Scalability + Correctness

Chris Rossbach + Calvin Lin

CS380p

Outline for Today

- Concurrency & Parallelism Basics
  - Decomposition redux
  - Measuring Parallel Performance
  - Performance Tradeoffs
  - Correctness and Performance

Acknowledgments: some materials in this lecture borrowed from or built on materials 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*

Review: Game of Life

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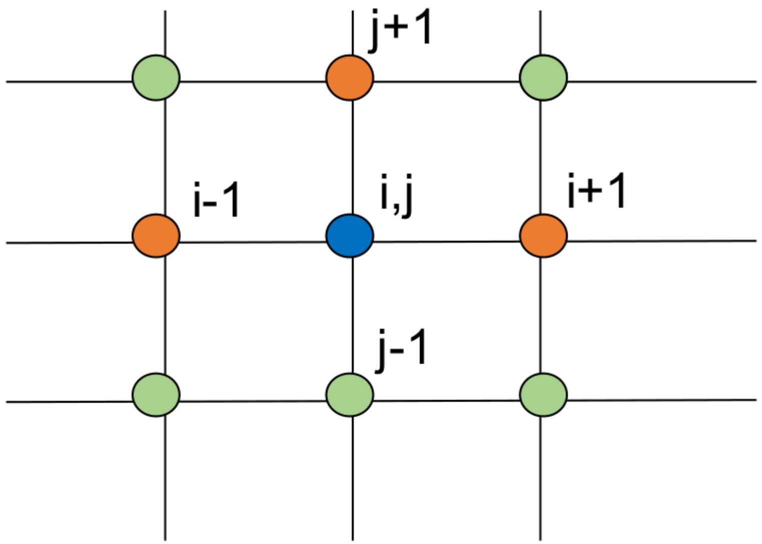
- Given a 2D Grid:
- $v_t(i,j) = F\left(v_{t-1}(of\ all\ its\ neighbors)\right)$



Domain decomposition

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Each CPU gets part of the input

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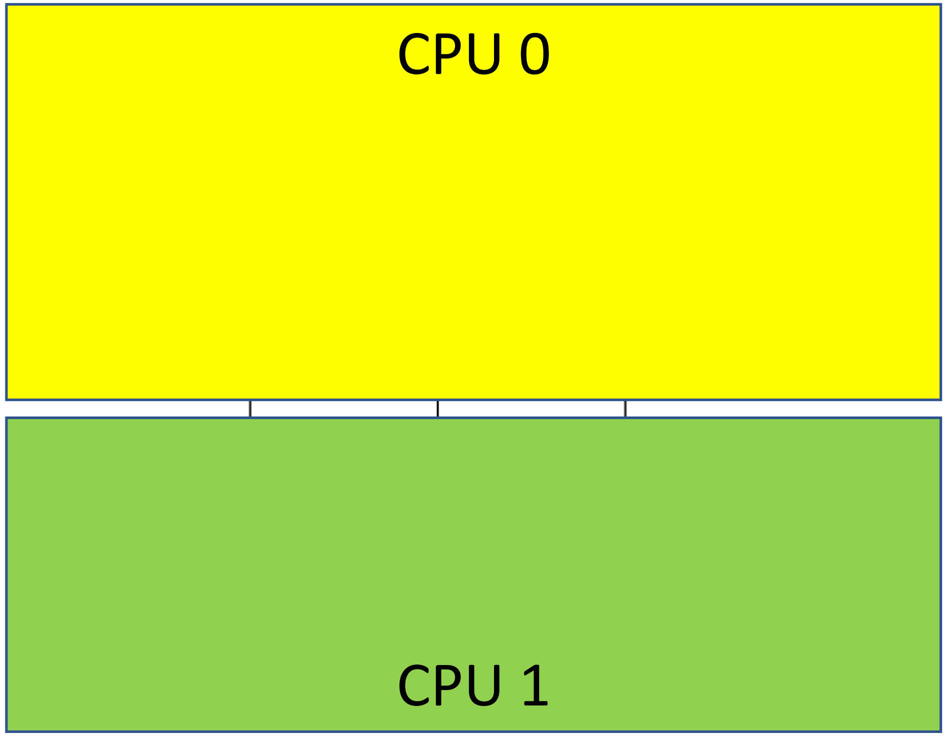

- What would a functional decomposition look like?
- Issues/obstacles with this domain decomposition?

Functional decomposition

CPU 0:
$tmp_{i,j} = F(v_{t-1}(neighbors))$

CPU 1:
$v_t(i,j) = tmp_{i,j}$

Functional decomposition

Each CPU gets part of the per-cell work

CPU 0:

$tmp_{i,j} = F(v_{t-1}(\text{neighbors}))$

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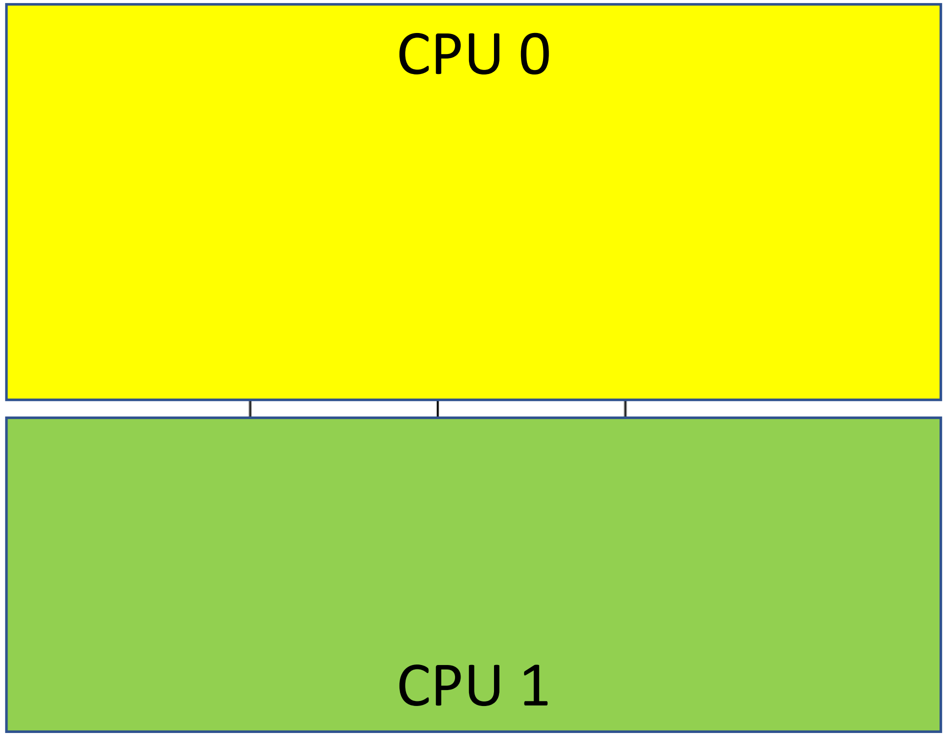

Domain decomposition

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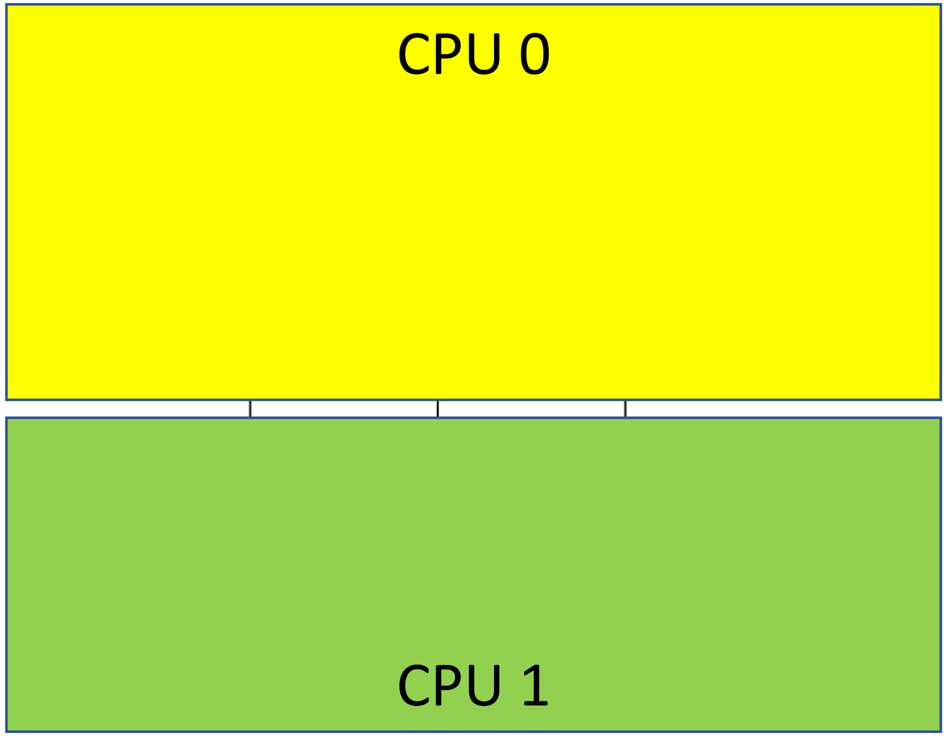
Issues?



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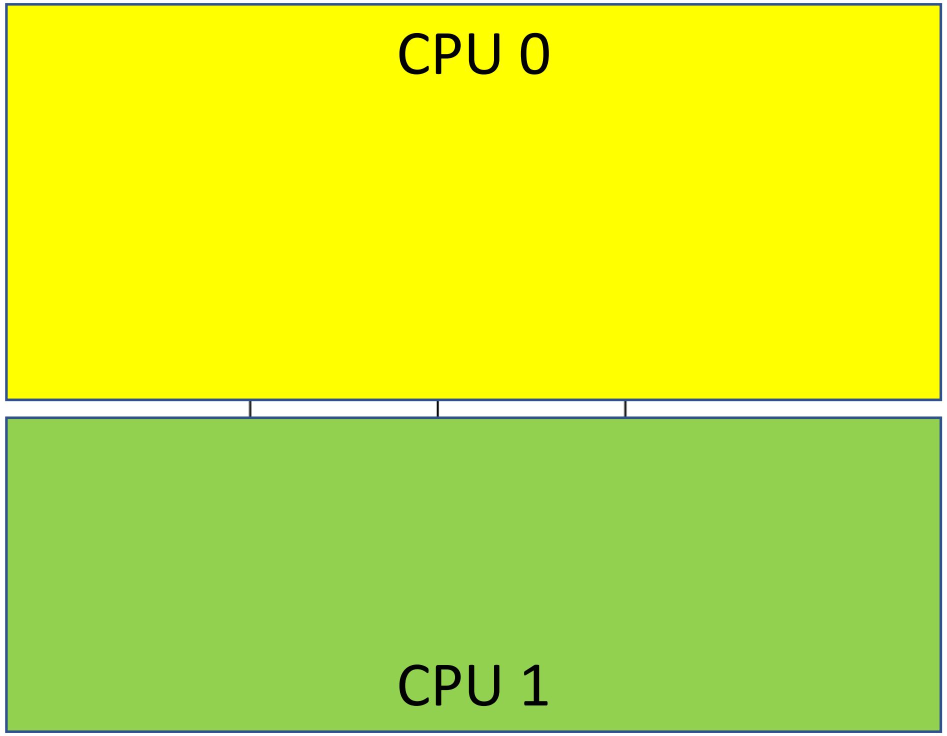

Issues?

- Accessing Data

Domain decomposition

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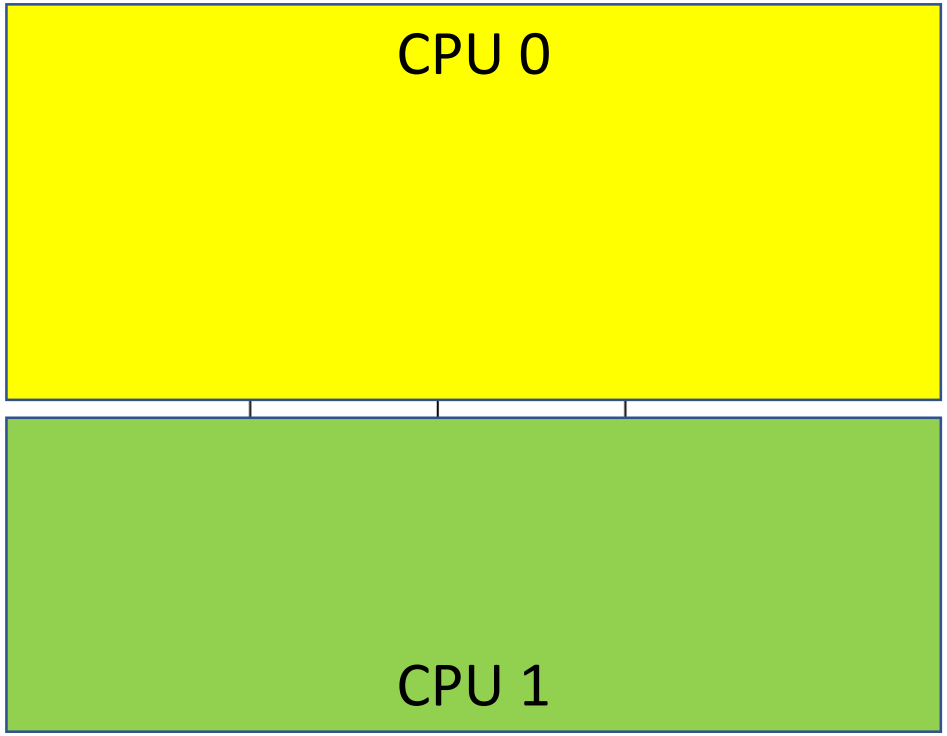
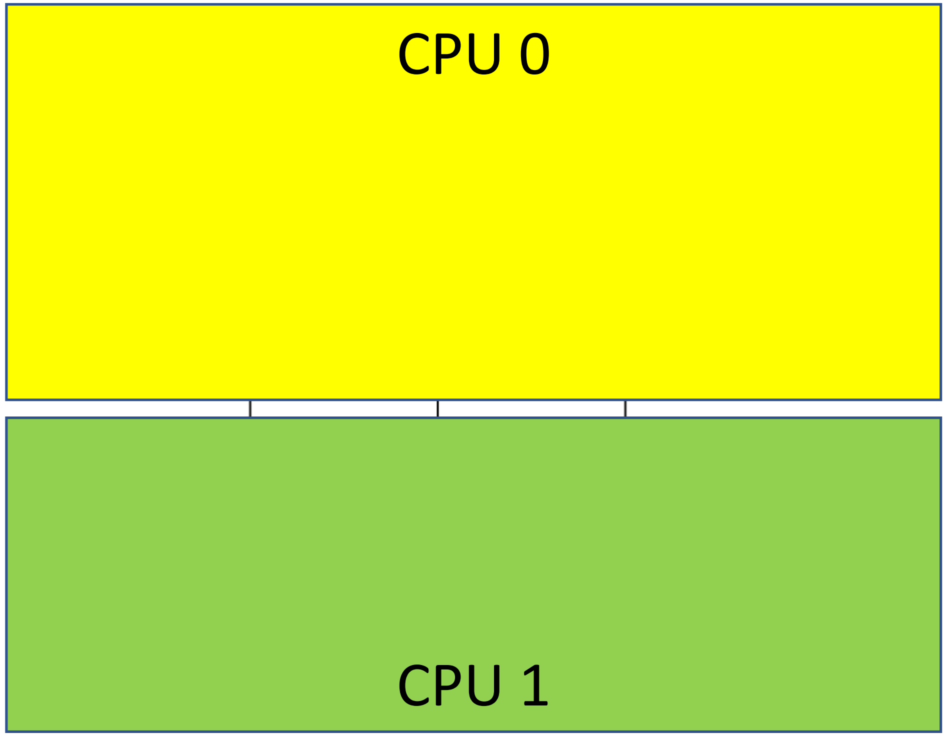


