ConWelcrency
ome to cs378h

Chris Rossbach

Concurrency
Welcome to cs378h

Chris Rossbach

Outline for Today

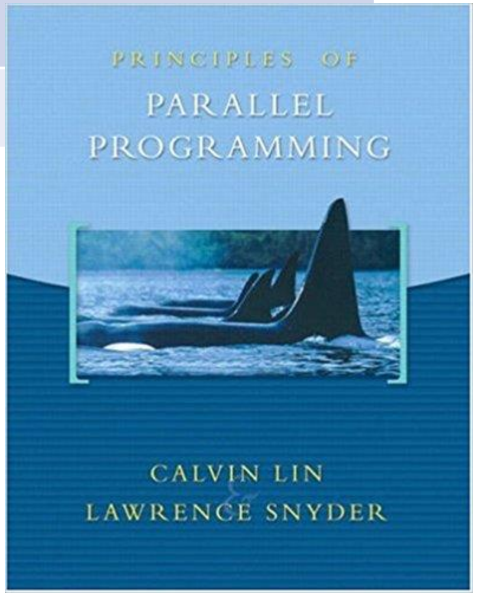
- Questions?
- Administrivia
- Course Overview
- Course Details and Logistics
- Concurrency & Parallelism Basics

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*

Course Details

Course Name:	**CS378 – Concurrency**
Unique Number:	53035
Lectures:	M,W 9:30-11:00AM here
Class Web Page:	http://www.cs.utexas.edu/users/rossbach/cs378h
Instructor:	Chris Rossbach
TA:	Allen Jue and Sasha Huang
Text:	Principles of Parallel Programming (ISBN-10: 0321487907)



Please read the syllabus!

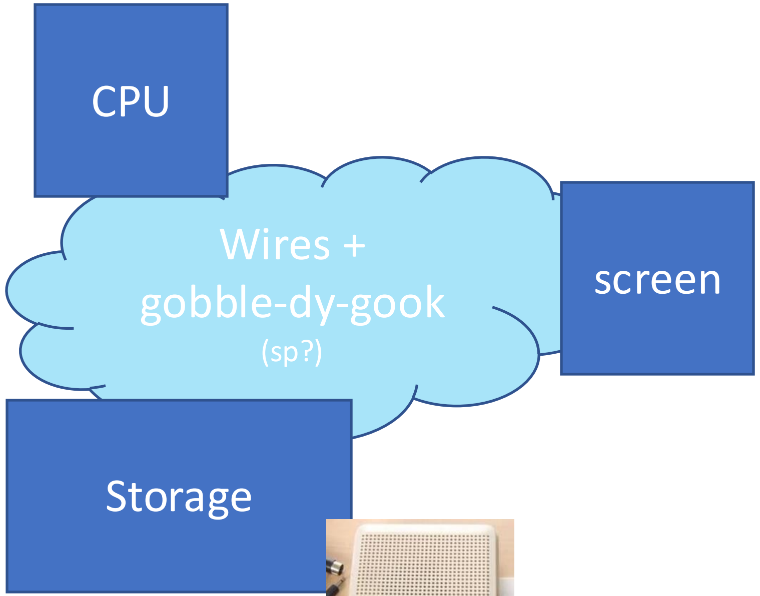
…More on this shortly…

Why you should take this course

- Concurrency is super-cool, and super-important
- You'll learn important concepts and background
- Have *fun* programming cool systems
  - GPUs! (optionally) FGPAs!
  - Modern Programming languages: Go! Rust!
  - Interesting synchronization primitives (not just boring old locks)
  - Programming tools people use to program *super-computers (ooh…)*

Two perspectives:
- The "just eat your kale and quinoa" argument
- The "it's going to be fun" argument

