedup exercise



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X/4 seconds

Serial

What is the “speedup” in this case?

Speedup exercise

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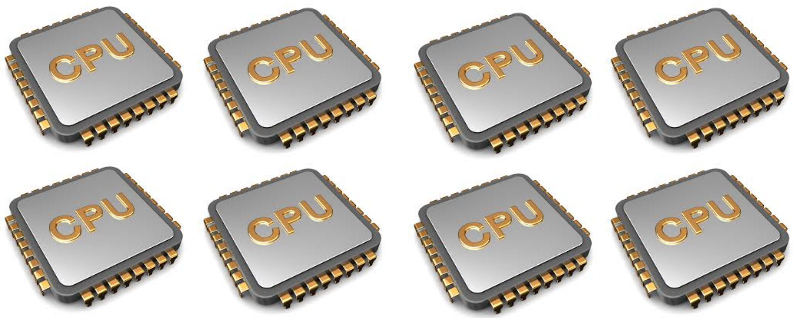

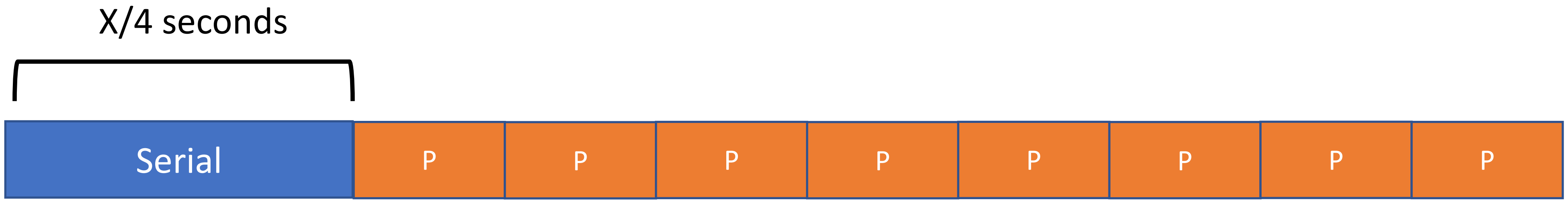
X/4 seconds

Serial

P P P P P P P P

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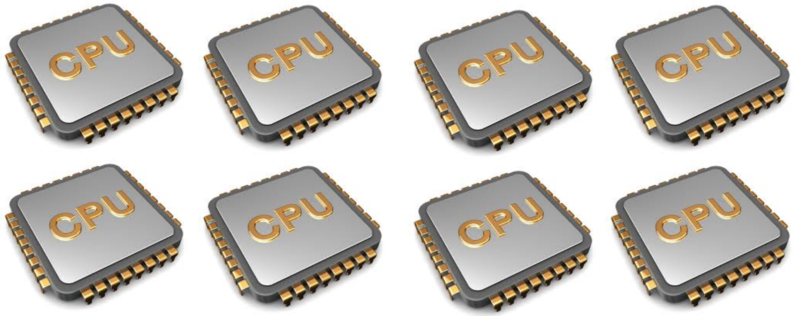

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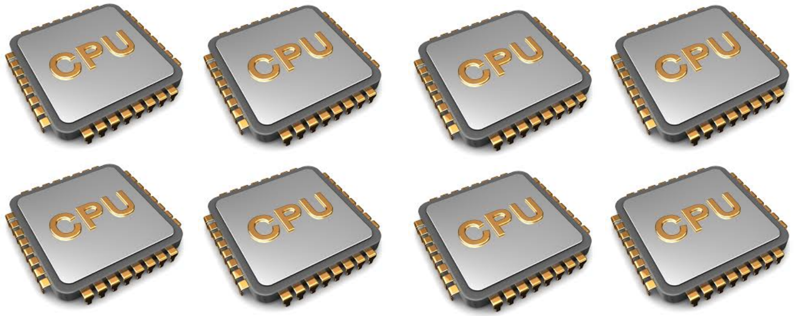

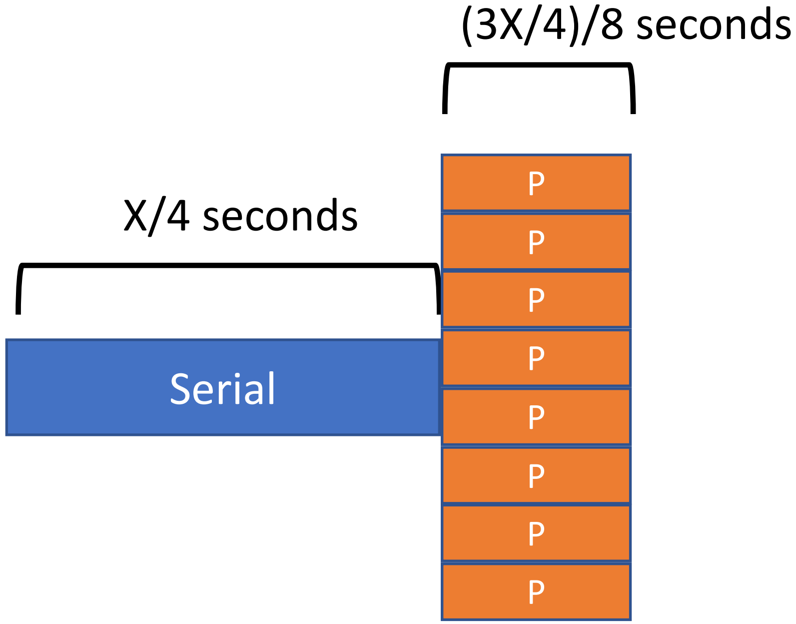

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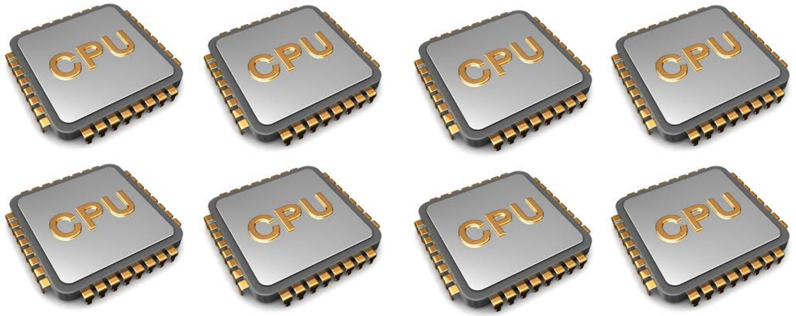
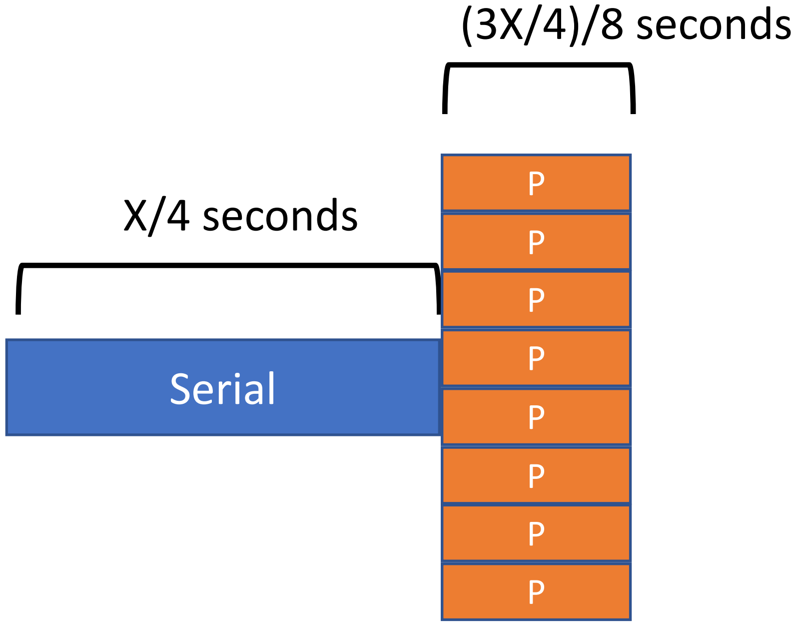
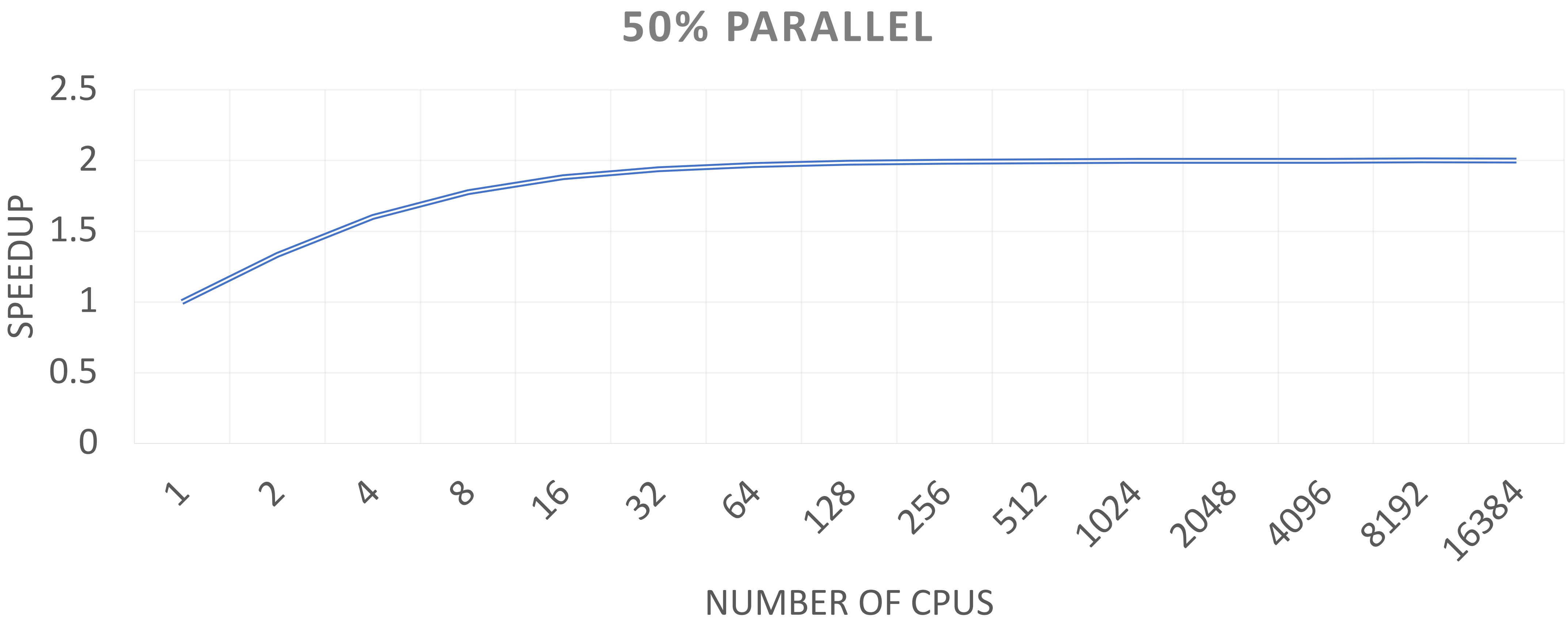