Issues?
- Accessing Data
  - Can we access v(i+1, j) from CPU 0

Domain decomposition

- Each CPU gets part of the input



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  - Can we access v(i+1, j) from CPU 0
    - …as in a "normal" serial program?
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  - *Scalability vs Latency*

Domain decomposition

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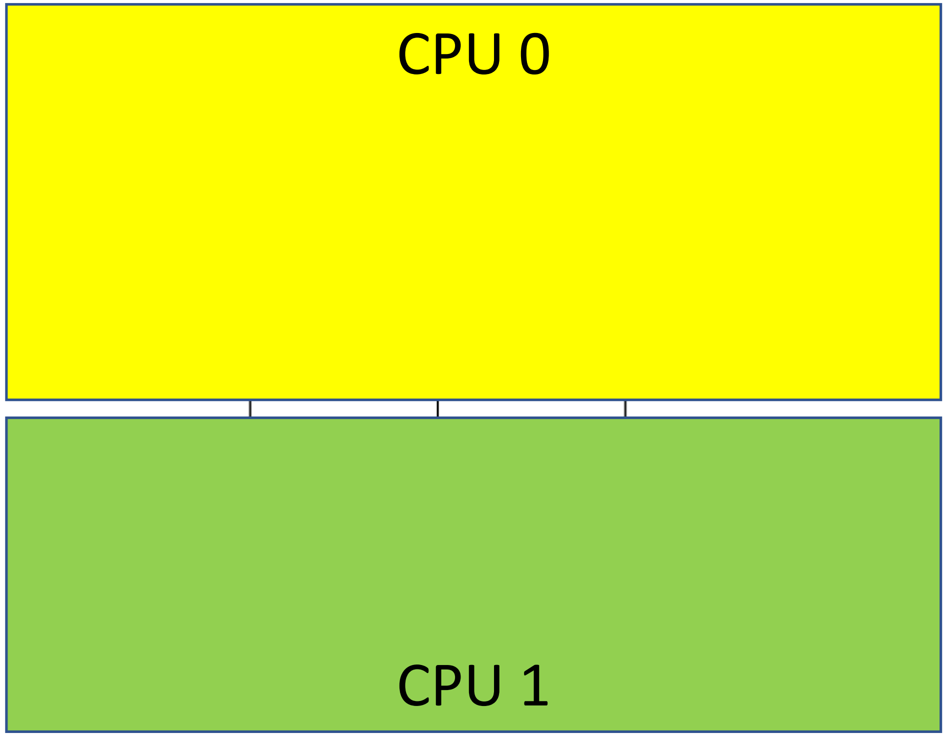

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  - *Task Management Overhead*

Domain decomposition

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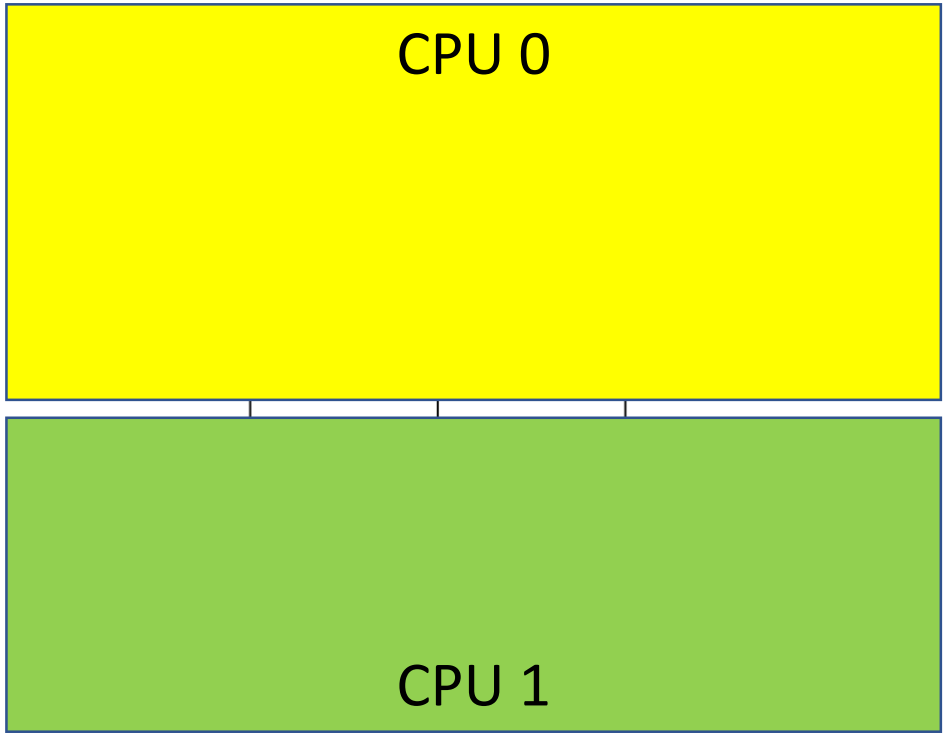

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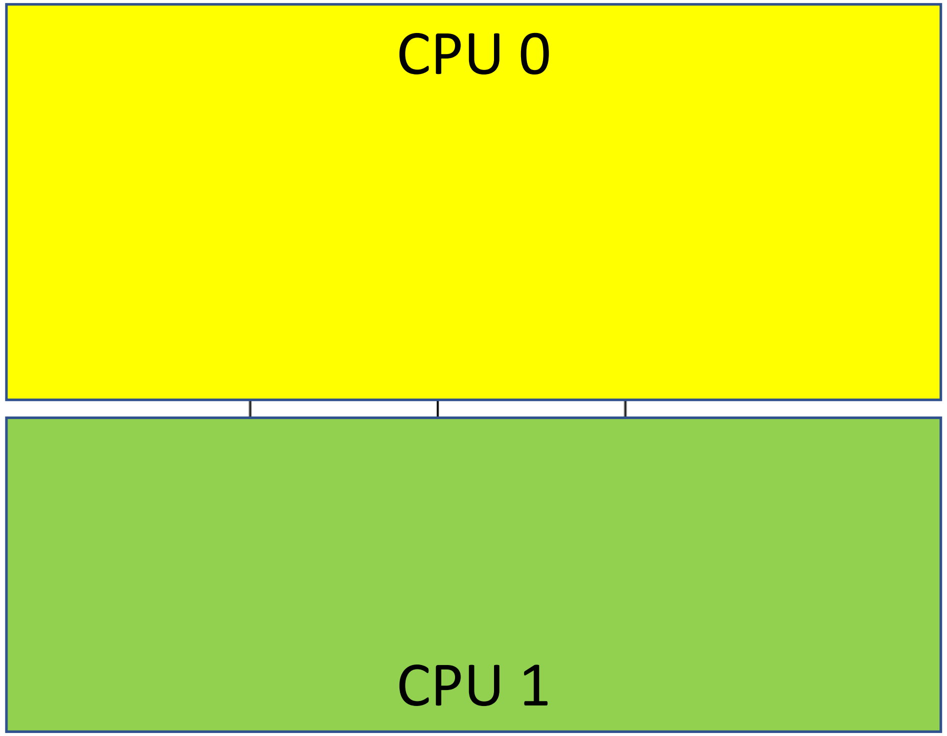

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  - *Task Management Overhead*
- *Load Balance*
- Correctness
  - order of reads and writes is non-deterministic
  - synchronization is required to enforce the order
  - *locks, semaphores, barriers, conditionals….*

Load Balancing

Load Balancing

- Slowest task determines performance

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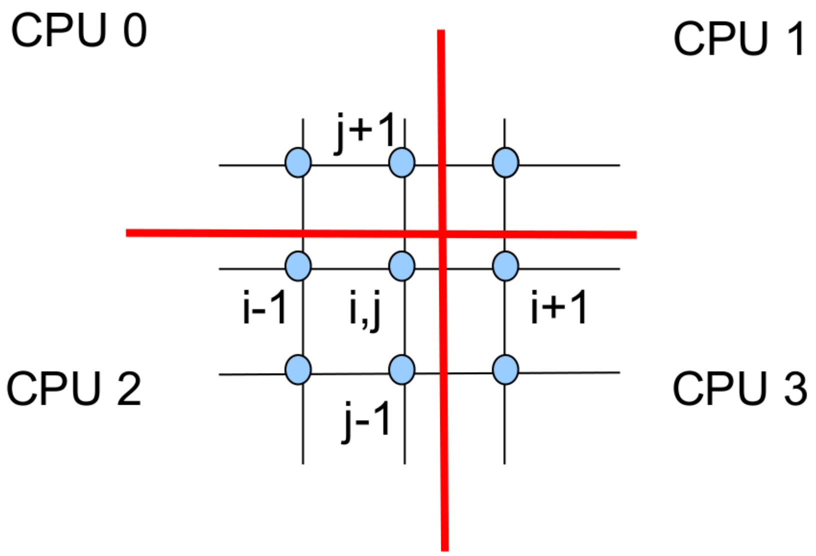

Load Balancing

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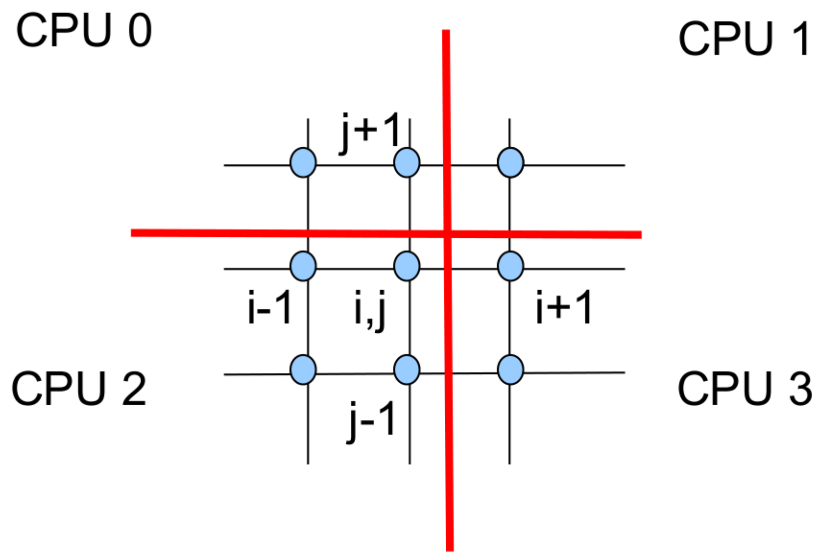

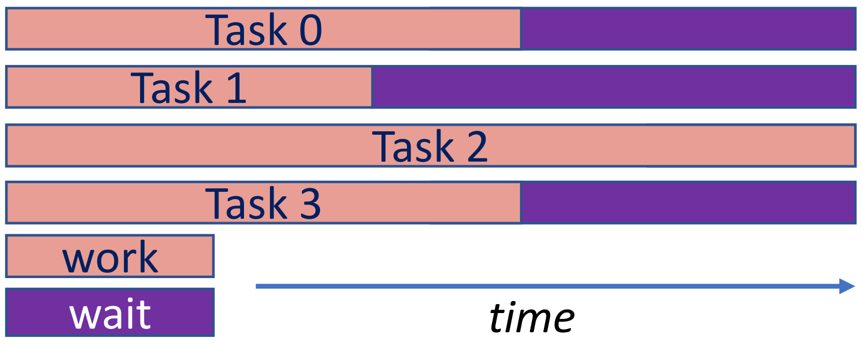

Granularity

Granularity

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

Granularity

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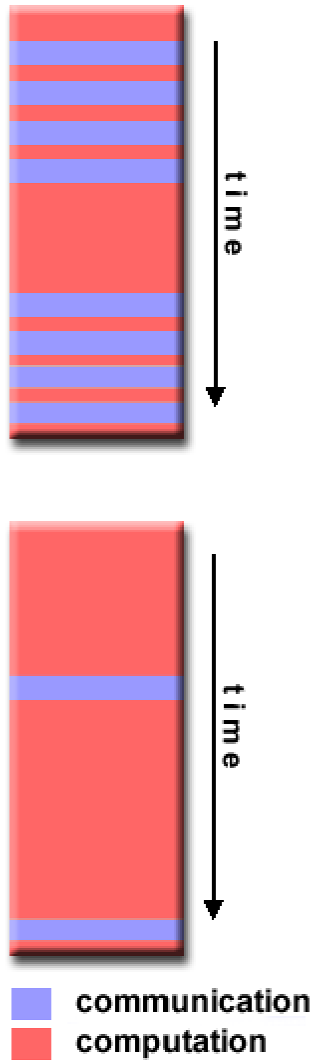
- Fine-grain parallelism
  - G is small
  - Good load balancing
  - Potentially high overhead
  - Hard to get correct
- Coarse-grain parallelism
  - G is large
  - Load balancing is tough
  - Low overhead
  - Easier to get correct



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:

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

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

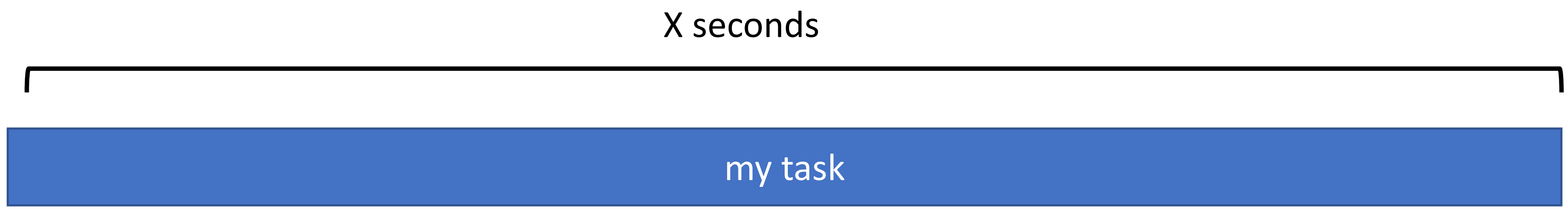
Performance: Amdahl's law

- Speedup is bound by serial component
- Sp
  -
  -
  -

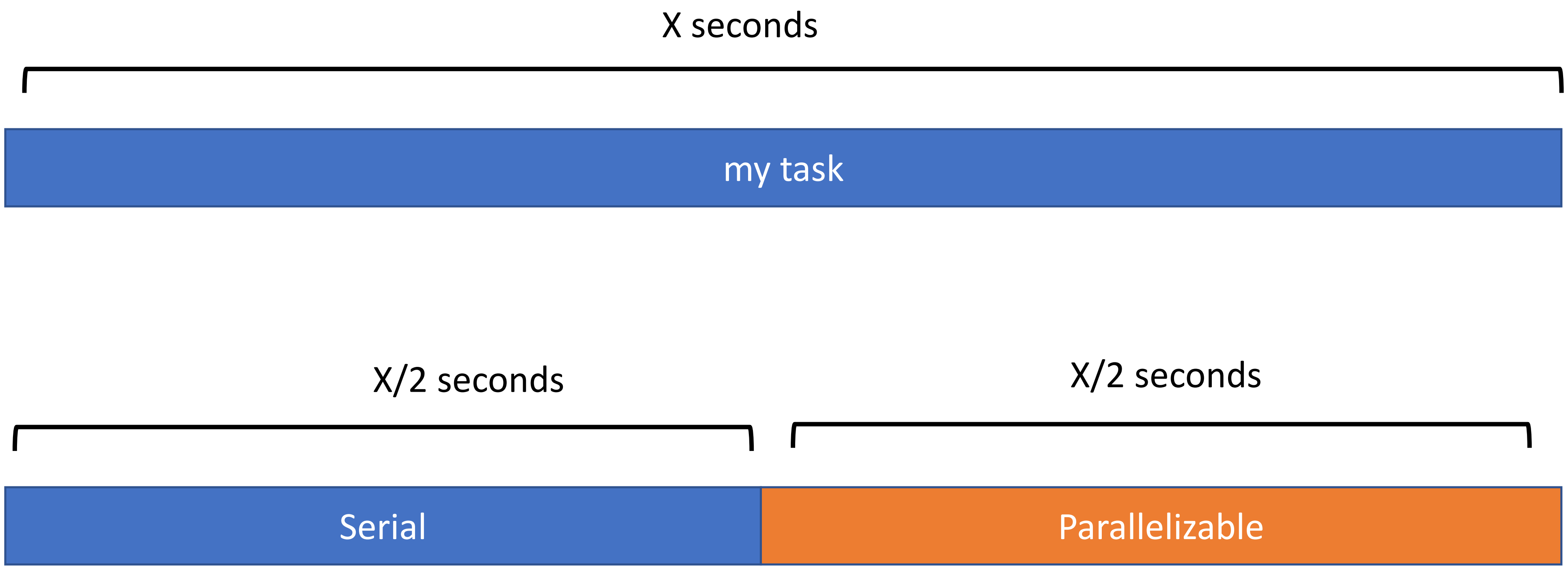
$$Speedup = \frac{\text{serial run time}}{\text{parallel run time}}$$

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

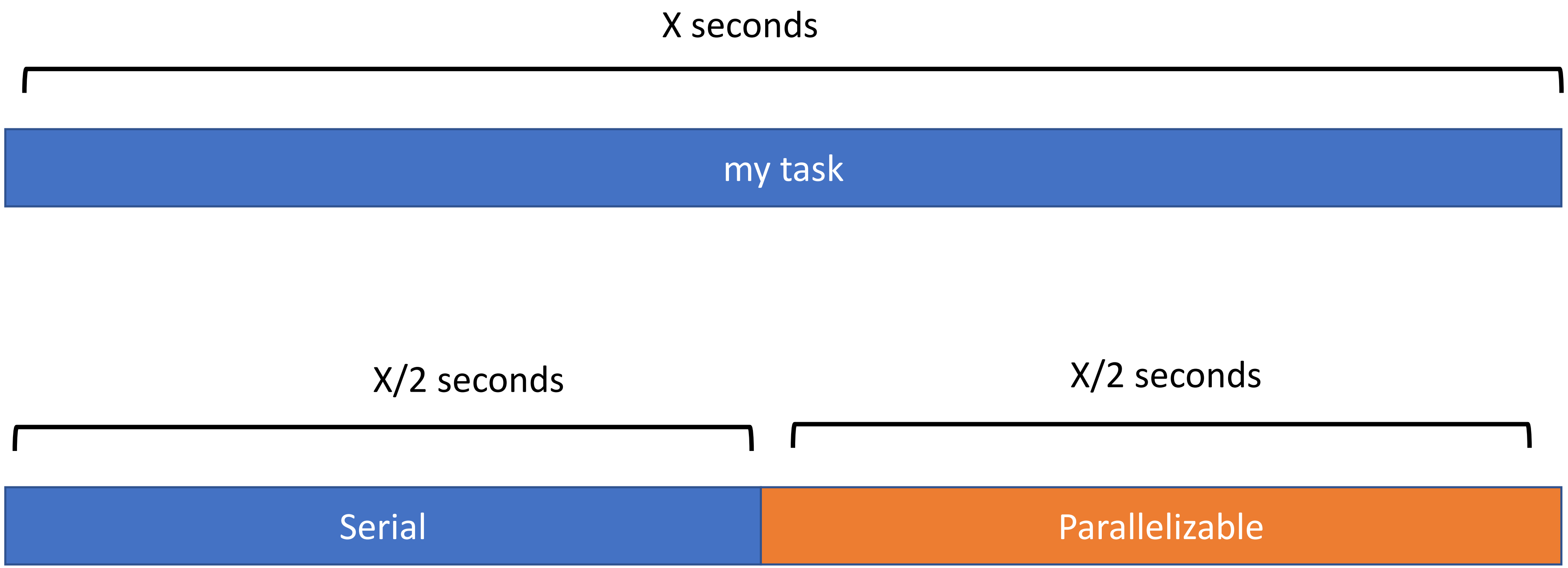
Amdahl’s law



Amdahl's law

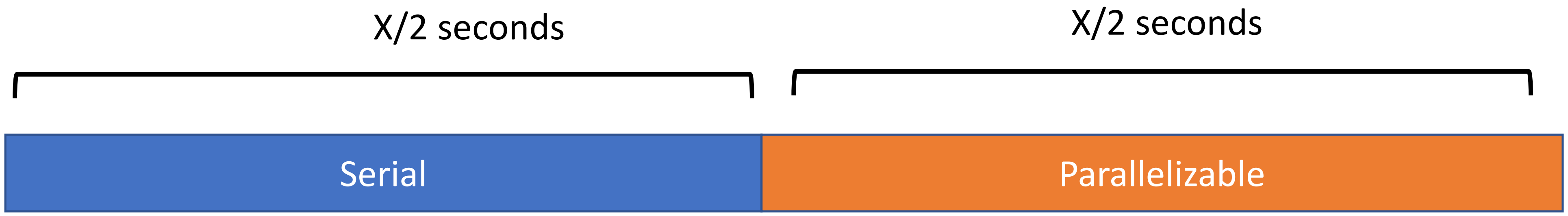

X seconds
my task
X/2 seconds
X/2 seconds
Serial
Parallelizable

Amdahl’s law



What makes something “serial” vs. parallelizable?

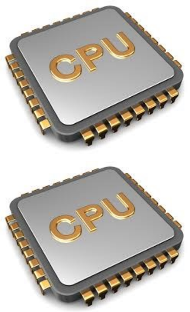
Amdahl's law

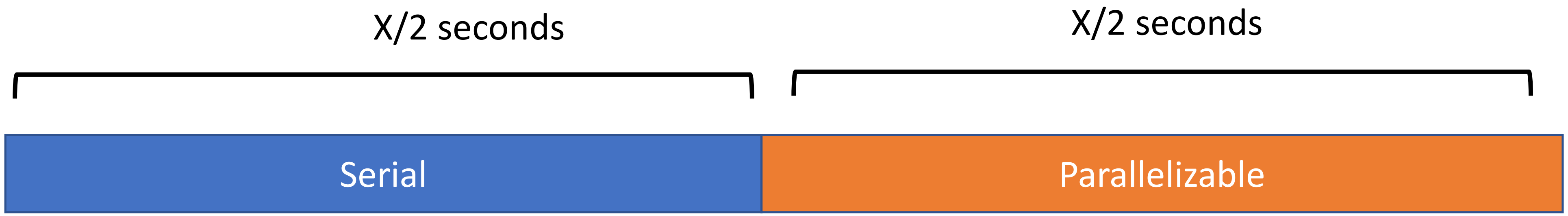


End to end time: X seconds

Amdahl's law

2 CPUs





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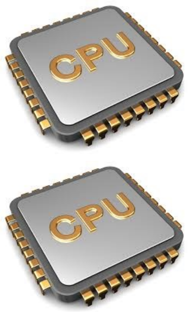

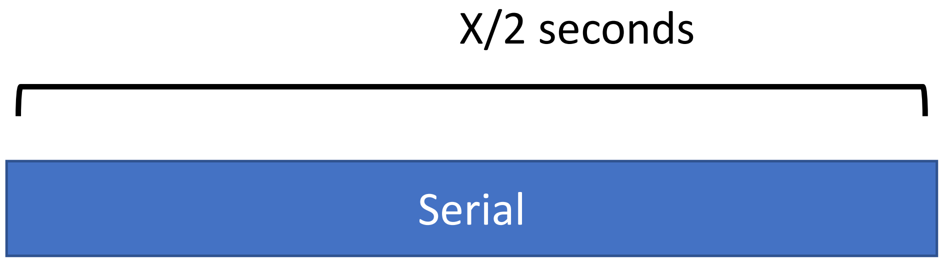

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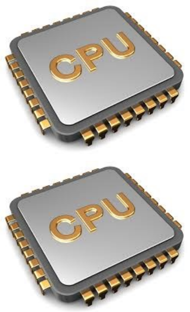

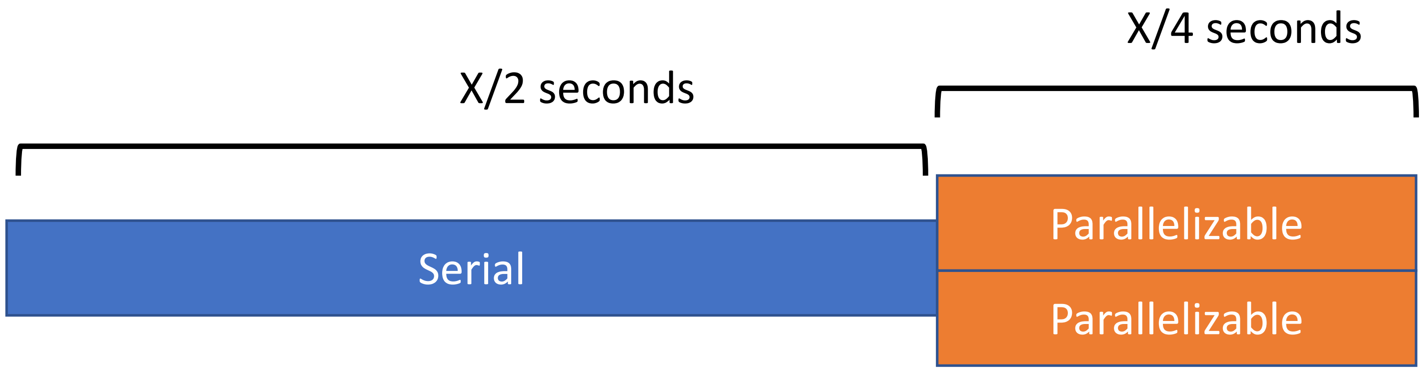

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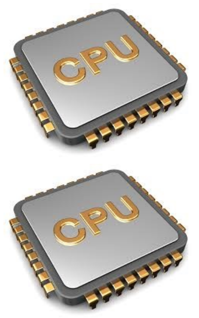

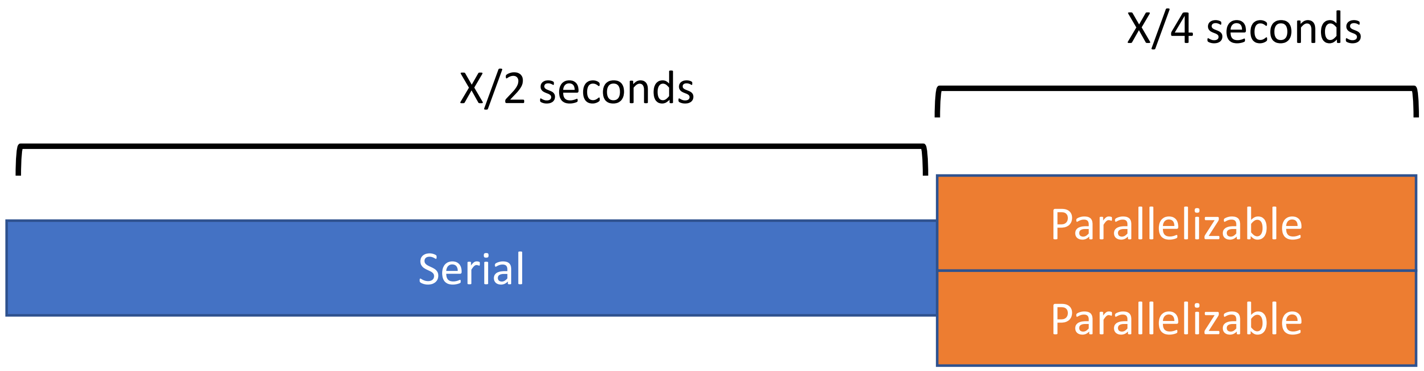

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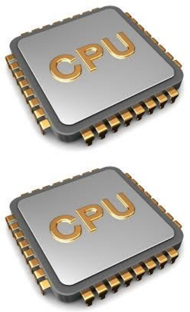
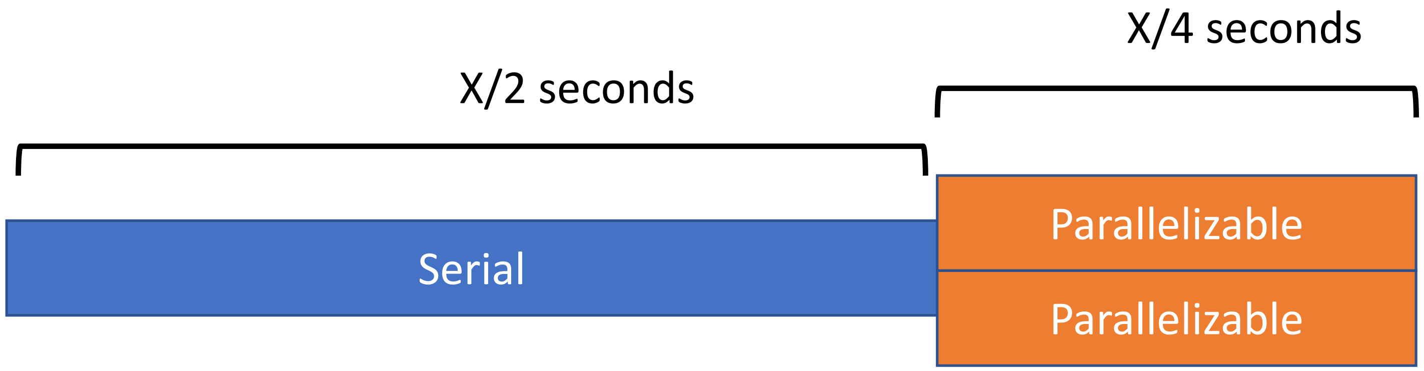
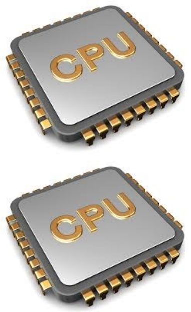