My first computer



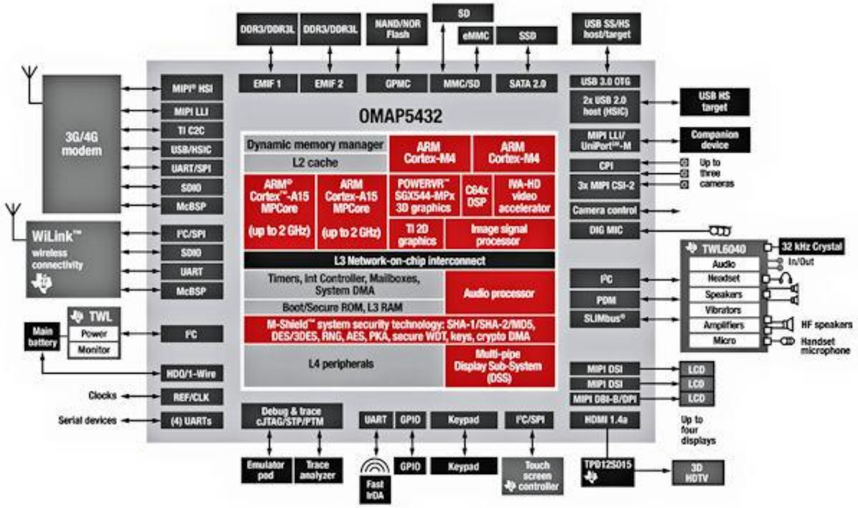
Tape drive!
(also good for playing heavy metal music)

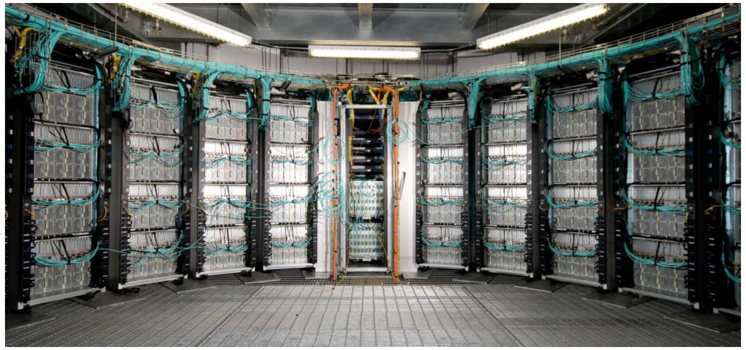
My current computer

Too boring…

Another of my current computers

A lot has changed but…
the common theme is…??