What is the "speedup" in this case?

$$Speedup = \frac{\text{serial run time}}{\text{parallel run time}} = \frac{1}{\frac{A}{\#CPUs} + (1 - A)} = \frac{1}{.75/8 + (1-.75)} = 2.91\text{x}$$

Amdahl Action Zone



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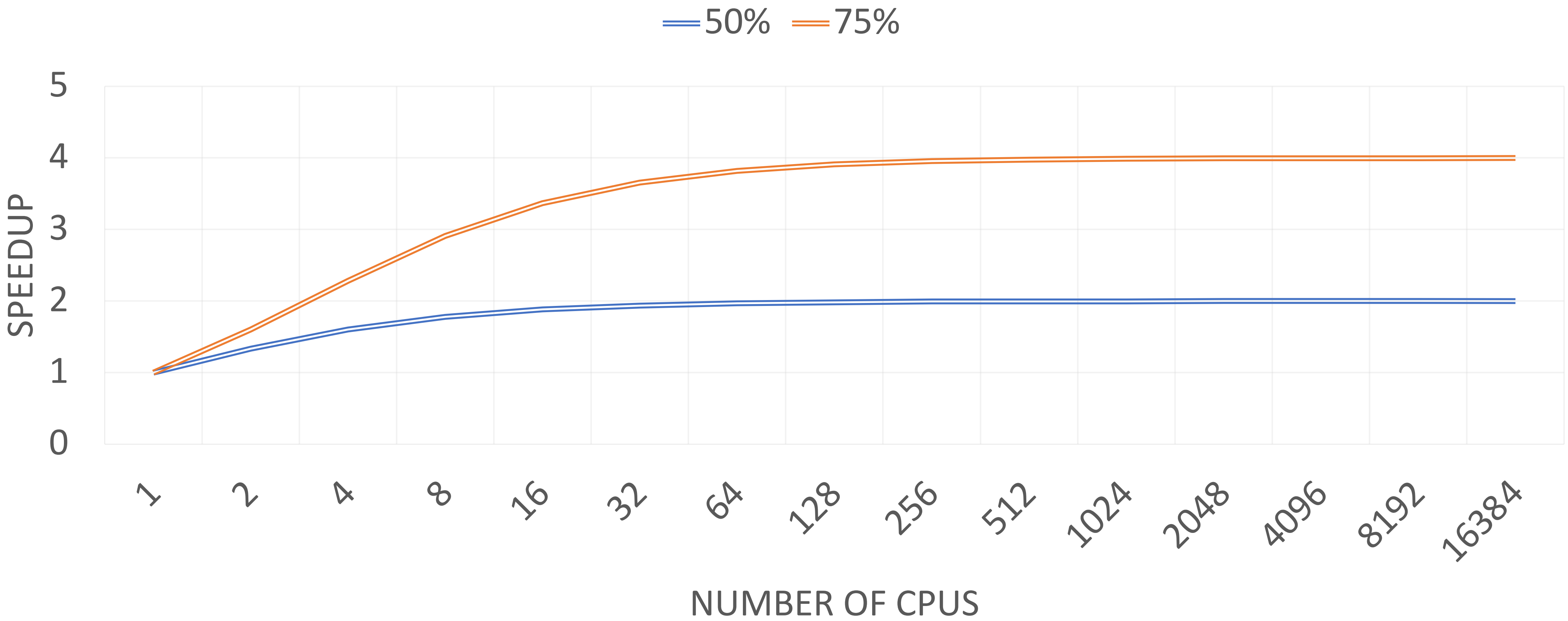

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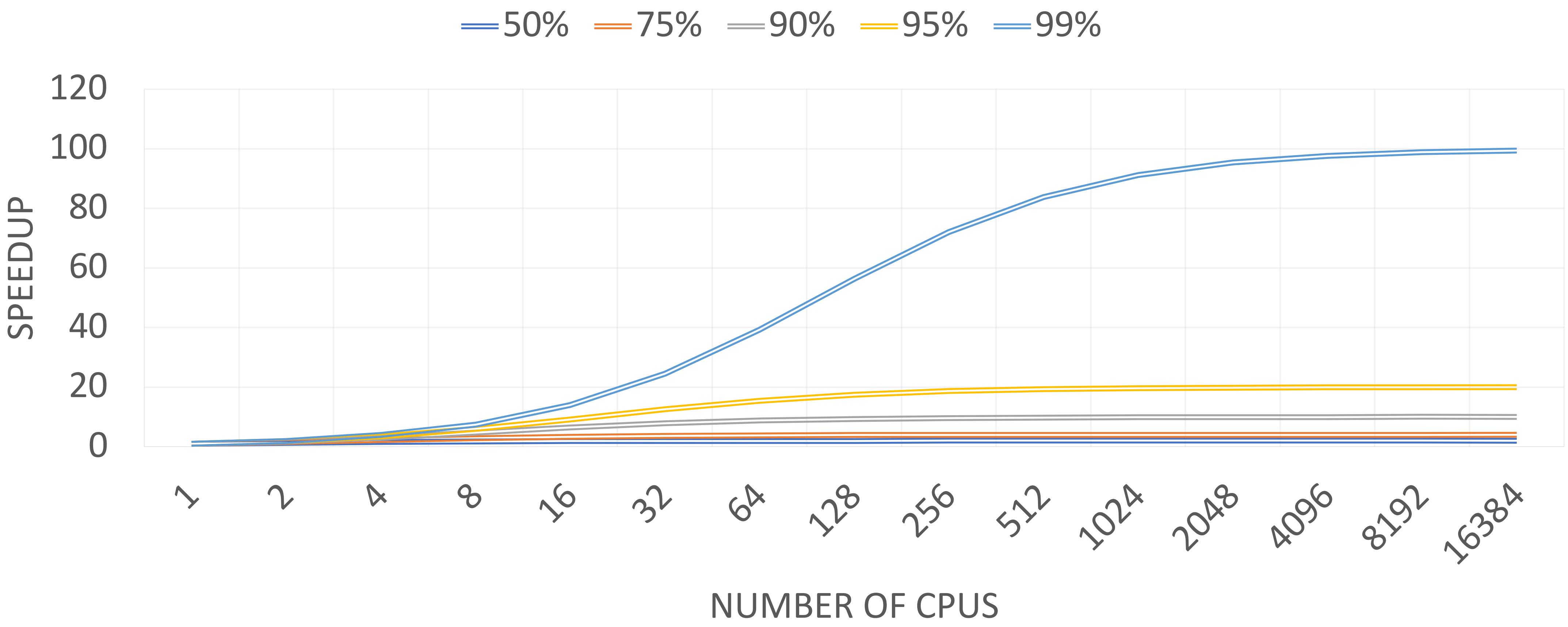