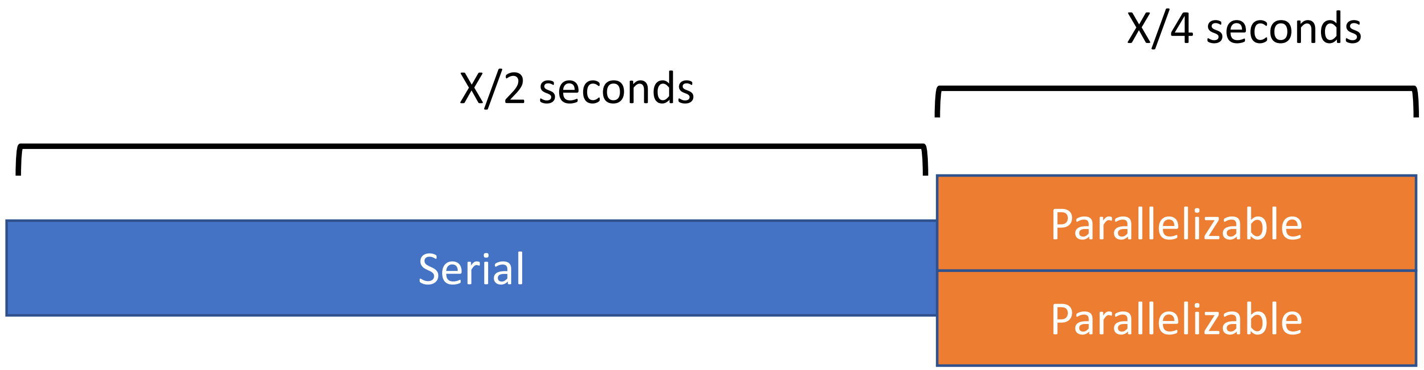


End to end time: (X/2 + X/4) = (3/4)X seconds

Amdahl’s law

2 CPUs



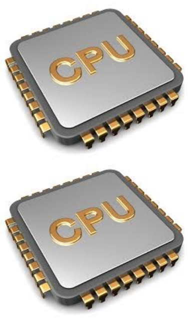


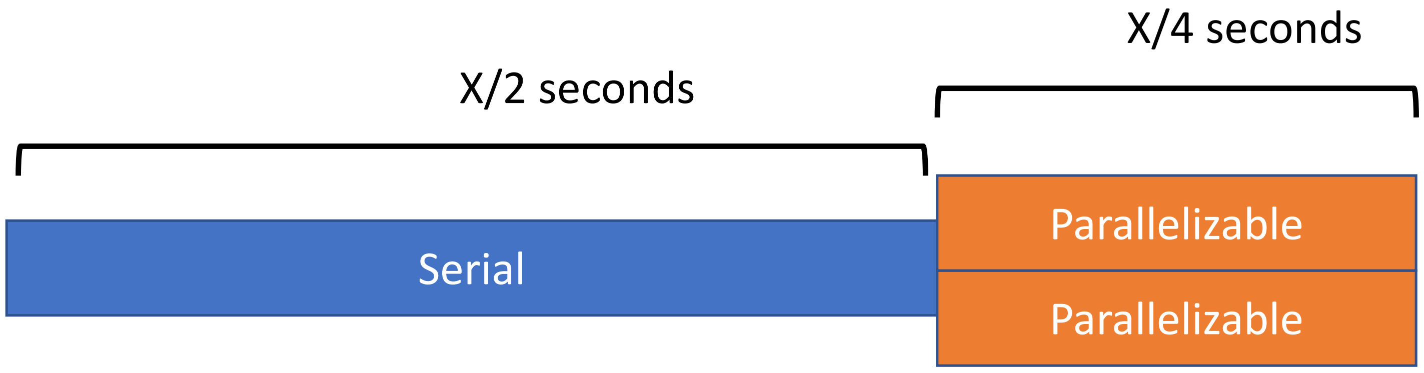
End to end time: (X/2 + X/4) = (3/4)X seconds

What is the “speedup” in this case?

Amdahl's law

2 CPUs





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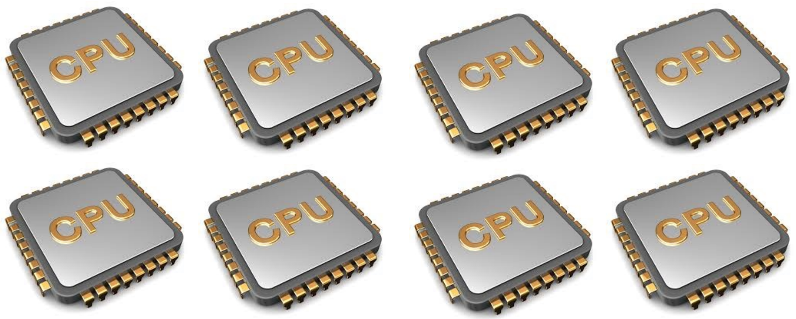
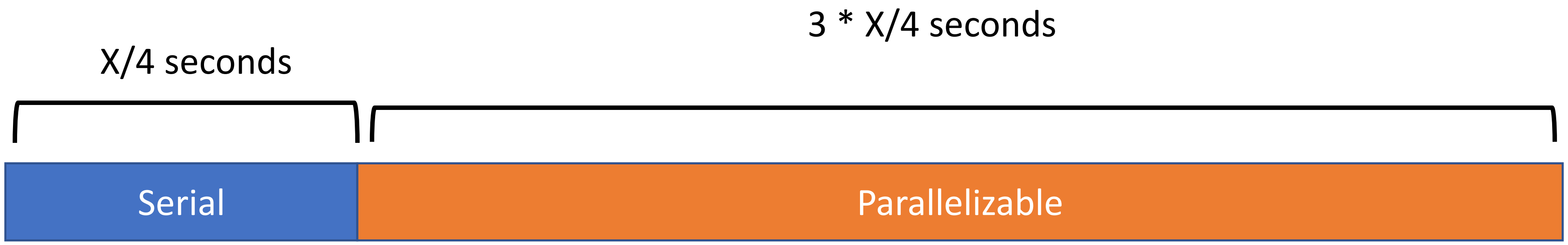
$$Speedup = \frac{\text{serial run time}}{\text{parallel run time}} = \frac{1}{\frac{A}{\#CPUs} + (1 - A)} = \frac{1}{\frac{.5}{2\text{ cpus}} + (1\text{-}.5)} = 1.333$$

Speedup exercise

8 CPUs





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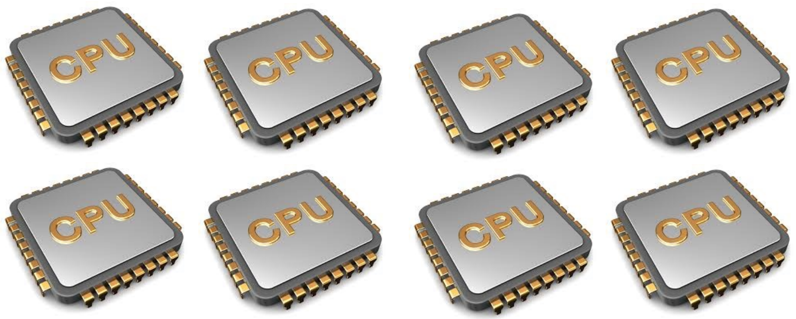

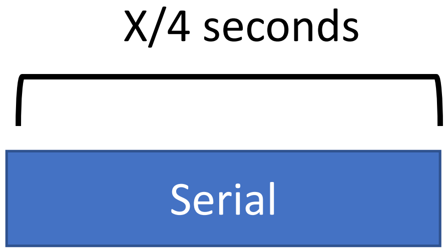

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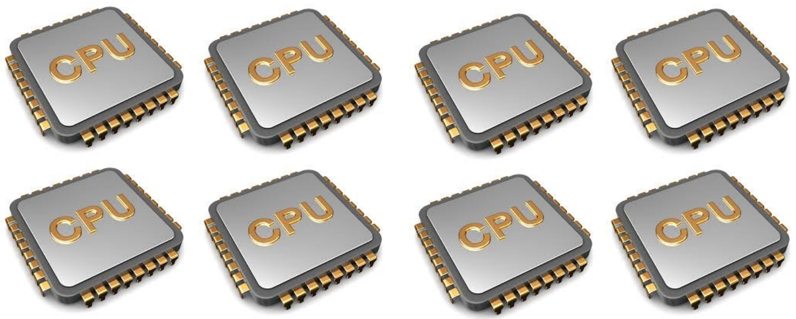

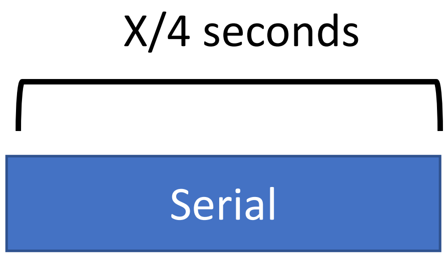

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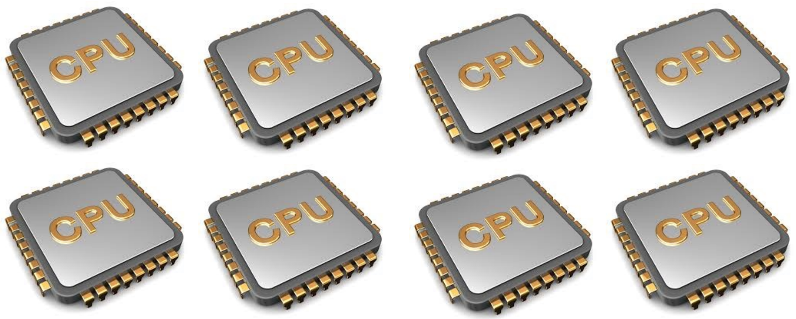

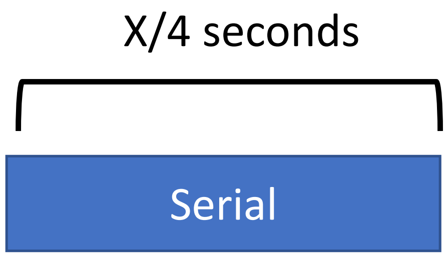

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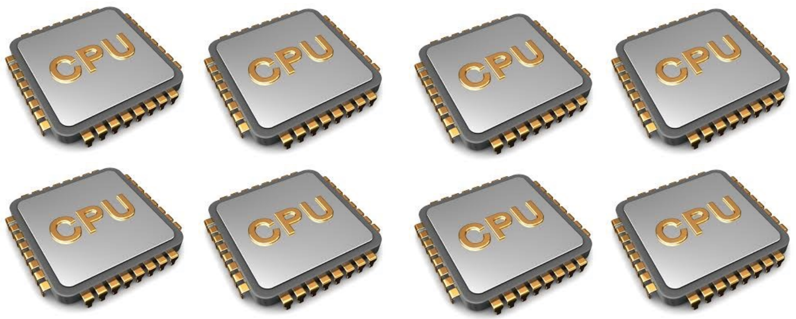

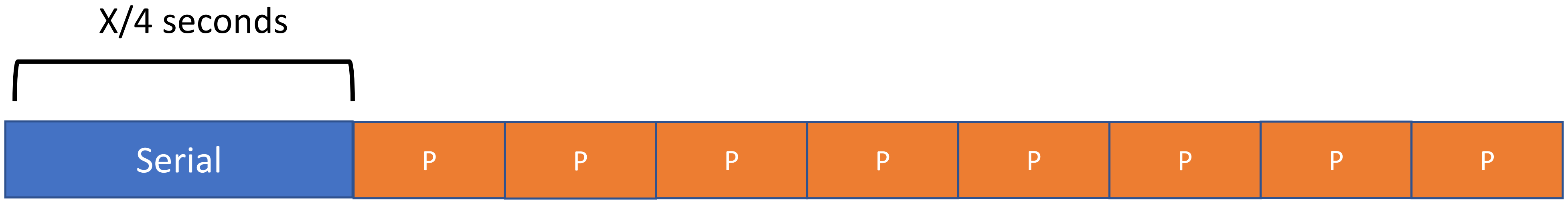

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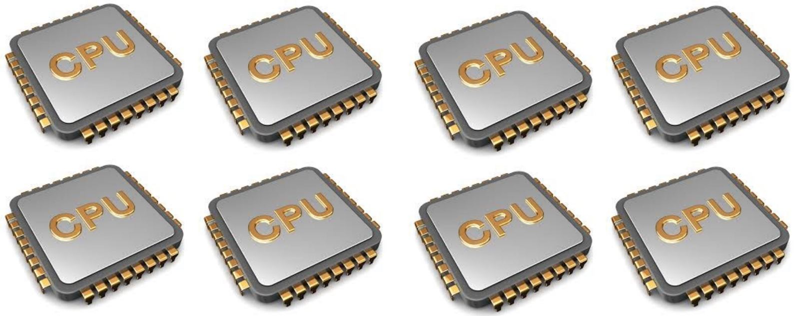

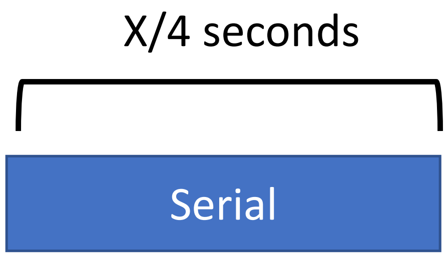

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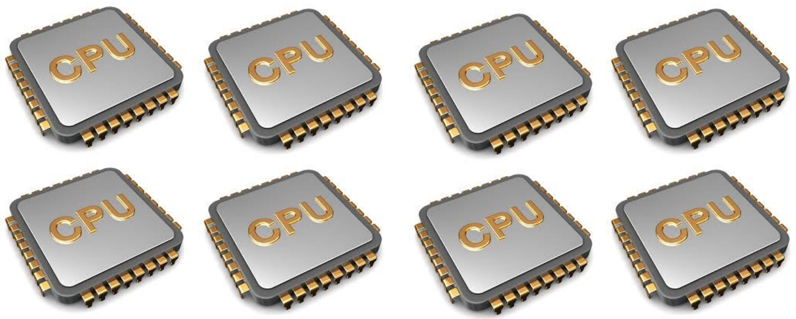