CPU

CPU

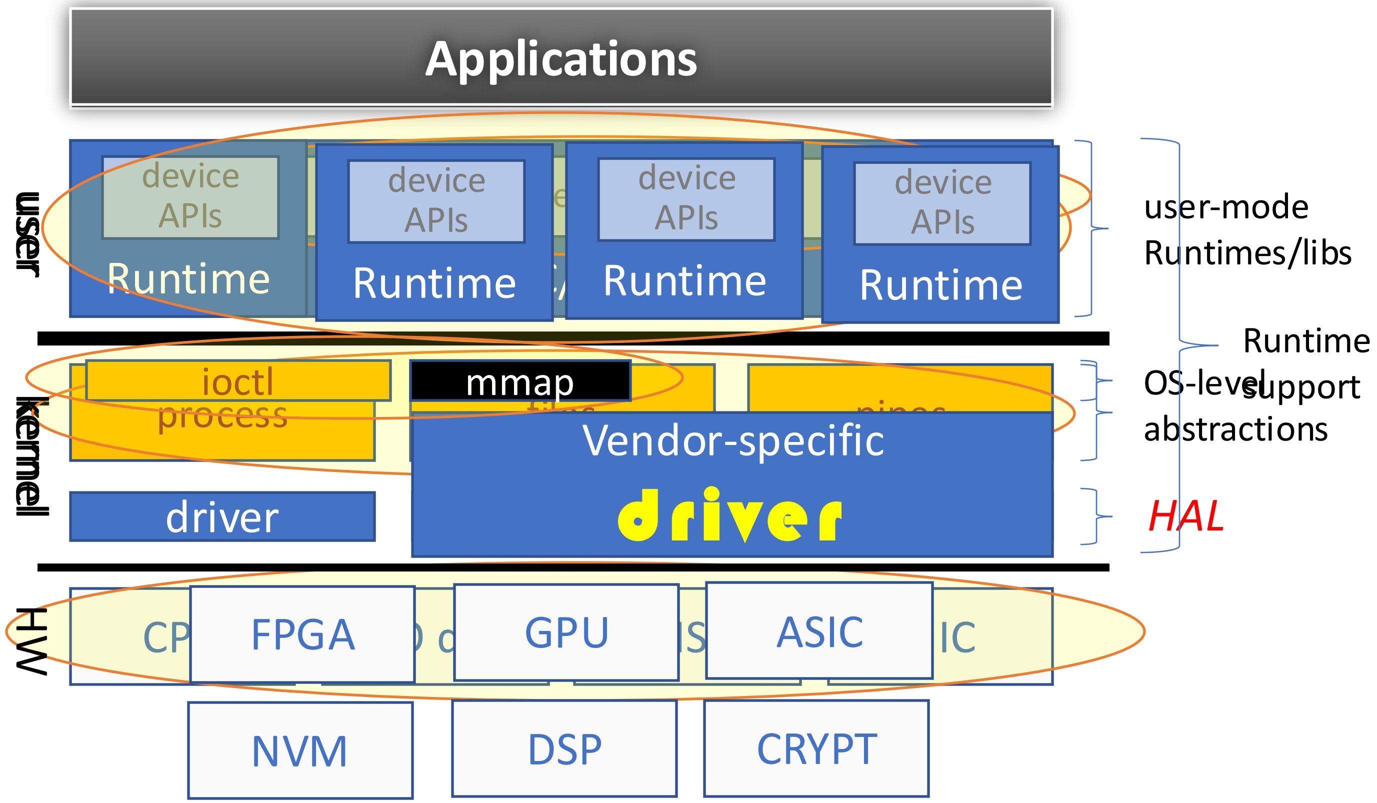
GPU

Image DSP

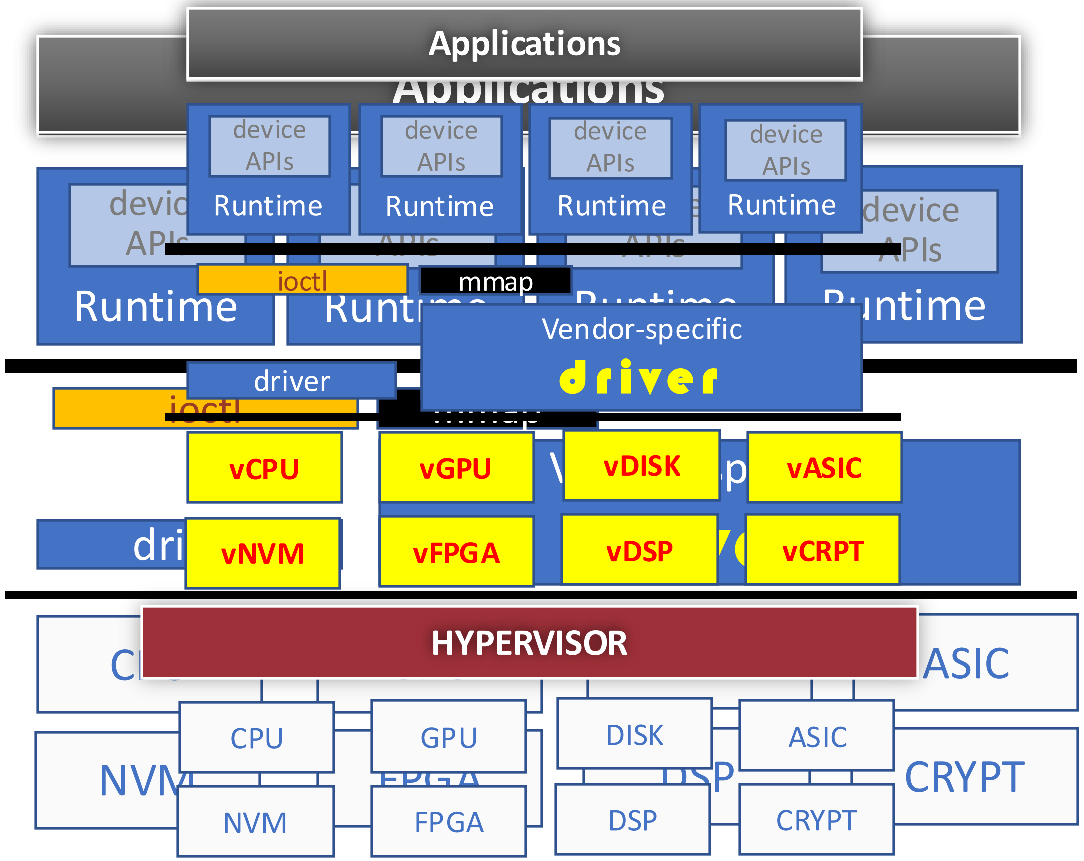
Crypto