Strong Scaling vs Weak Scaling

Amdahl vs. Gustafson

Strong Scaling vs Weak Scaling

Amdahl vs. Gustafson

Strong Scaling vs Weak Scaling

Amdahl vs. Gustafson

- $N = \#CPUs,\ S = serial\ portion = 1 - A$
- Amdahl's law: $Speedup(N) = \frac{1}{\frac{A}{N}+S}$
  - **Strong scaling:** $Speedup(N)$ calculated given total amount of work is fixed
  - Solve same problems faster when problem size is fixed and #CPU grows
  - Assuming parallel portion is fixed, speedup soon seizes to increase

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- Gustafson's law: *Speedup(N)* = S + (S-1)*N
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  - **Consequence:** speedup upper bound is much higher

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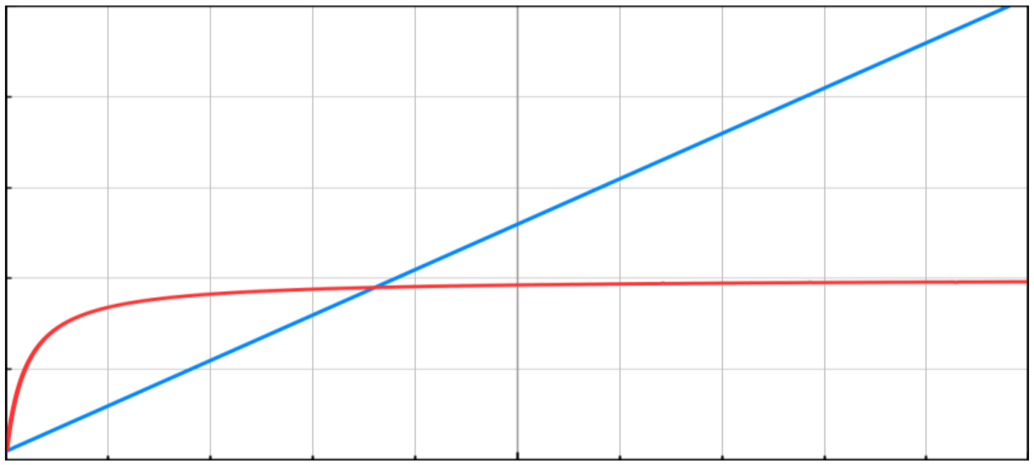

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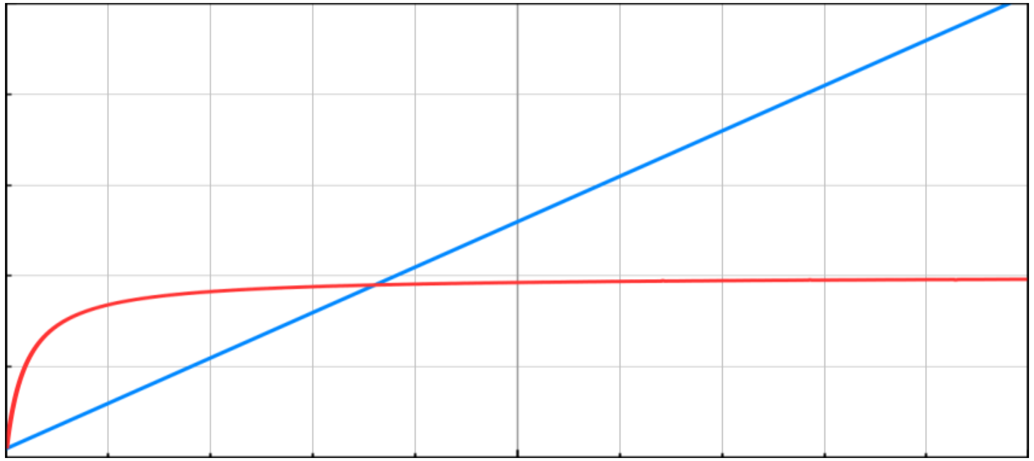

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When is Gustavson's law a better metric?
When is Amdahl's law a better metric?

Super-linear speedup

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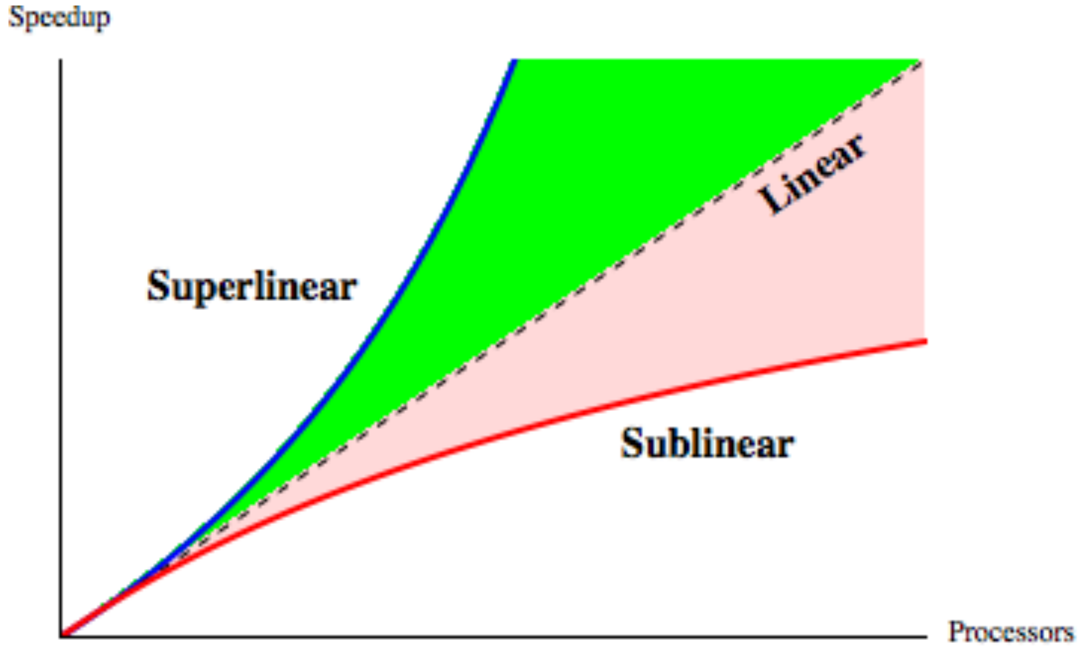