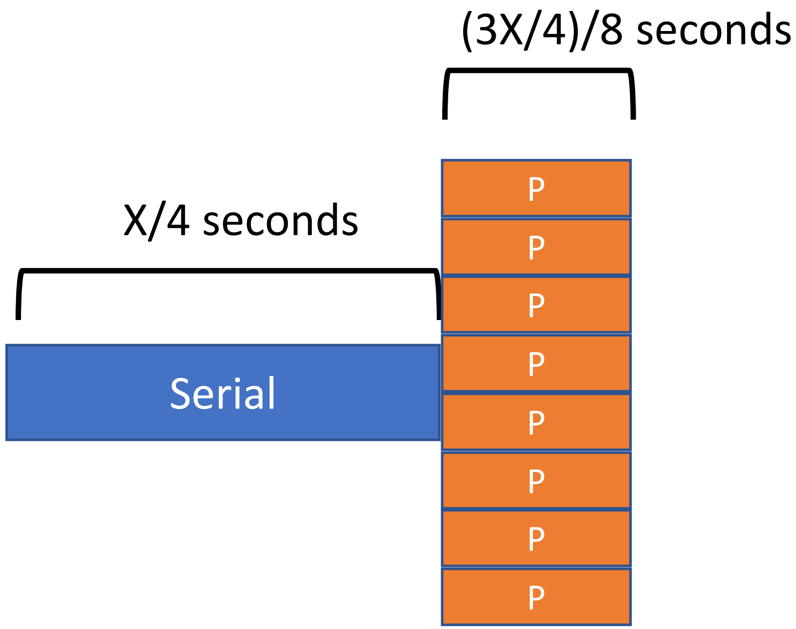

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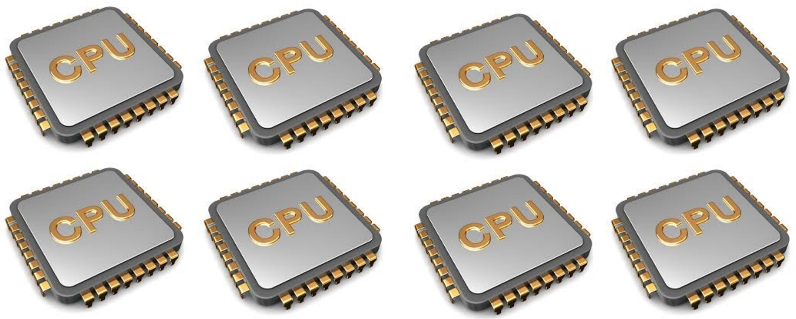
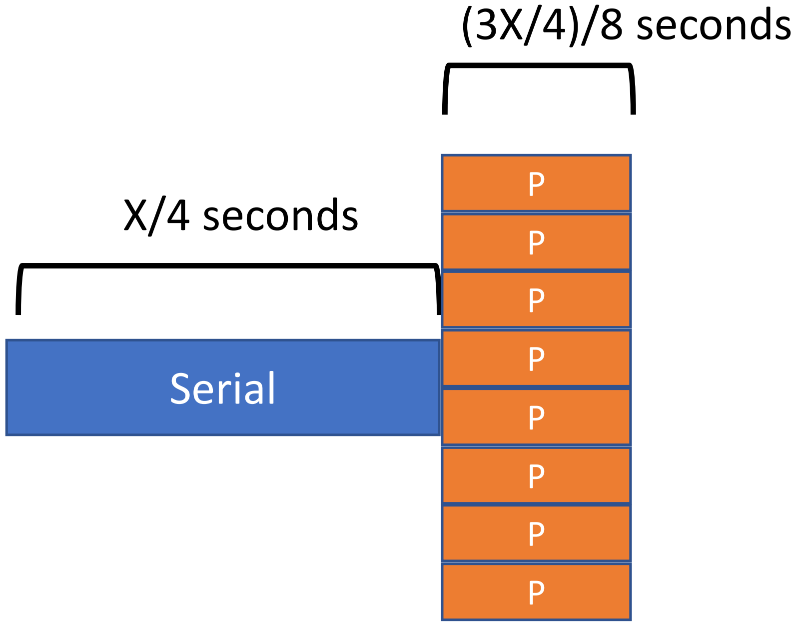
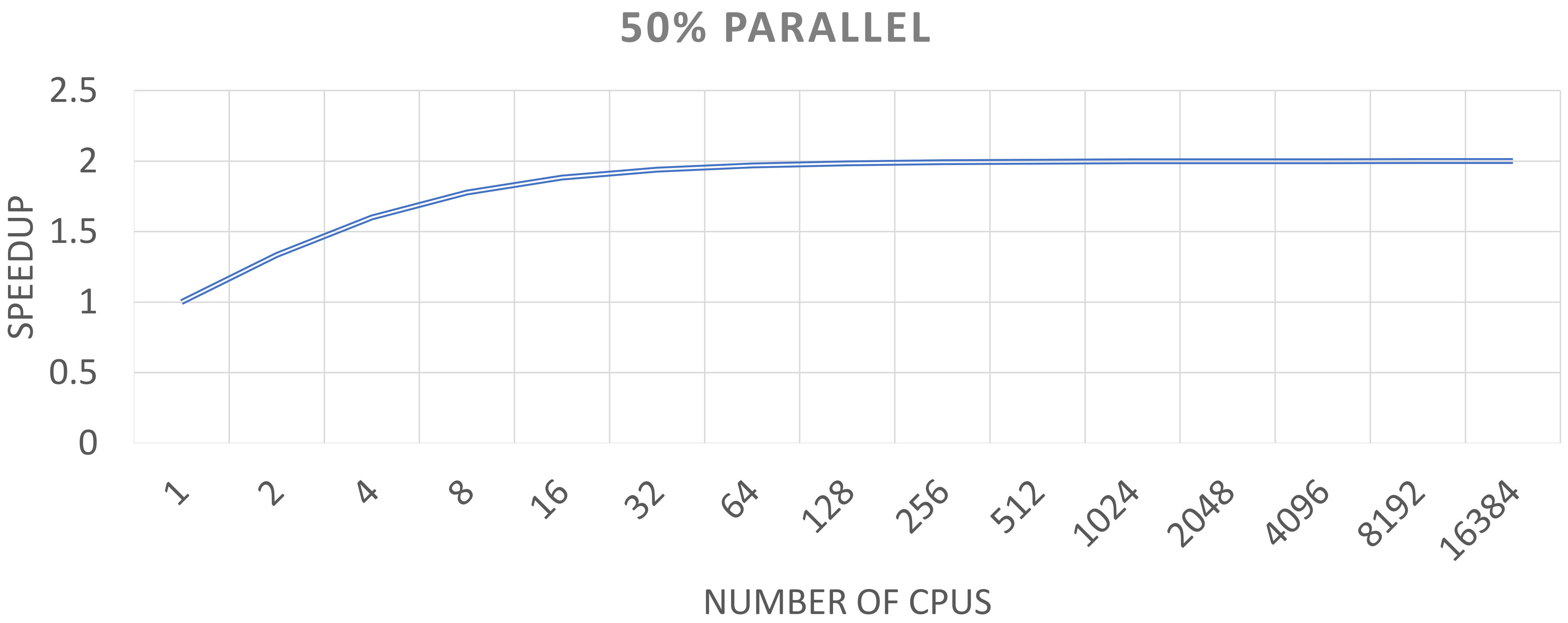




What is the "speedup" in this case?

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

Amdahl Action Zone



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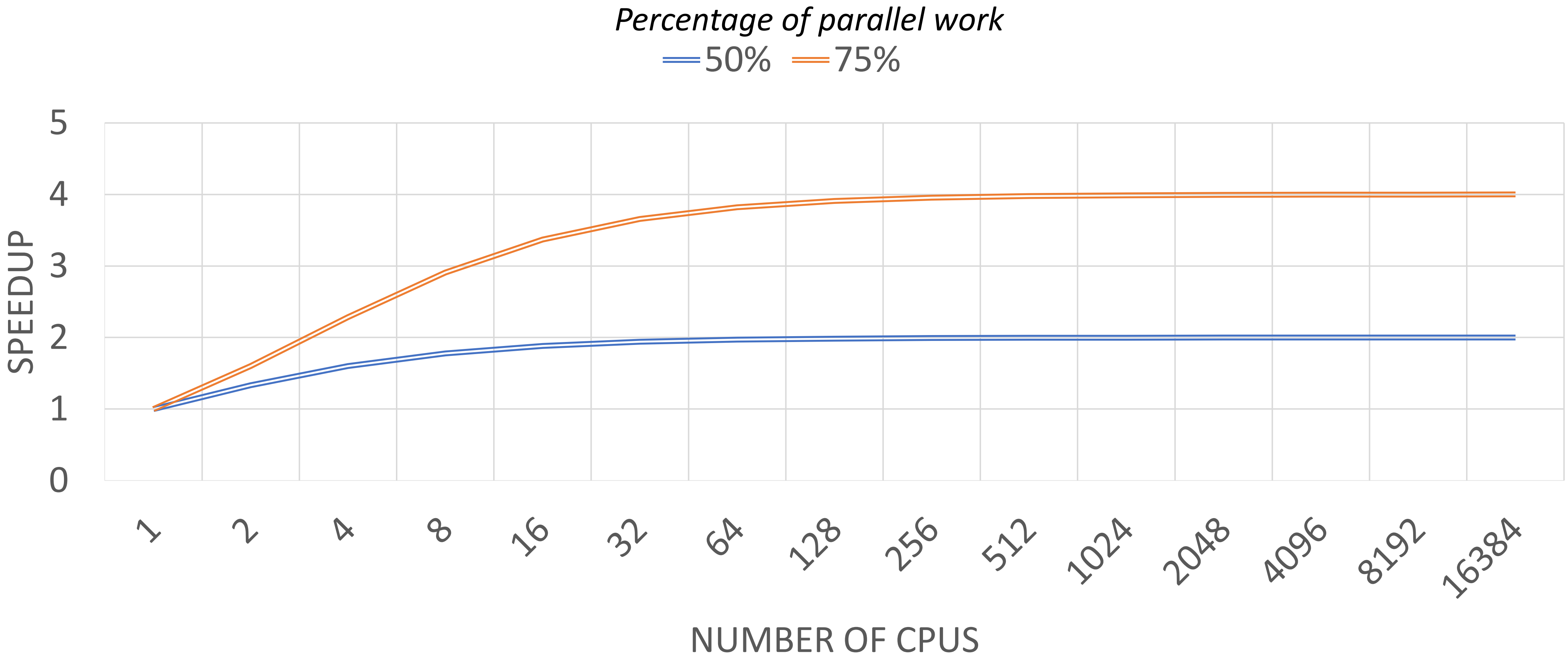

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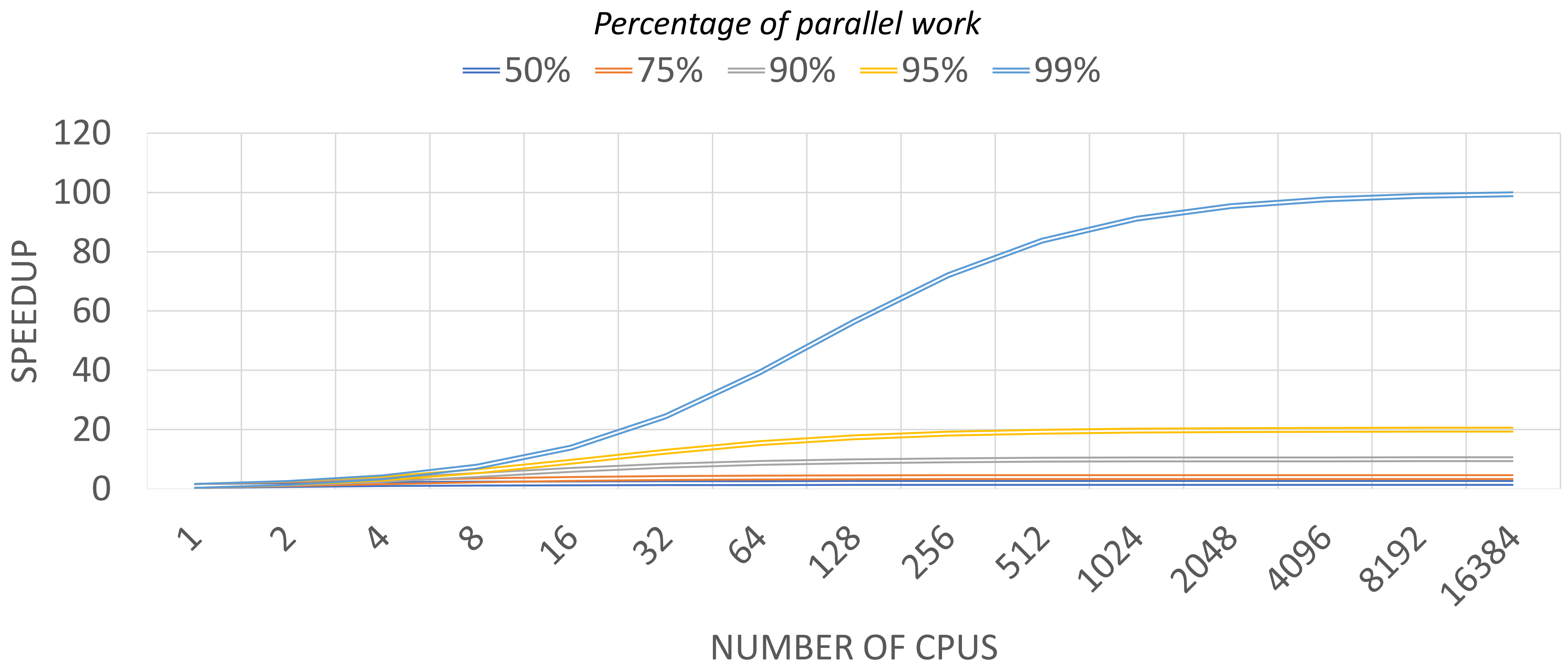
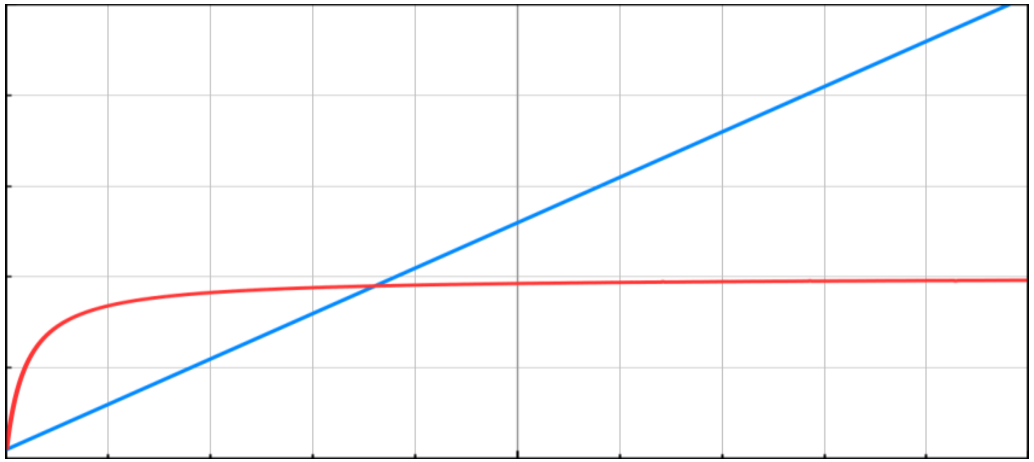