…

Modern Technology Stack



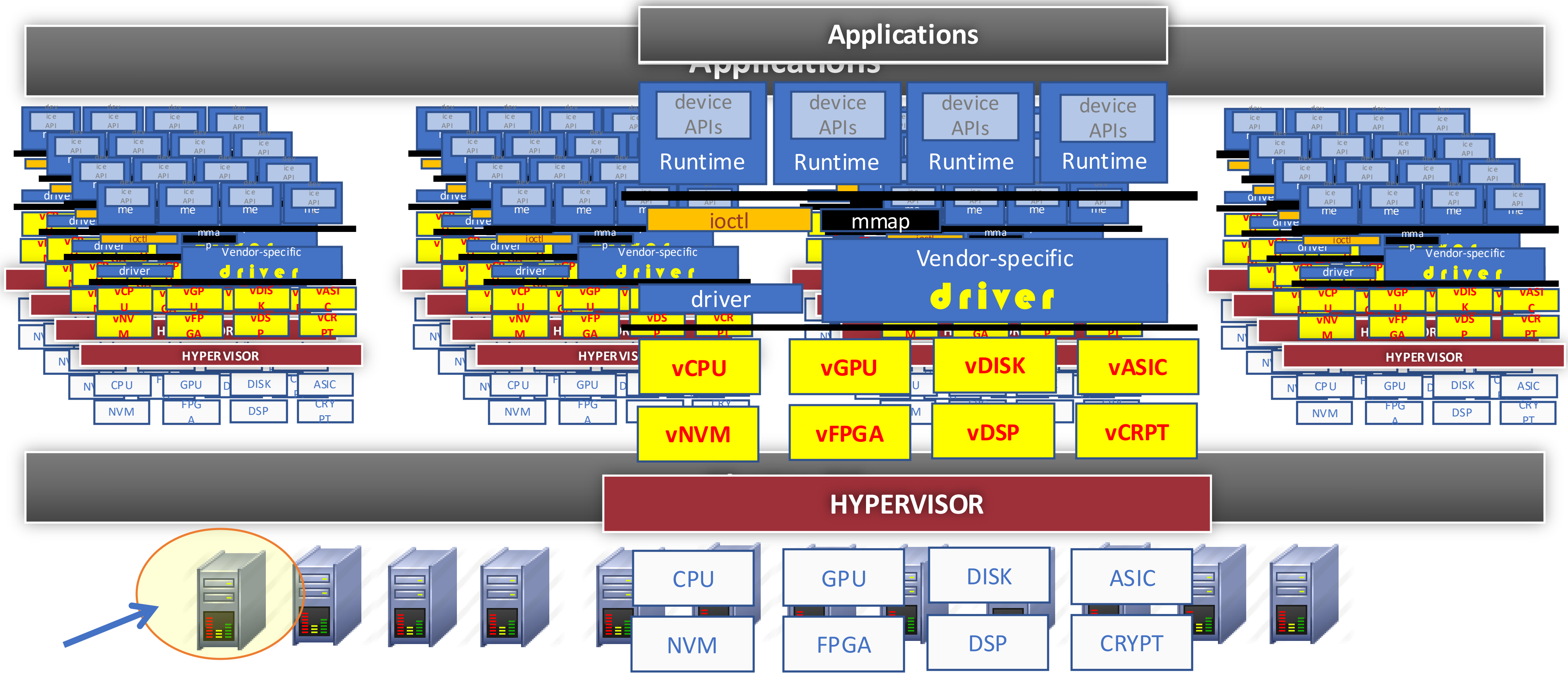
Concurrency and Parallelism are Everywhere