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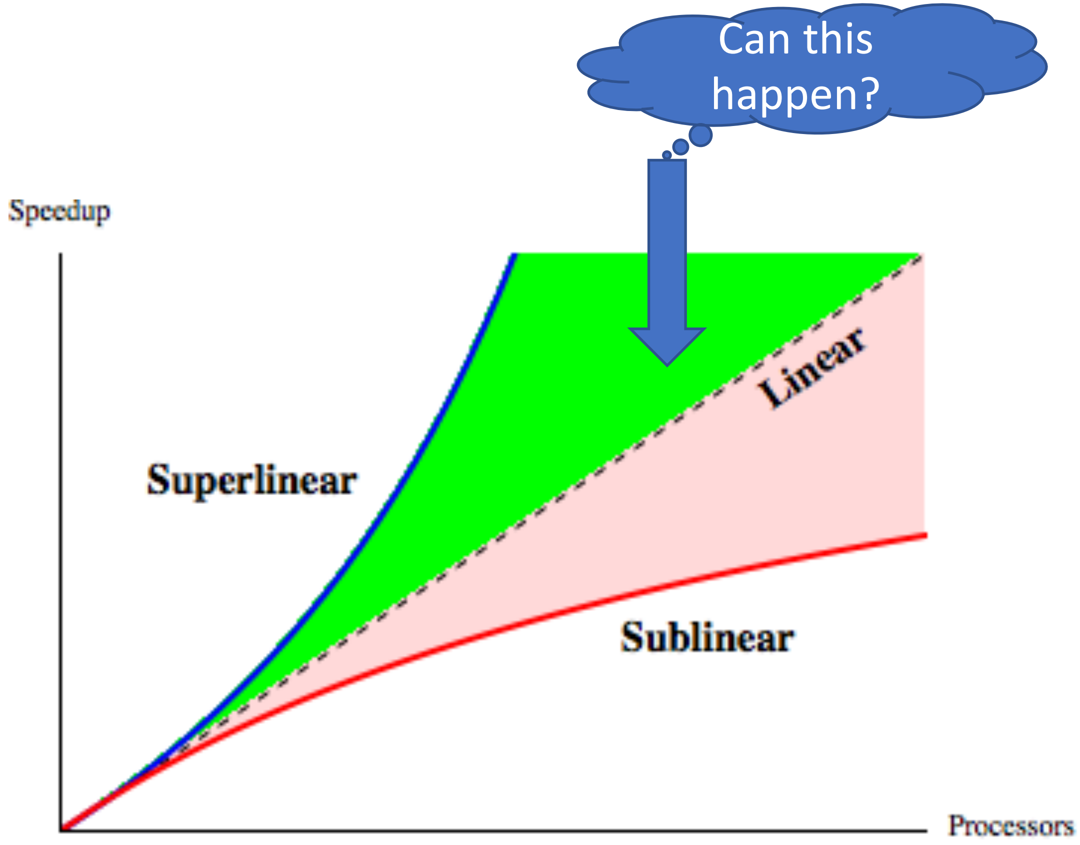

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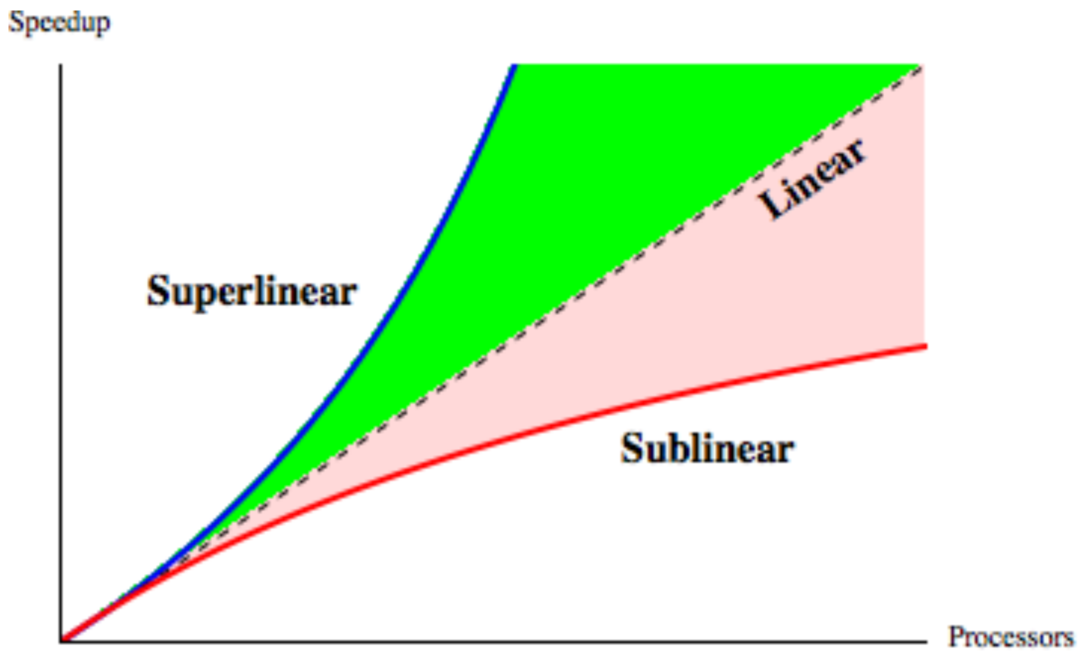
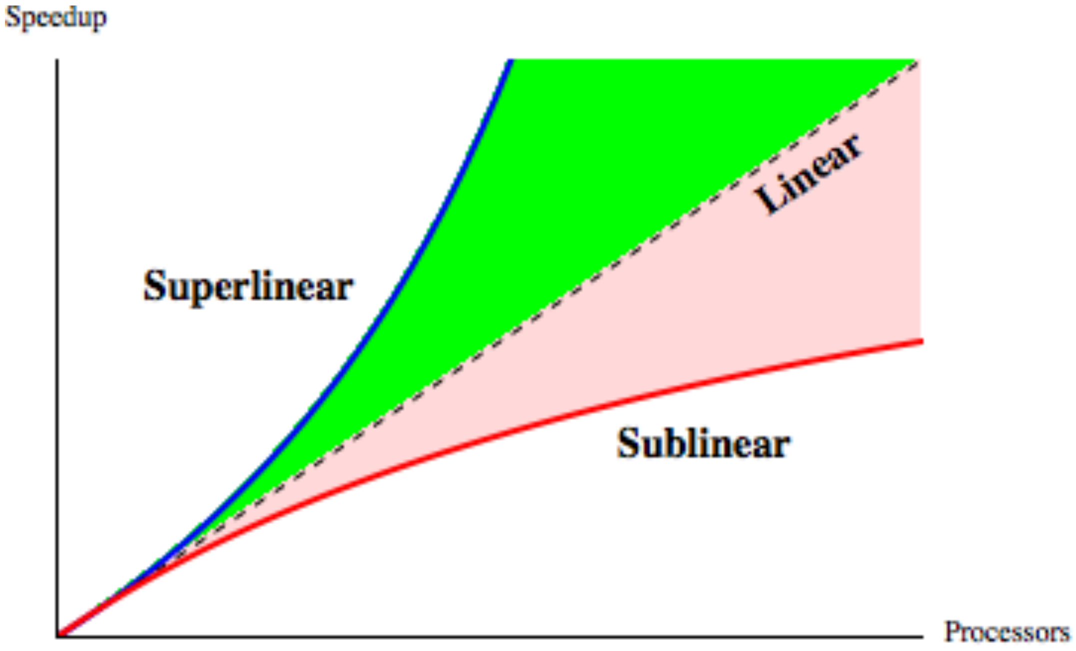


Super-linear speedup

- Possible due to cache



Super-linear speedup

- Possible due to cache
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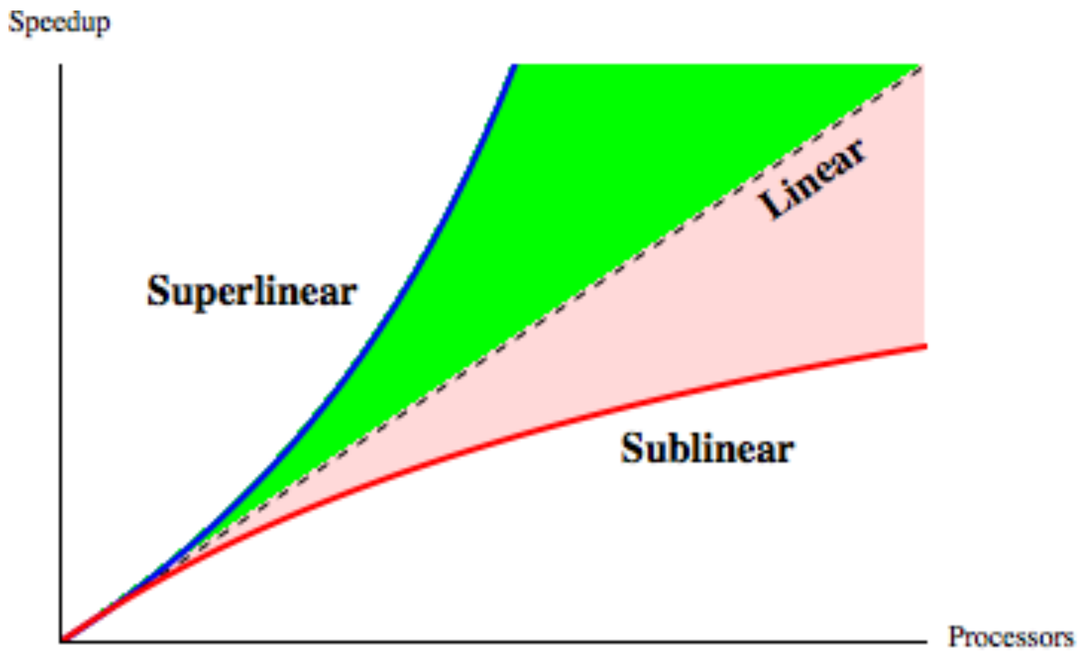
- Baseline: ***best*** serial algorithm