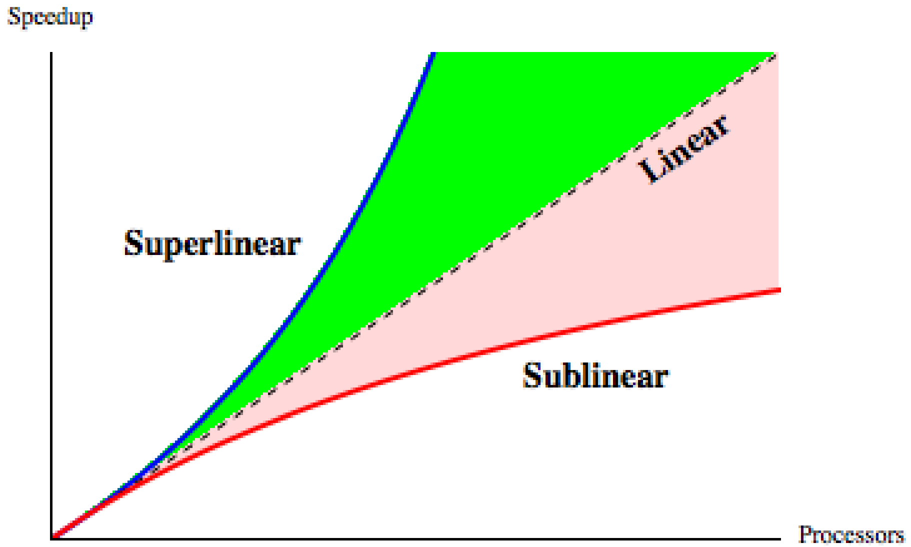
Strong Scaling vs Weak Scaling

Amdahl vs. Gustafson

- $N = \#CPUs,\ S = serial\ portion = 1 - A$
- Amdahl's law: $Speedup(N) = \frac{1}{\frac{A}{N}+S}$
    - **Strong scaling:** *Speedup(N)* calculated with total work fixed
    - Solve same fixed size problem, #CPUs grows
    - Fixed parallel portion → speedup stops increasing
- Gustafson's law: $Speedup(N) = N + (N{-}1) \cdot S$
    - **Weak scaling:** *Speedup(N)* calculated with work-per-CPU fixed
    - Add more CPUs → Add more work → granularity stays fixed
    - Problem size grows: solve larger problems
    - Consequence: speedup upper bound much greater

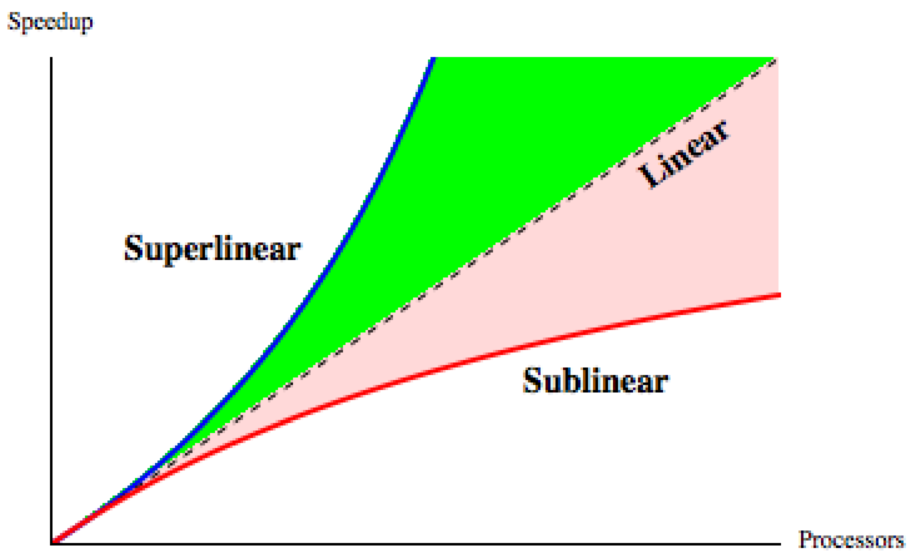


Super-linear speedup



Super-linear speedup

- Possible due to cache
- But usually just poor methodology
- Baseline: ***best*** serial algorithm



Super-linear speedup

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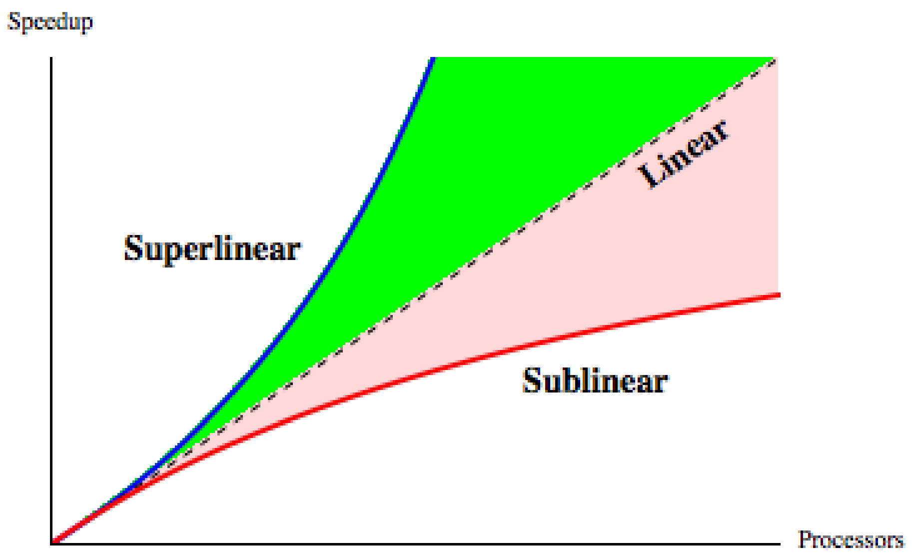
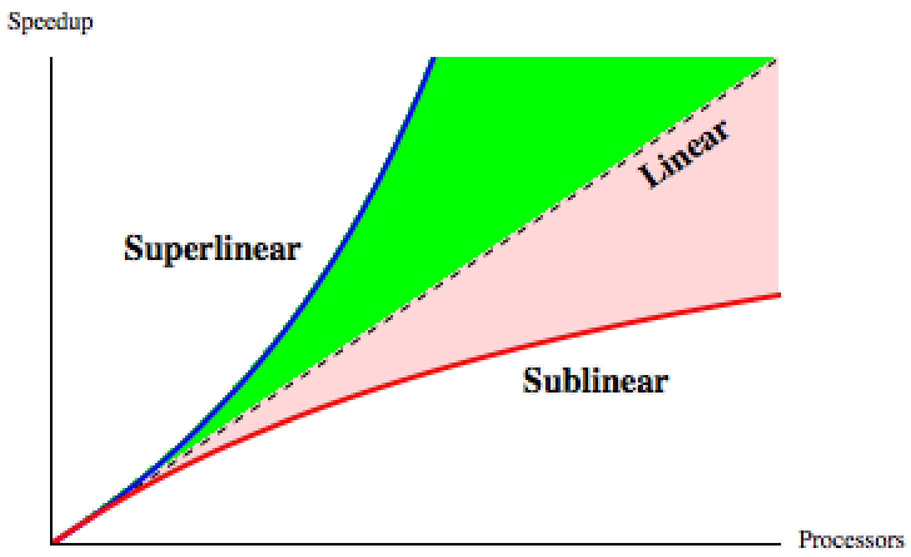
- Baseline: ***best*** serial algorithm
- Example:



Super-linear speedup

- Possible due to cache
- But usually just poor methodology
- Baseline: ***best*** serial algorithm
- Example:
    - Efficient **bubble sort** takes:
        - Parallel 40s
        - Serial 150s
        - $Speedup = \frac{150}{40} = 3.75$?
    - NO!
        - Serial quicksort runs in 30s
        - $\Longrightarrow Speedup = 0.75$



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;
```

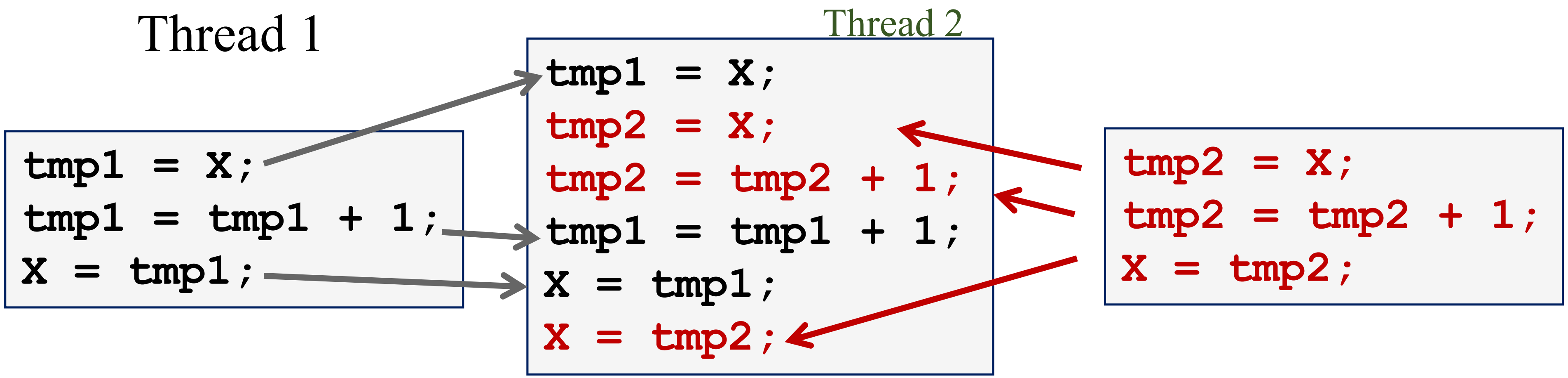
Thread 2

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

Schedules/Interleavings

Model of concurrent execution

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



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*

Locks fix this with Mutual Exclusion

```
void increment() {
    lock.acquire();
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Mutual exclusion ensures only safe interleavings

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

Is mutual exclusion a good abstraction?

Correctness conditions

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

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while(1) {
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Correctness conditions

- Safety
  - Only one thread in the critical region

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while(1) {
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   Exit section
   Non-critical section
}
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Correctness conditions

- Safety
  - Only one thread in the critical region
- Liveness
  - Some thread that enters the entry section eventually enters the critical region
  - Even if other thread takes forever in non-critical region

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while(1) {
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   Non-critical section
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```

Correctness conditions

- Safety
  - Only one thread in the critical region
- Liveness
  - Some thread that enters the entry section eventually enters the critical region
  - Even if other thread takes forever in non-critical region
- Bounded waiting
  - A thread that enters the entry section enters the critical section within some bounded number of operations.

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  - *If a thread i is in entry section, then there is a bound on the number of times that other threads are allowed to enter the critical section before thread i's request is granted*

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> Theorem: Every property is a combination of a safety property and a liveness property.
>
> -Bowen Alpern & Fred Schneider [1985]
>
> https://www.cs.cornell.edu/fbs/publications/defliveness.pdf

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Mutex, spinlock, etc. are ways to implement these

```
while(1) {
    [          ]
    Critical section
    [          ]
    Non-critical section
}
```

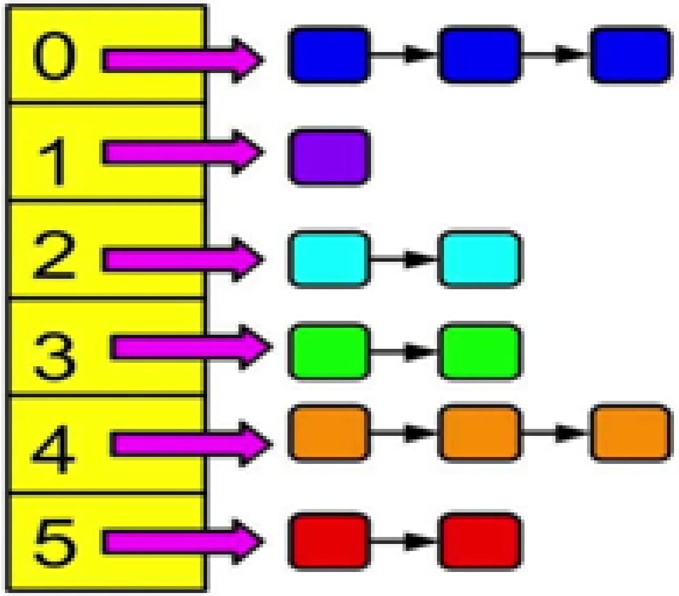
Let’s talk concurrency control

Let’s talk concurrency control

Consider a hash-table

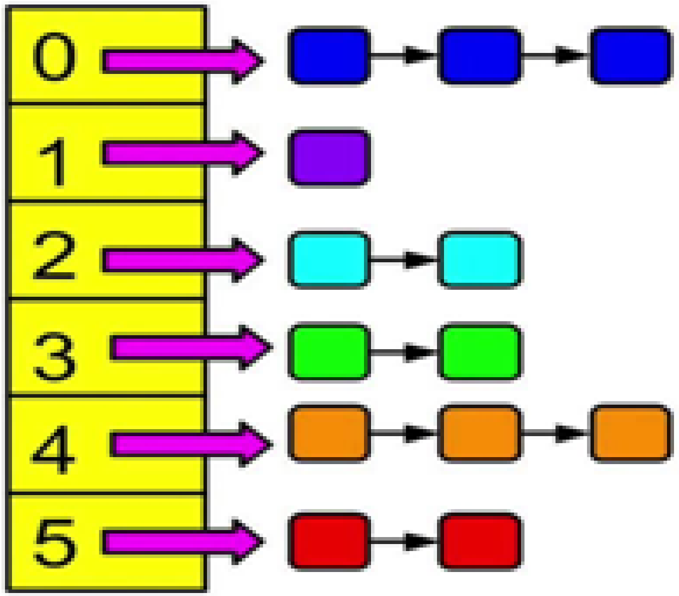
Let’s talk concurrency control

Consider a hash-table



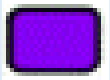
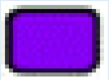
Let’s talk concurrency control

Consider a hash-table



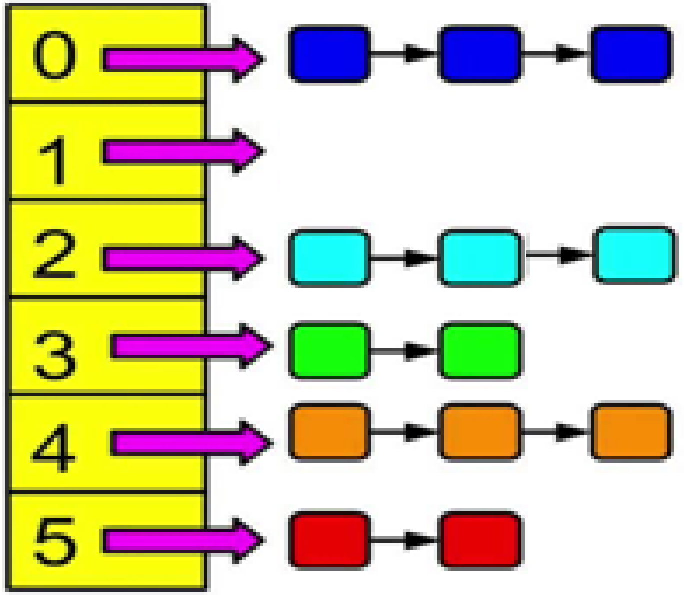
thread T1

ht.add();

if(ht.contains())
    ht.del();