Wait!

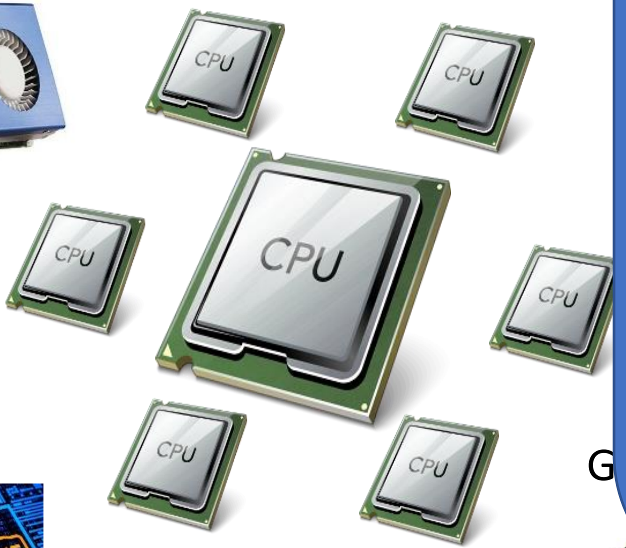
- What's concurrency?
- What's parallelism?

Concurrency and Parallelism are Everywhere



Concurrency and Parallelism are everywhere

DSP



Crypto

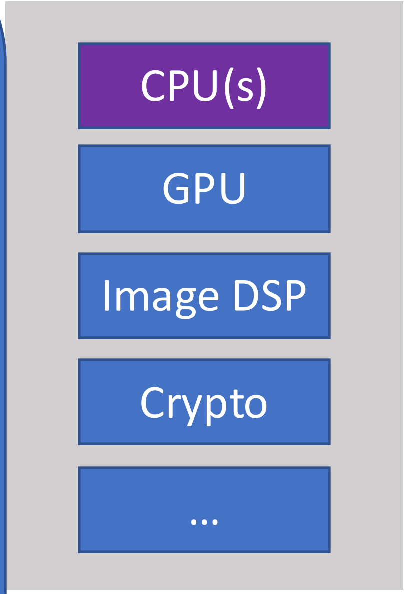
G

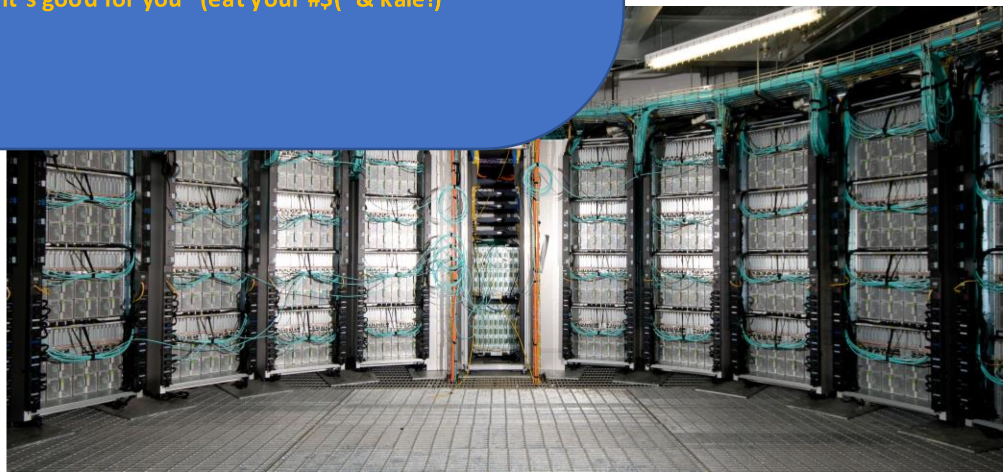
How much parallel and concurrent programming have you learned so far?