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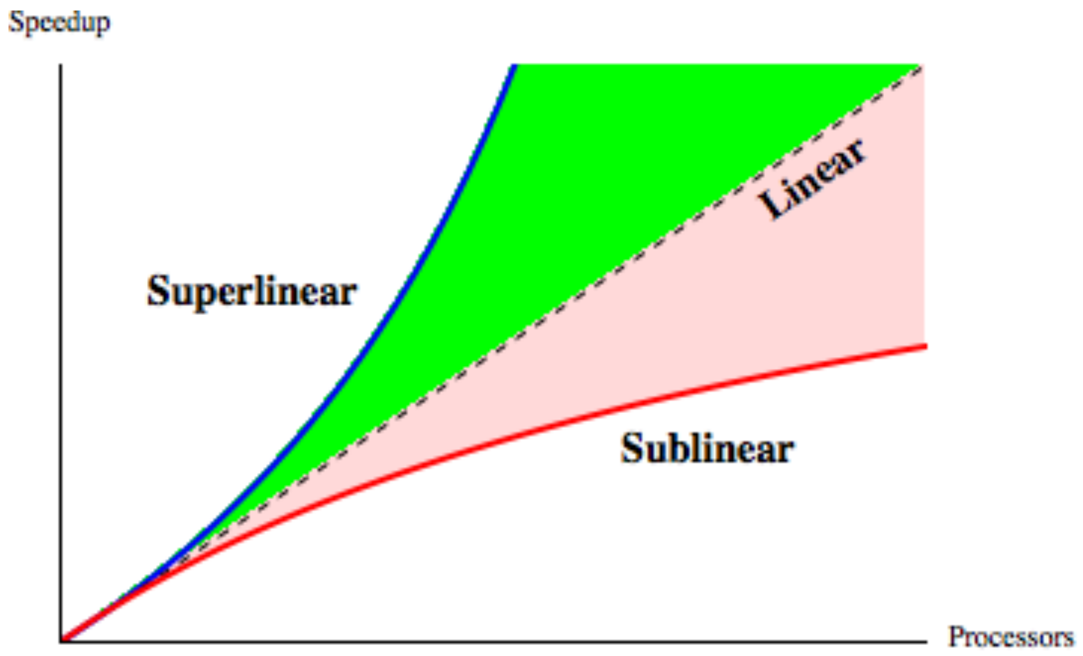

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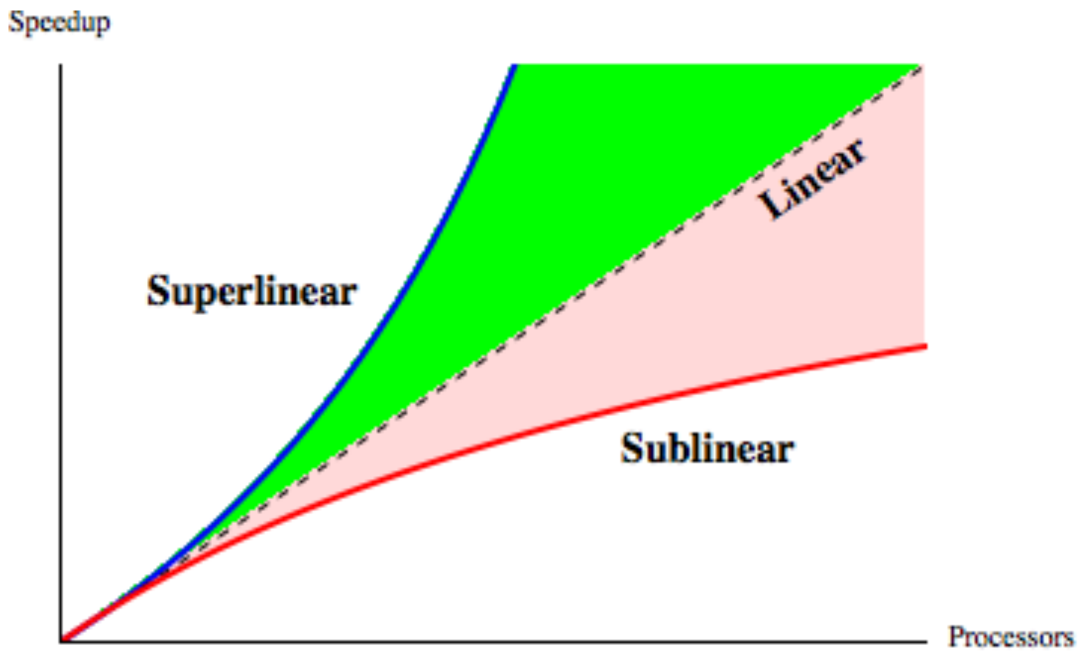
Efficient **bubble sort**



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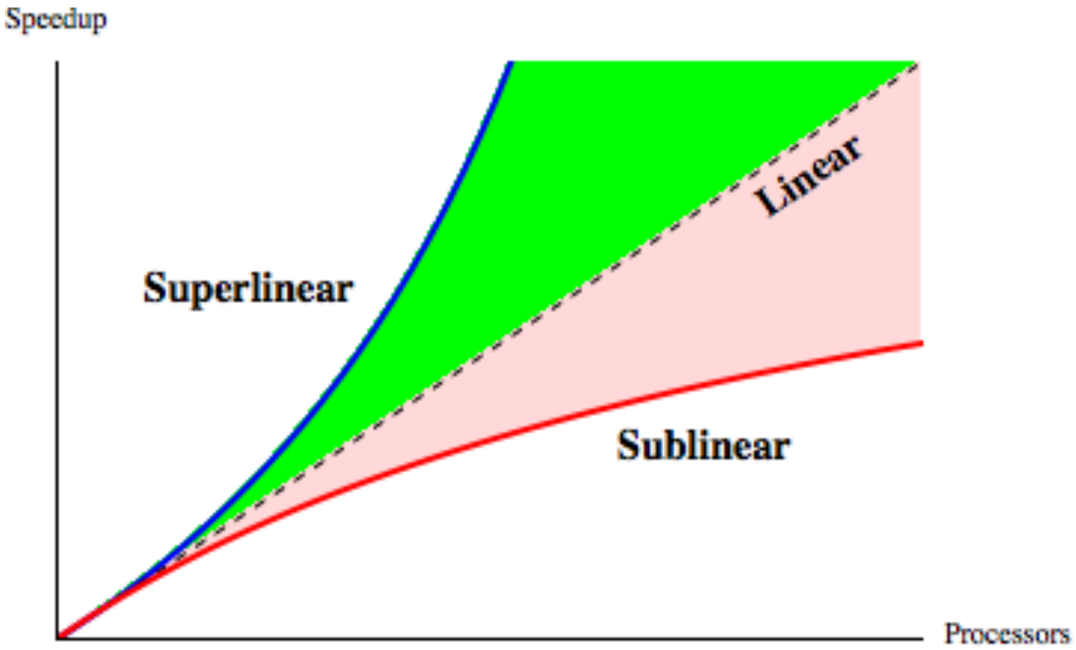
Efficient **bubble sort**
•*Serial: 150s*