Let’s talk concurrency control

Consider a hash-table



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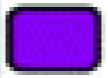
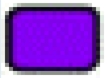
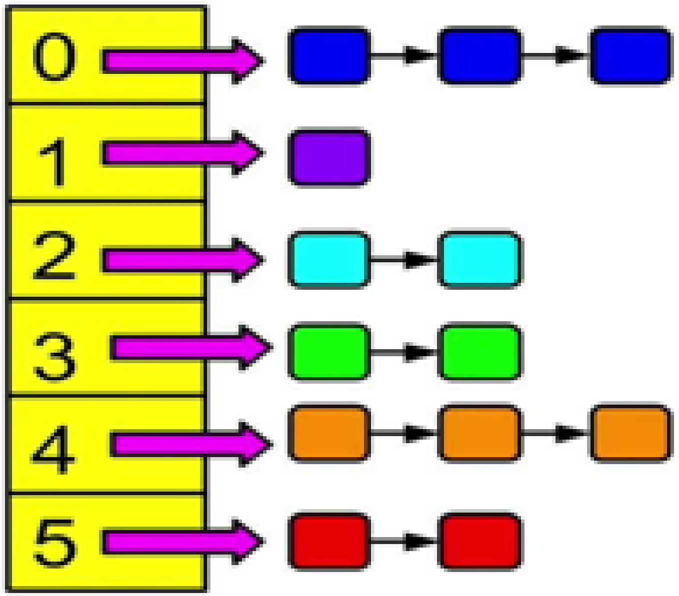
if(ht.contains())

    ht.del();

Let's talk concurrency control

Consider a hash-table



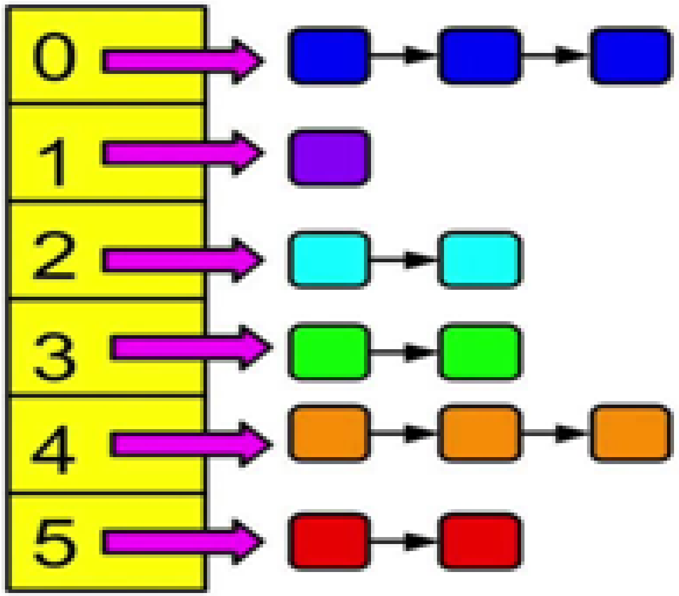
thread T1

```
ht.add(■);

if(ht.contains(■))
    ht.del(■);
```

Let’s talk concurrency control

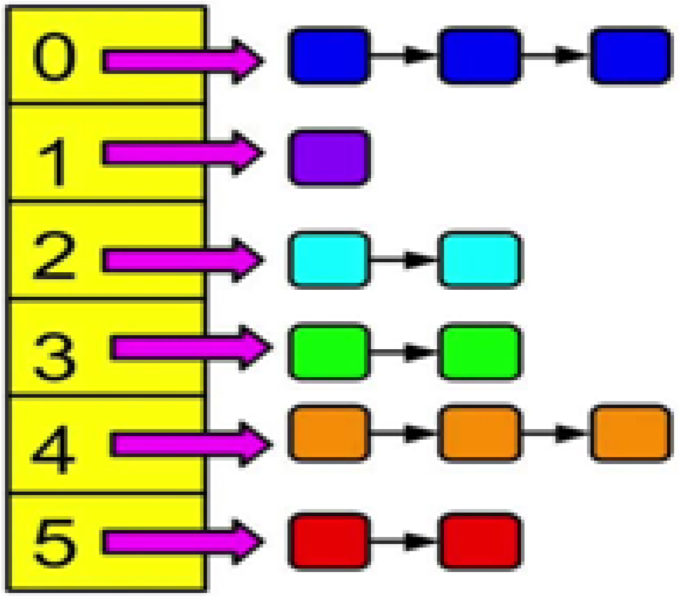
Consider a hash-table



thread T1	thread T2
`ht.add( );`	`ht.add( );`
`if(ht.contains( ))` `ht.del( );`	`if(ht.contains( ))` `ht.del( );`

Let’s talk concurrency control

Consider a hash-table



thread T1	thread T2
ht.add( );	
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Let’s talk concurrency control

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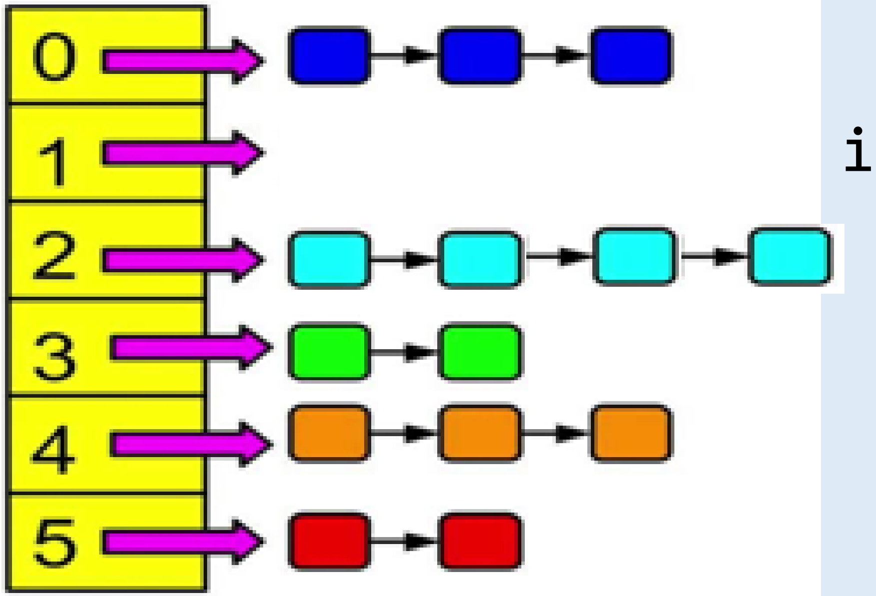
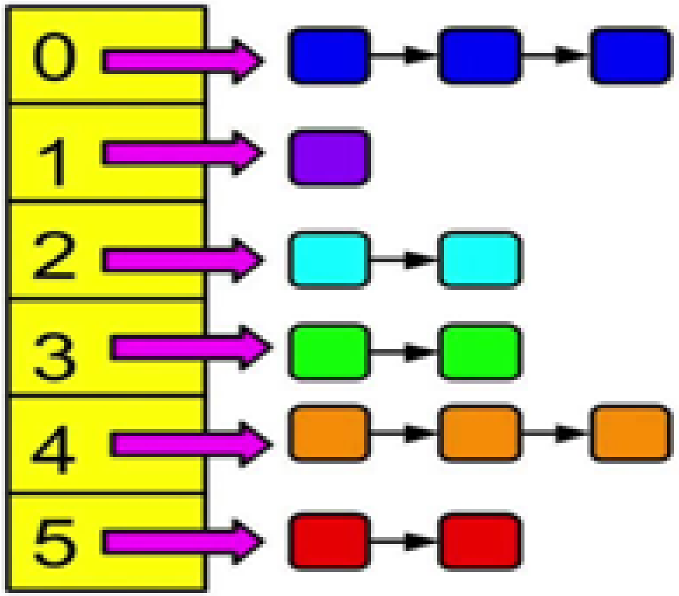


thread T1	thread T2
ht.add();	
	ht.add();
if(ht.contains())	
	if(ht.contains())
	ht.del();
ht.del();	

Pessimistic concurrency control: coarse locks

Consider a hash-table



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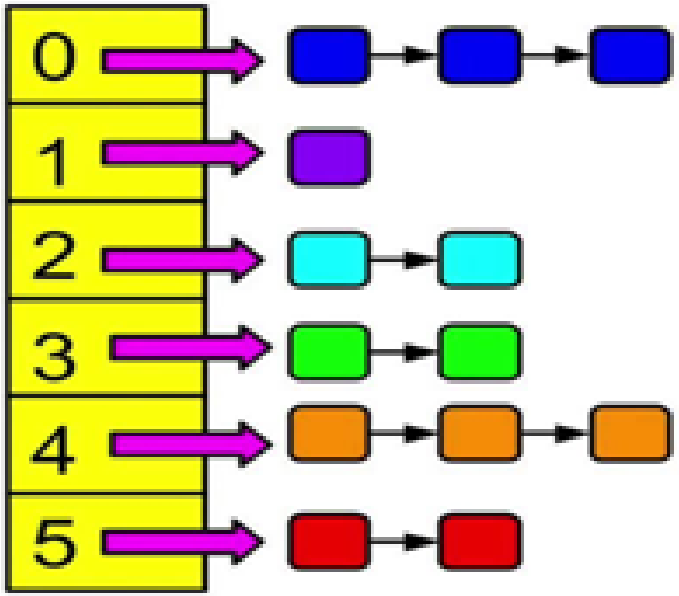
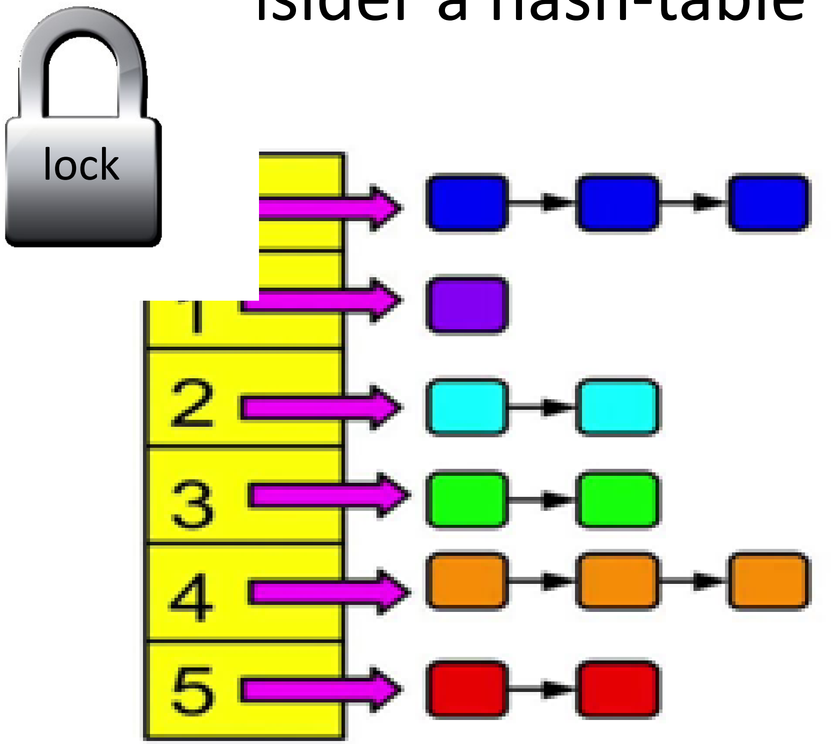


thread T1	thread T2
`ht.add();`	`ht.add();`
`if(ht.contains())`	`if(ht.contains())`
`ht.del();`	`ht.del();`

Pessimistic concurrency control: coarse locks

ısider a hash-table



thread T1	thread T2
`ht.add( );`	`ht.add( );`
`if(ht.contains( ))`	`if(ht.contains( ))`
`    ht.del( );`	`    ht.del( );`

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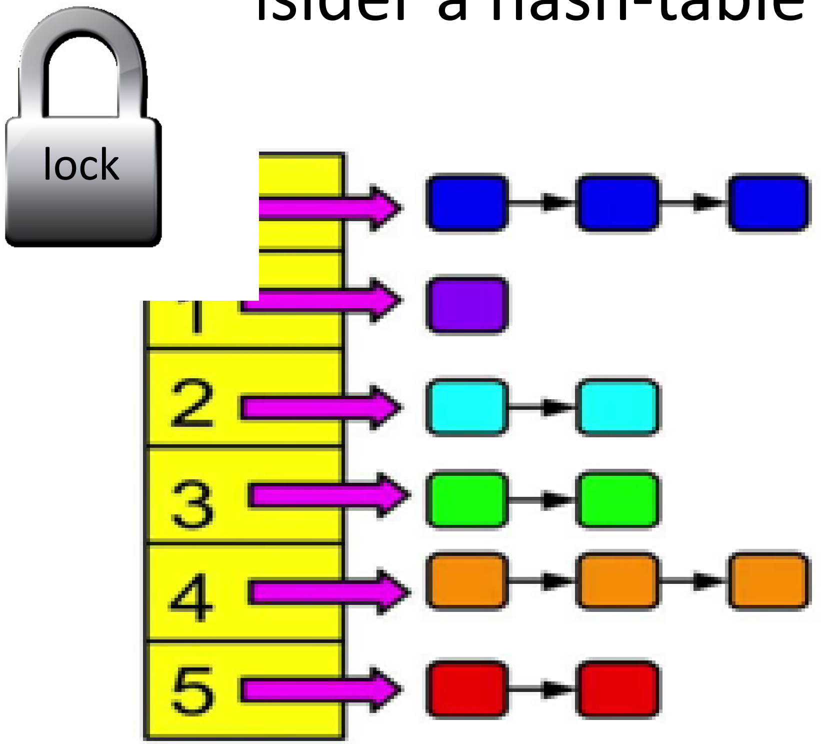
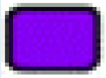
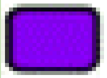
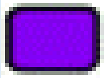
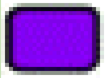


thread T1	thread T2
ht.lock();	
ht.add();	ht.add();
if(ht.contains())	if(ht.contains())
ht.del();	ht.del();