- Concurrency/parallelism can’t be avoided anymore (want a job?)
- A program or two playing with locks and threads isn’t enough
- I’ve worked in industry a lot—I know

Course goal is to expose you to lots of ways of programming systems like these

…So “you should take this course because it’s good for you” (eat your #$(*& kale!)





Goal: Make Concurrency Your Close Friend
Method: Use Many Different Approaches to Concurrency

Abstract	Concrete
Locks and Shared Memory Synchronization	Shared Counter, Prefix Sum with pthreads
Language Support	Go lab: condition variables, channels, go routines Rust lab: 2PC
Parallel Architectures	GPU Programming Lab ***(Optional) FPGA Programming Lab***
HPC	***(Optional) MPI lab***
Distributed Computing / Big Data	Rust 2PC
Modern/Advanced Topics	• Specialized Runtimes / Programming Models • Auto-parallelization • Race Detection
Whatever Interests YOU	Project

Logistics Reprise

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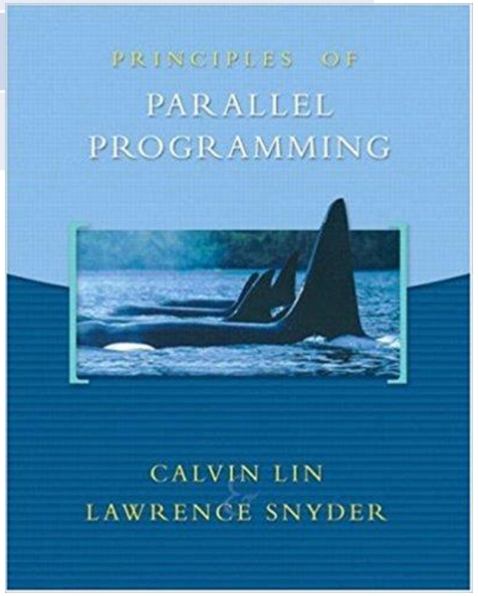

Seriously, read the syllabus!
Also, start Lab 1!