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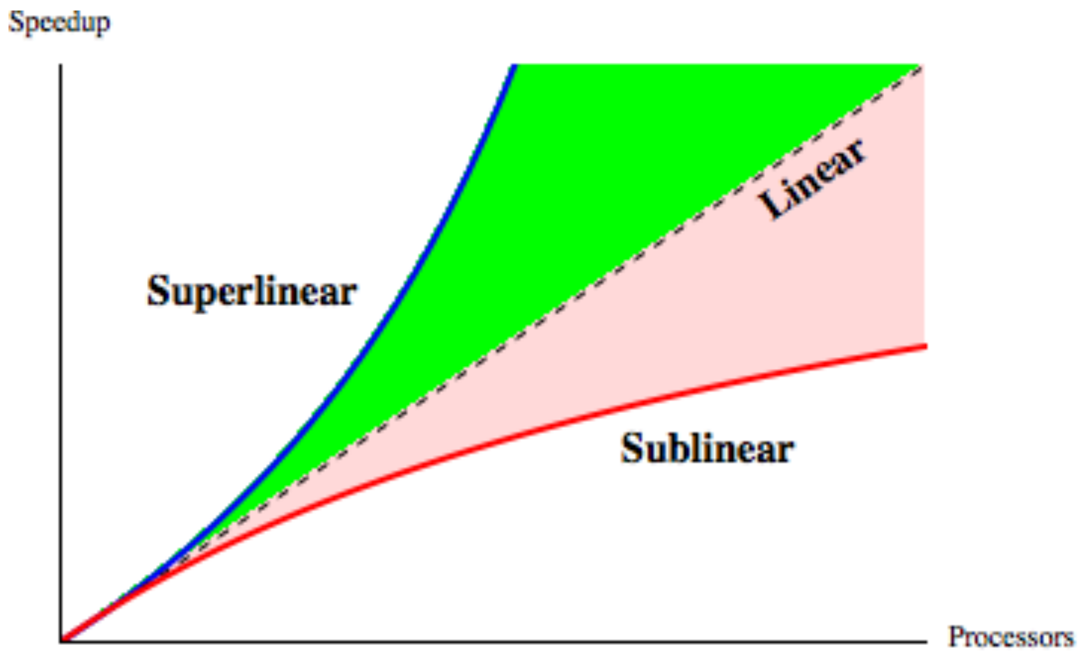
Efficient **bubble sort**
•*Serial: 150s*
•*Parallel 40s*



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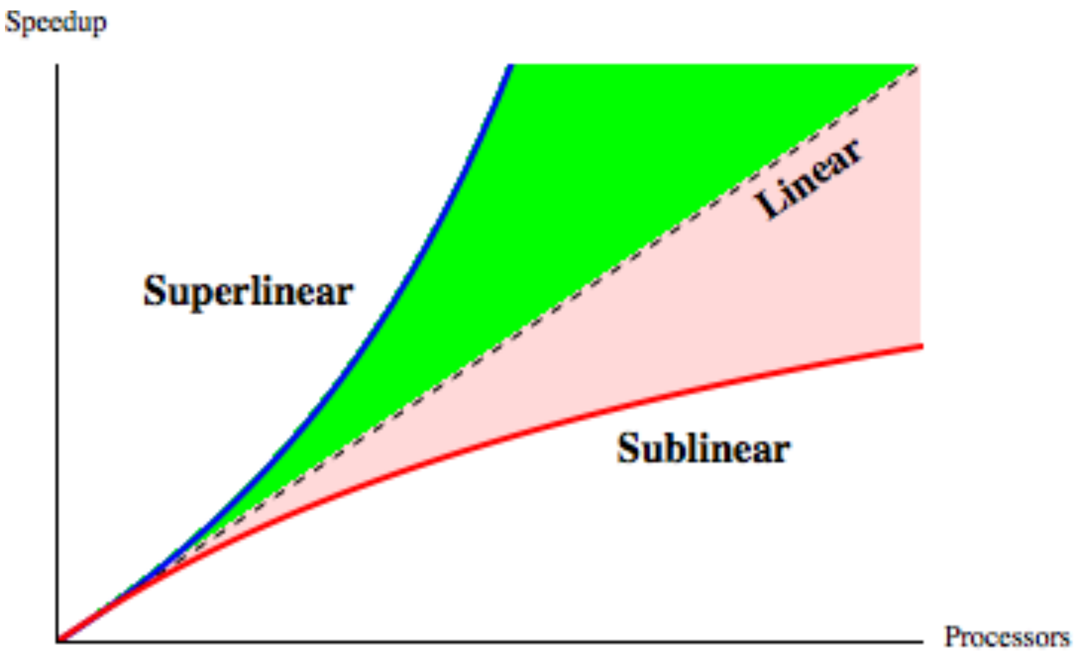

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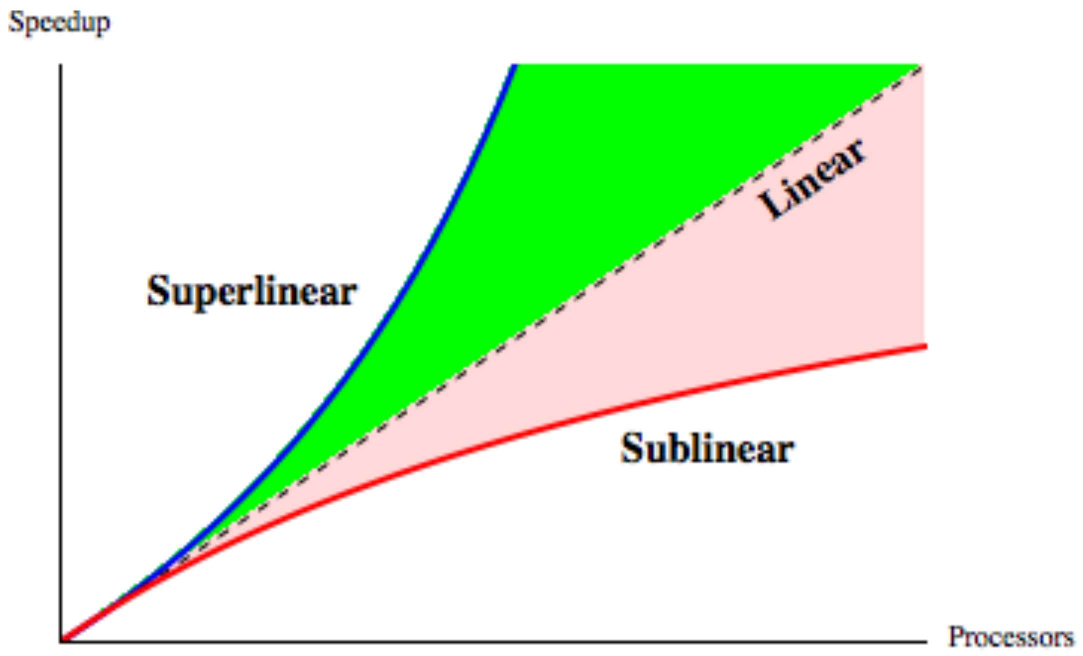
$$\frac{150}{40} = 3.75\ ?$$



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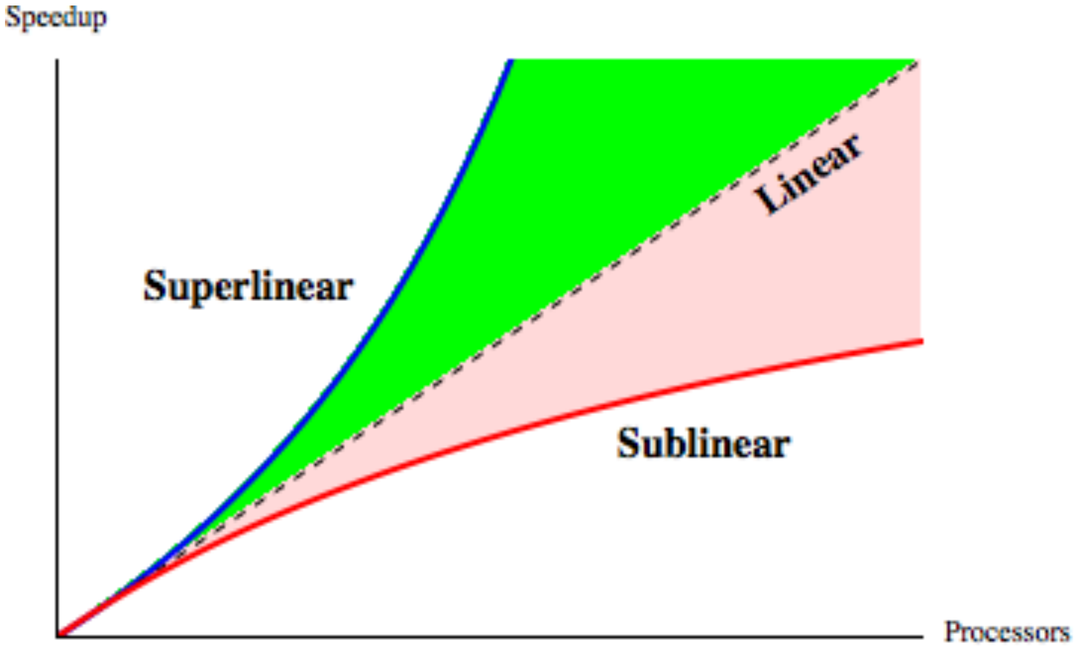