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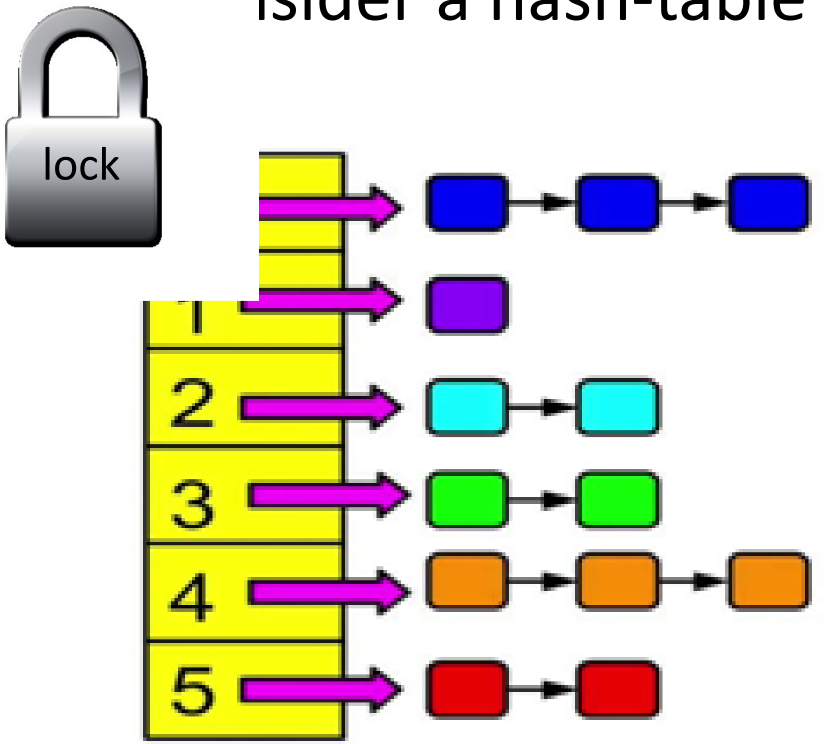

thread T1	thread T2
ht.lock();	
ht.add( );	ht.add( );
if(ht.contains( ))	if(ht.contains( ))
ht.del( );	ht.del( );
ht.unlock();	

Pessimistic concurrency control: coarse locks

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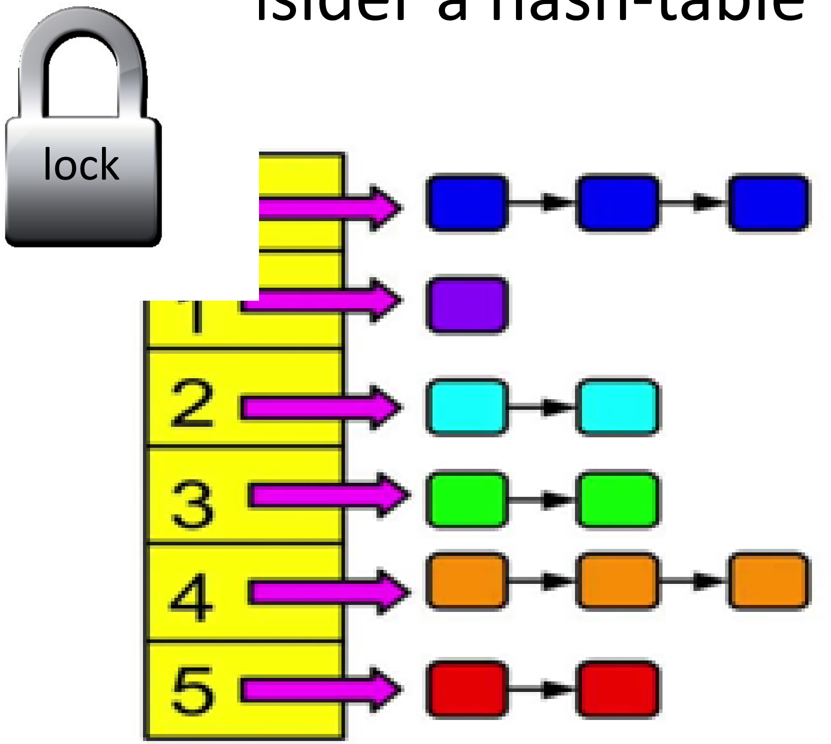

thread T1	thread T2
ht.lock();	**ht.lock();**
ht.add( );	ht.add( );
if(ht.contains( ))	if(ht.contains( ))
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Pessimistic concurrency control: coarse locks

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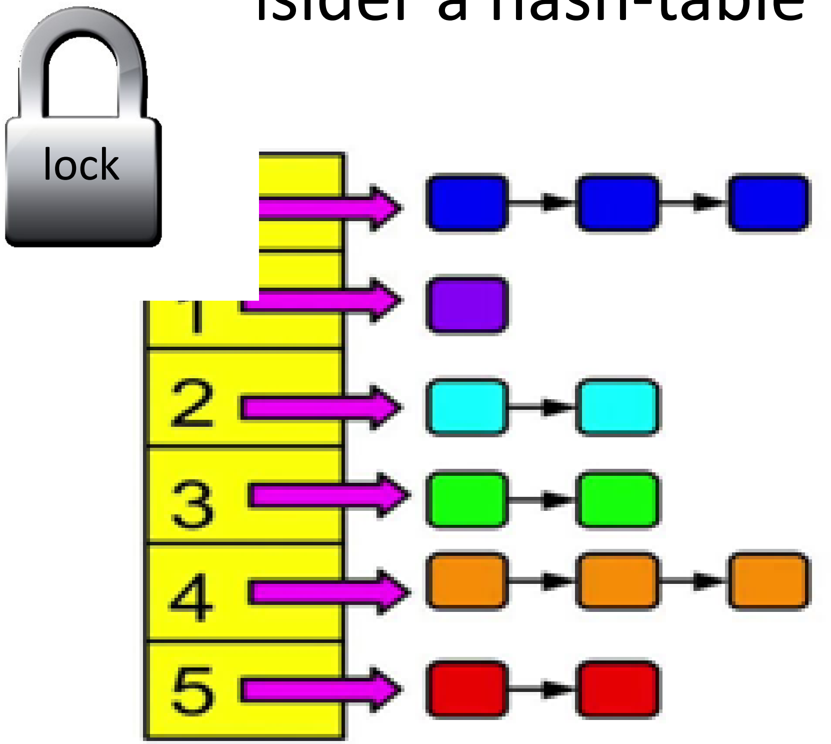

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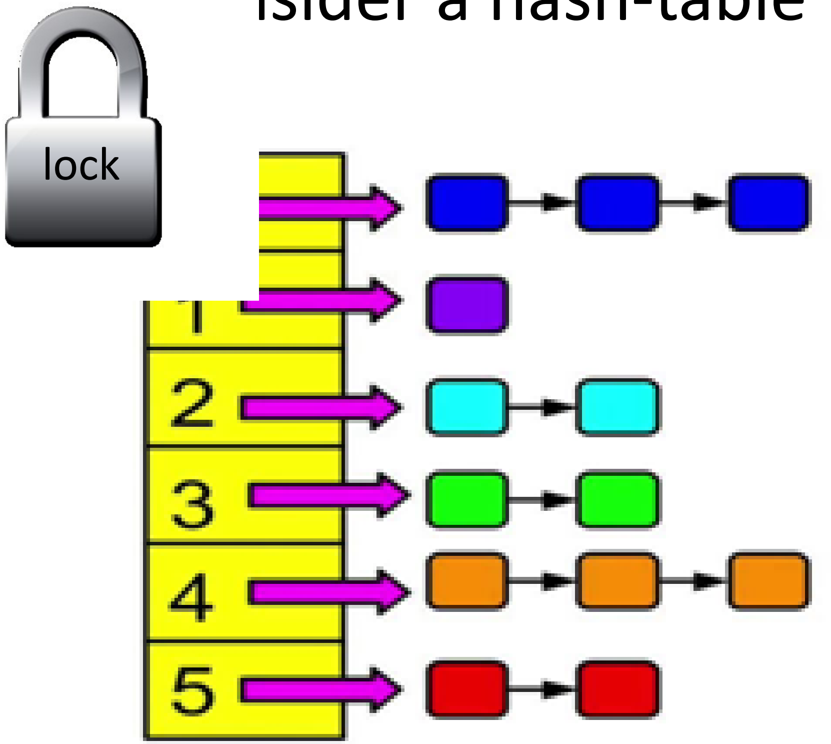

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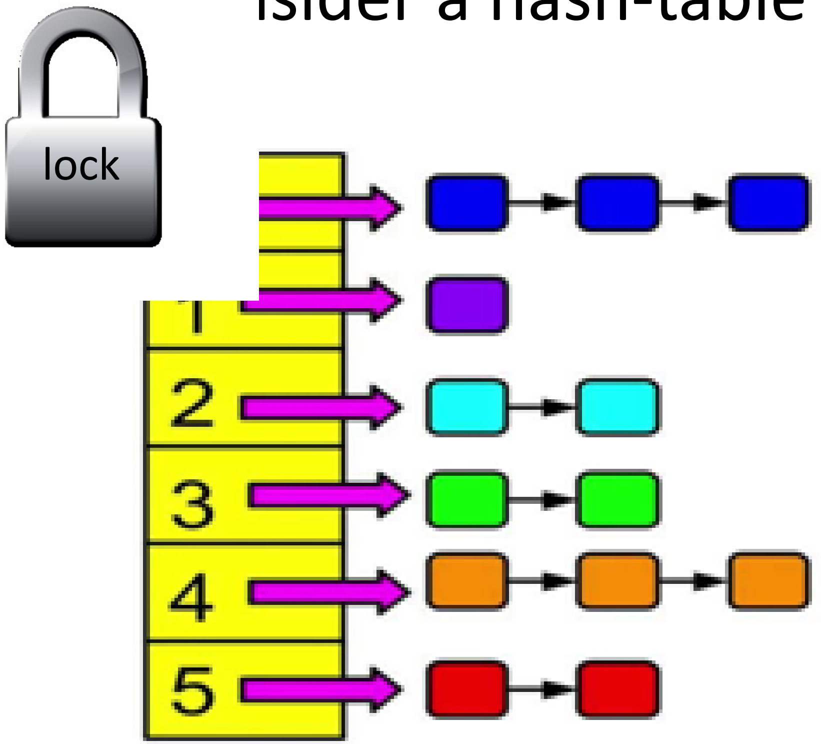
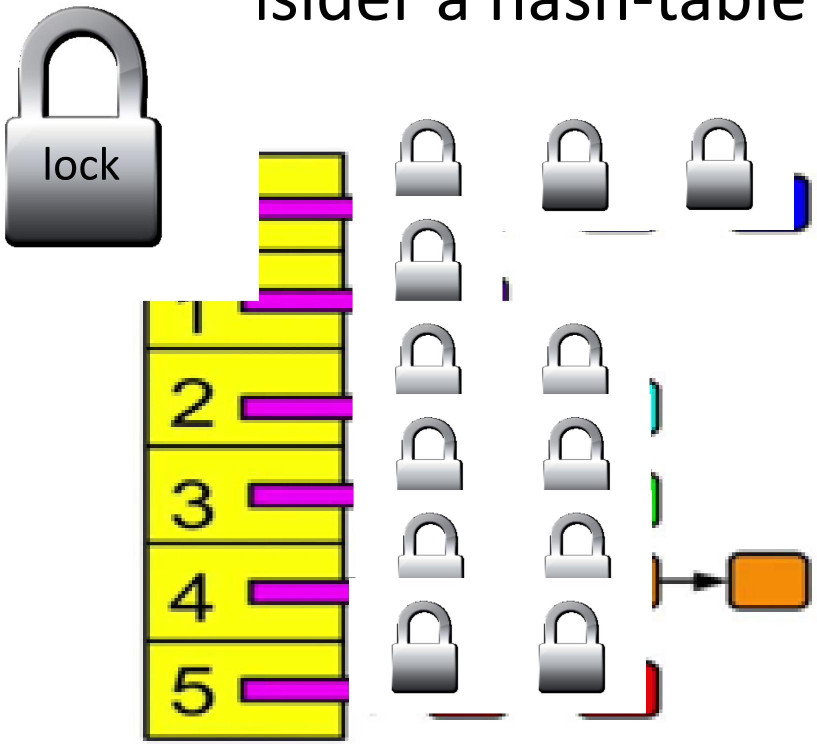


thread T1	thread T2
ht.lock();	**ht.lock();**
ht.add();	ht.add();
if(ht.contains())	if(ht.contains())
ht.del();	ht.del();
ht.unlock();	**ht.unlock();**

Coarse lock:
Non-conflicting ops serialized
Low Complexity -- Low Performance

Pessimistic concurrency control: fine locks

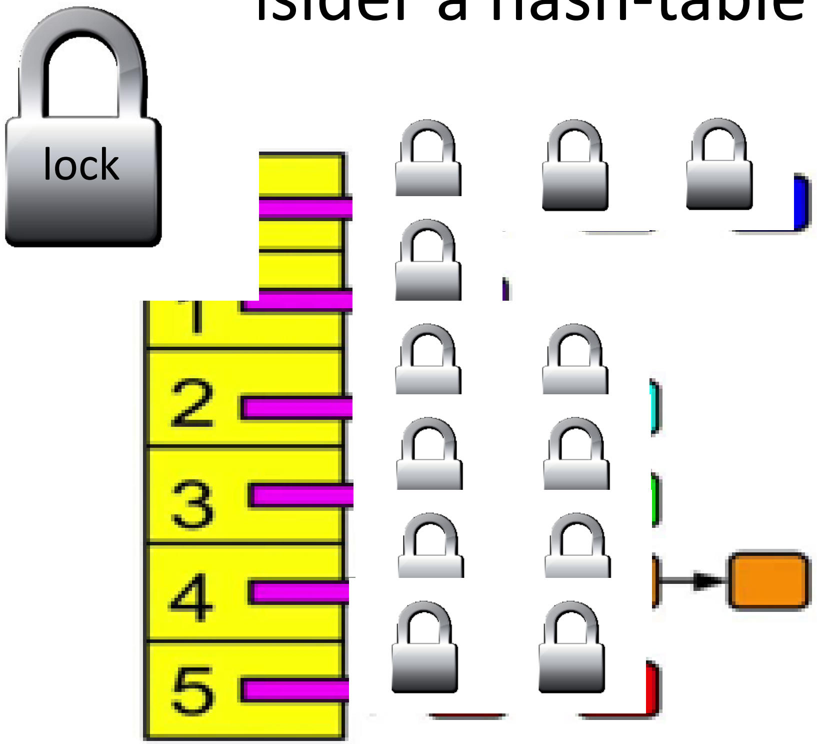
sider a hash-table



thread T1	thread T2
figure-out-locks();	figure-out-locks();
lock-them-inorder();	lock-them-inorder();
ht.add( );	ht.add( );
if(ht.contains( ))	if(ht.contains( ))
ht.del( );	ht.del( );
unlock-locks();	unlock-locks();

Pessimistic concurrency control: fine locks

ısider a hash-table



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if(ht.contains( ))	if(ht.contains( ))
ht.del( );	ht.del( );
unlock-locks();	unlock-locks();

Fine-grain lock:
Non-conflicting parallel
High Complexity -- High Performance

Why Locks are Hard

- Coarse-grain locks
  - Simple to develop
  - Easy to avoid deadlock
  - Few data races
  - Limited concurrency
- Fine-grain locks
  - Greater concurrency
  - Greater code complexity
  - Potential deadlocks
    - Not composable
  - Potential data races
    - Which lock to lock?

Why Locks are 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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`move(a, b, key1);`	
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  UNLOCK(s);
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    - Which lock to lock?

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DEADLOCK!