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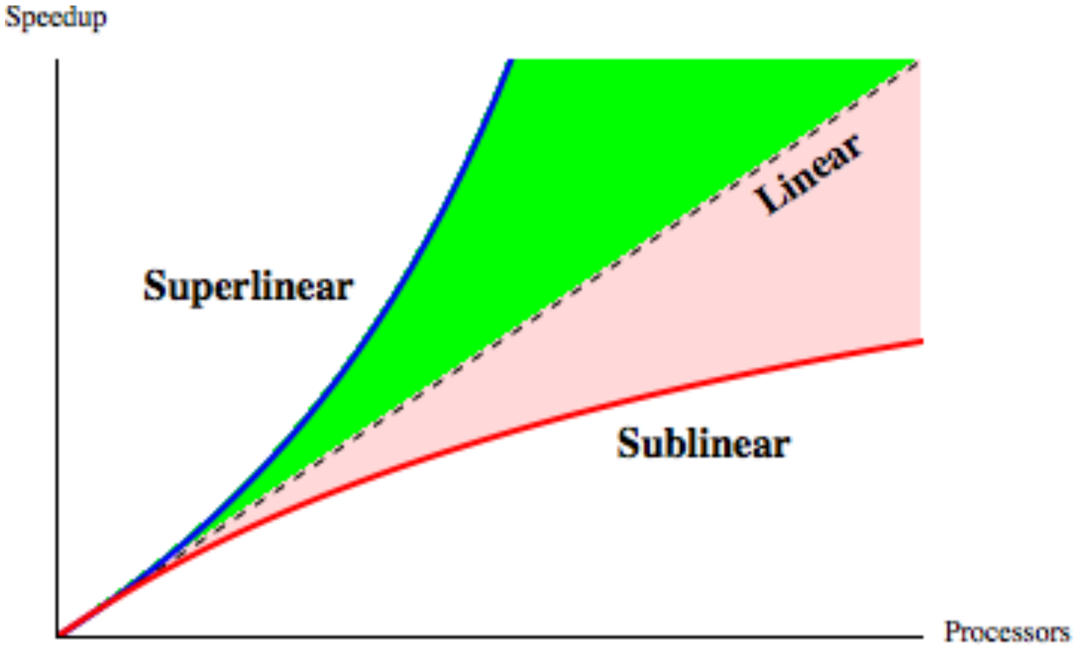

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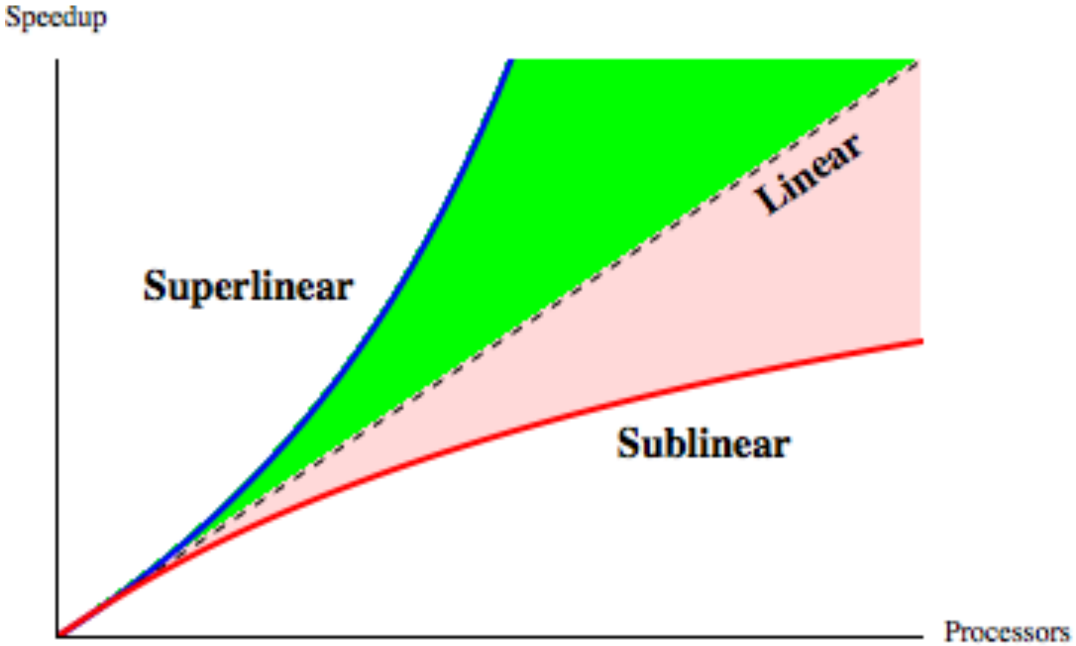
•*Serial quicksort: 30s*
•*Speedup = 30/40 = 0.75X*



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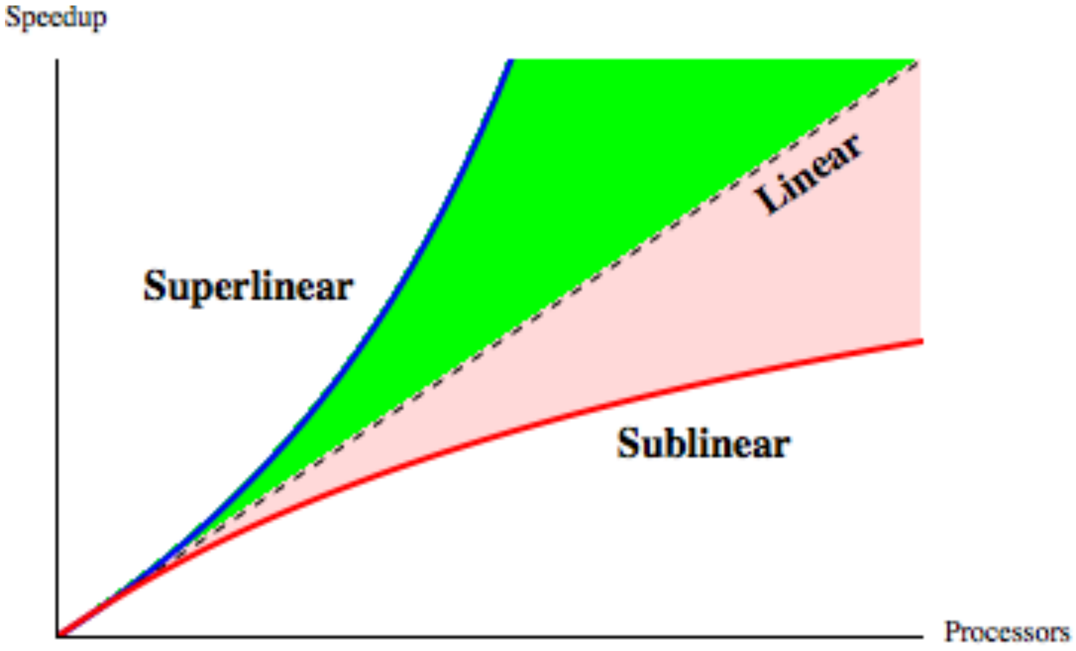

Why insist on best serial algorithm as baseline?

Concurrency and Correctness

If two threads execute this program concurrently, how many different final values of X are there?

Initially, X == 0.

Thread 1

```
void increment() {
    int temp = X;
    temp = temp + 1;
    X = temp;
}
```

Thread 2

```
void increment() {
    int temp = X;
    temp = temp + 1;
    X = temp;
}
```

Answer:

- **A. 0**
- **B. 1**
- **C. 2**
- **D. More than 2**

Schedules/Interleavings

Model of concurrent execution

- Interleave statements from each thread into a single thread
- If **any** interleaving yields incorrect results, synchronization is needed

Thread 1

```
tmp1 = X;
tmp1 = tmp1 + 1;
X = tmp1;
```

Thread 2

```
tmp2 = X;
tmp2 = tmp2 + 1;
X = tmp2;
```

Schedules/Interleavings

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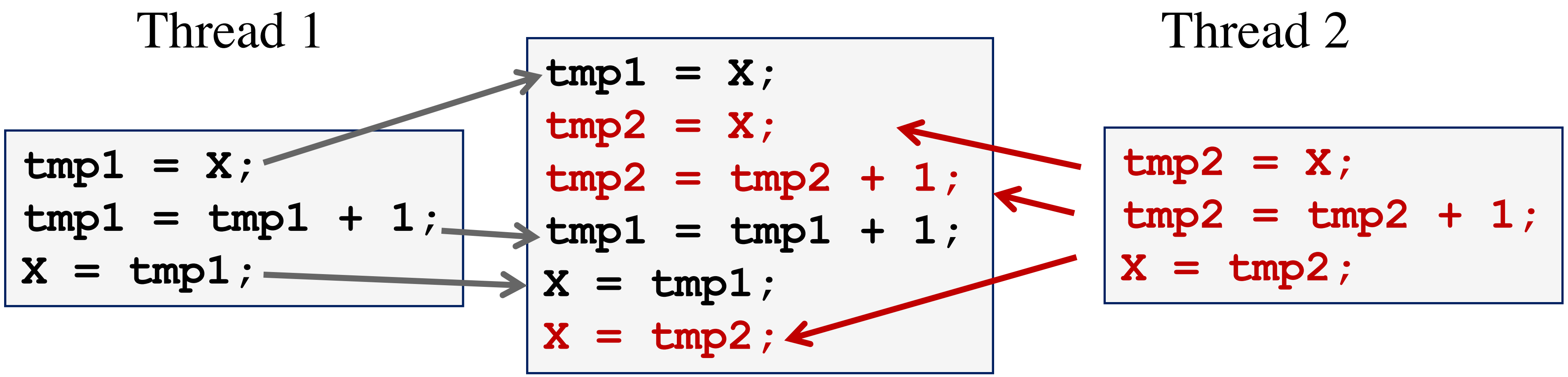

Thread 1

```
tmp1 = X;
tmp1 = tmp1 + 1;
X = tmp1;
```

```
tmp1 = X;
tmp2 = X;
tmp2 = tmp2 + 1;
tmp1 = tmp1 + 1;
X = tmp1;
X = tmp2;
```

Thread 2

```
tmp2 = X;
tmp2 = tmp2 + 1;
X = tmp2;
```

If X==0 initially, X == 1 at the end. WRONG result!

Locks fix this with Mutual Exclusion

```
void increment() {
   lock.acquire();
   int temp = X;
   temp = temp + 1;
   X = temp;
   lock.release();
}
```

Mutual exclusion ensures only safe interleavings

- *But it limits concurrency, and hence scalability/performance*

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Is mutual exclusion a good abstraction?

Why are Locks “Hard?”

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  - Simple to develop
  - Easy to avoid deadlock
  - Few data races
  - Limited concurrency

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    - Greater concurrency
    - Greater code complexity
    - Potential deadlocks
        - Not composable
    - Potential data races
        - Which lock to lock?

Why are Locks “Hard?”

- Coarse-grain locks
  - Simple to develop
  - Easy to avoid deadlock
  - Few data races
  - Limited concurrency

```
// WITH FINE-GRAIN LOCKS
void move(T s, T d, Obj key){
  LOCK(s);
  LOCK(d);
  tmp = s.remove(key);
  d.insert(key, tmp);
  UNLOCK(d);
  UNLOCK(s);
}
```

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Thread 0	**Thread 1**
`move(a, b, key1);`	
	`move(b, a, key2);`

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Thread 0

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Thread 1

```
move(b, a, key2);
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DEADLOCK!

Review: correctness conditions

```
while(1) {
   Entry section
   Critical section
   Exit section
   Non-critical section
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```

Review: correctness conditions

- Safety
    - Only one thread in the critical region

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  - Some thread that enters the entry section eventually enters the critical region
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  - A thread that enters the entry section enters the critical section within some bounded number of operations.

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Theorem: Every property is a combination of a safety property and a liveness property.

-Bowen Alpern & Fred Schneider

https://www.cs.cornell.edu/fbs/publications/defliveness.pdf

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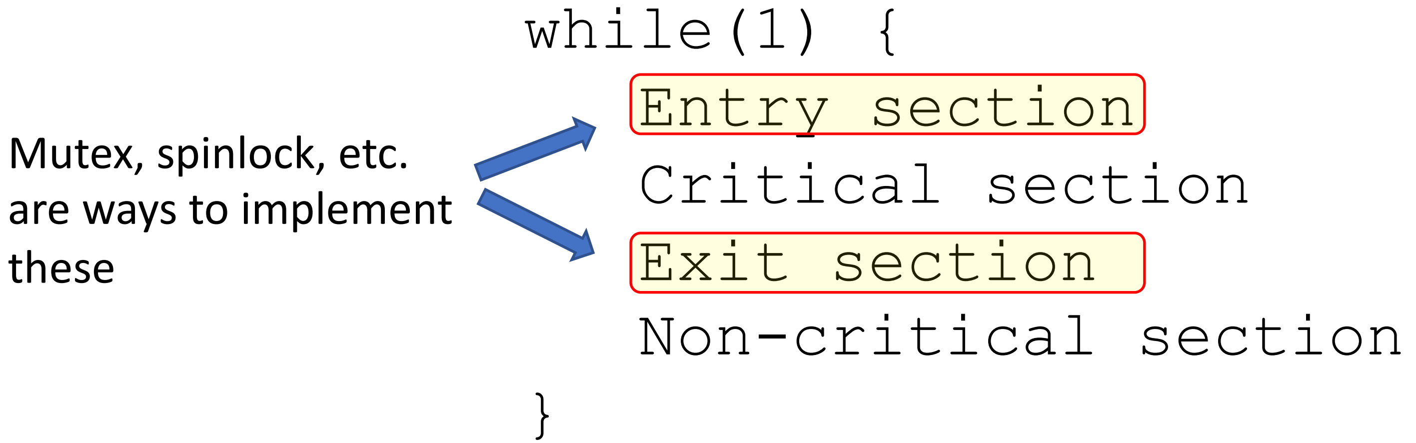

Mutex, spinlock, etc. are ways to implement these

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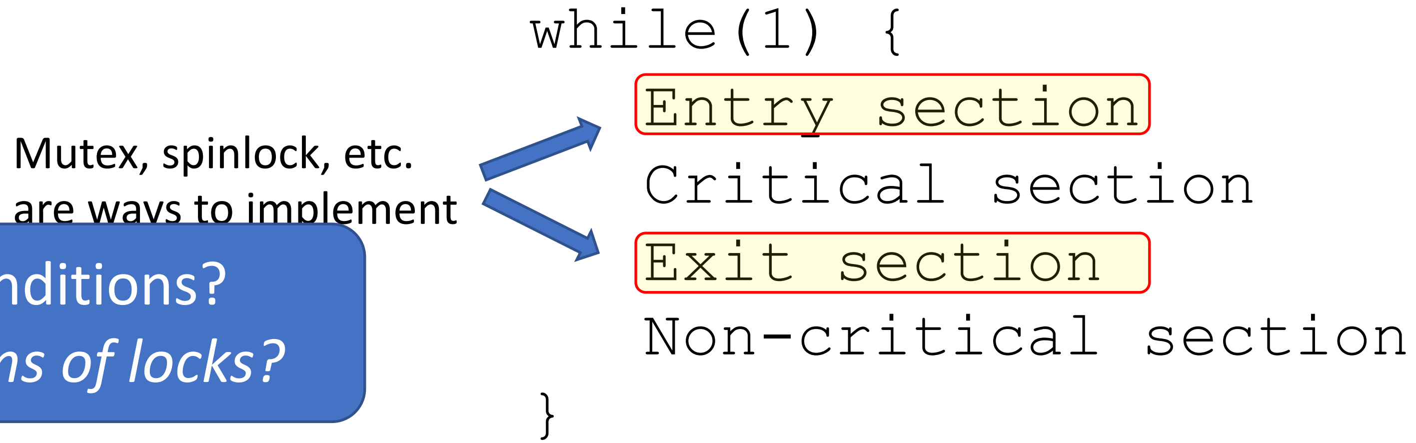

Mutex, spinlock, etc. are ways to implement

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Did we get all the important conditions?
Why is correctness defined in terms of locks?

Implementing Locks

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- B. Memory usage
- C. Lock::Acquire() latency
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- E. Does not work

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Completely and utterly broken.
How can we fix it?

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