Two Super-Serious Notes

- Inclusivity and respect are *absolute* musts

- Don’t make your repos public or look at other people’s public repos
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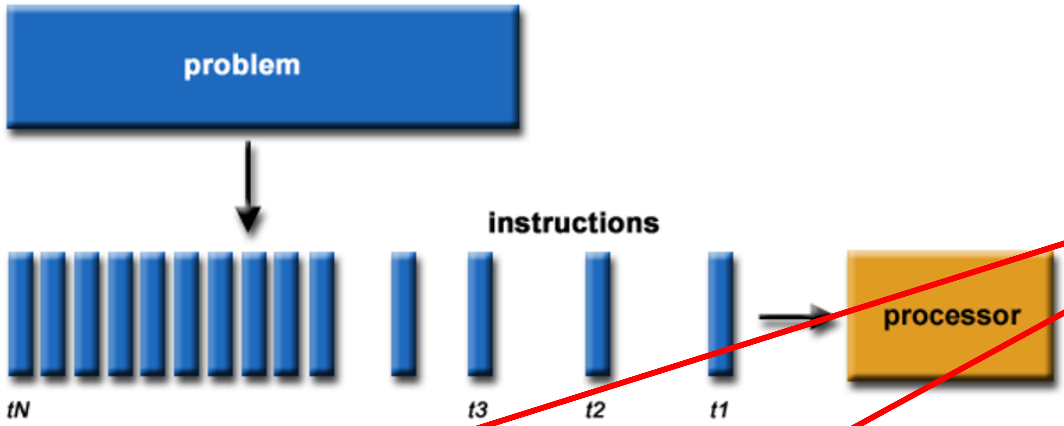
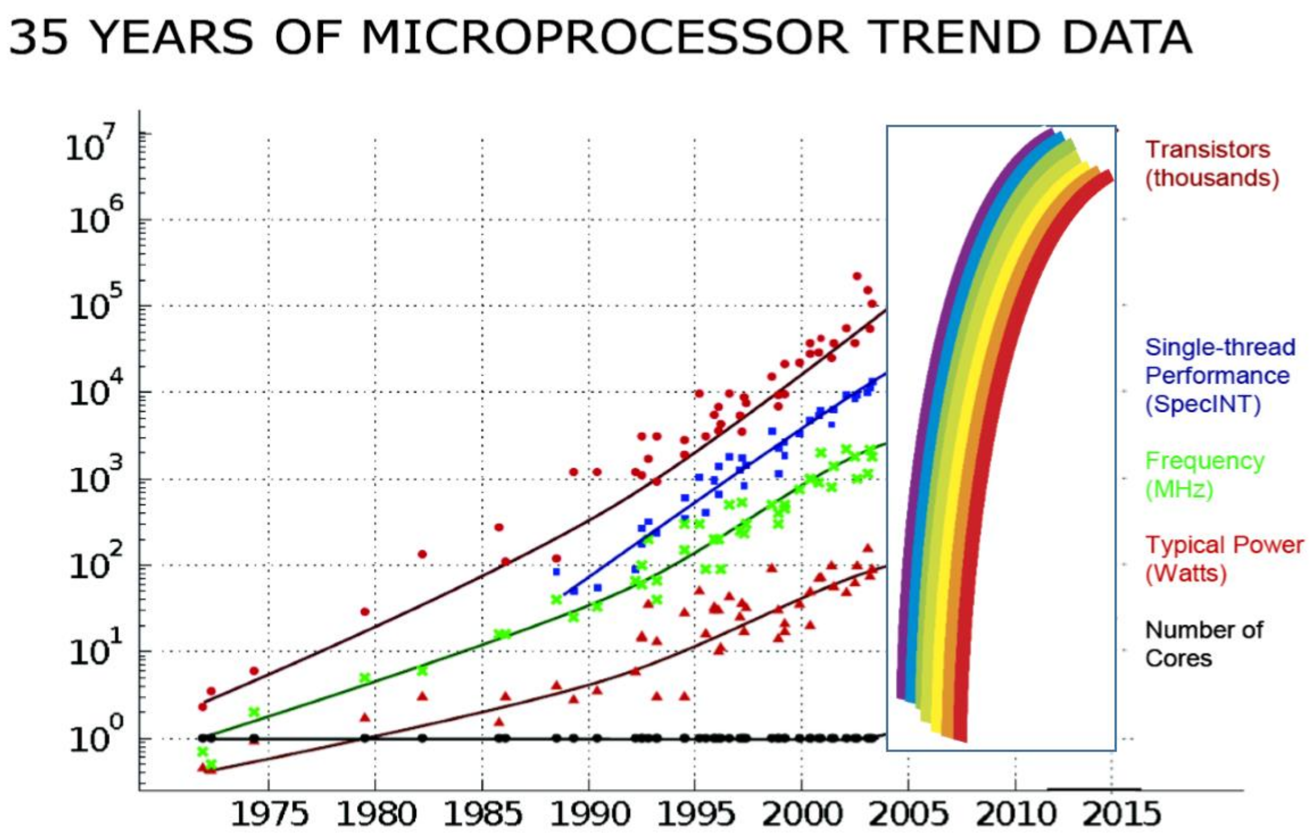
Serial vs. Parallel Program



Key concerns:

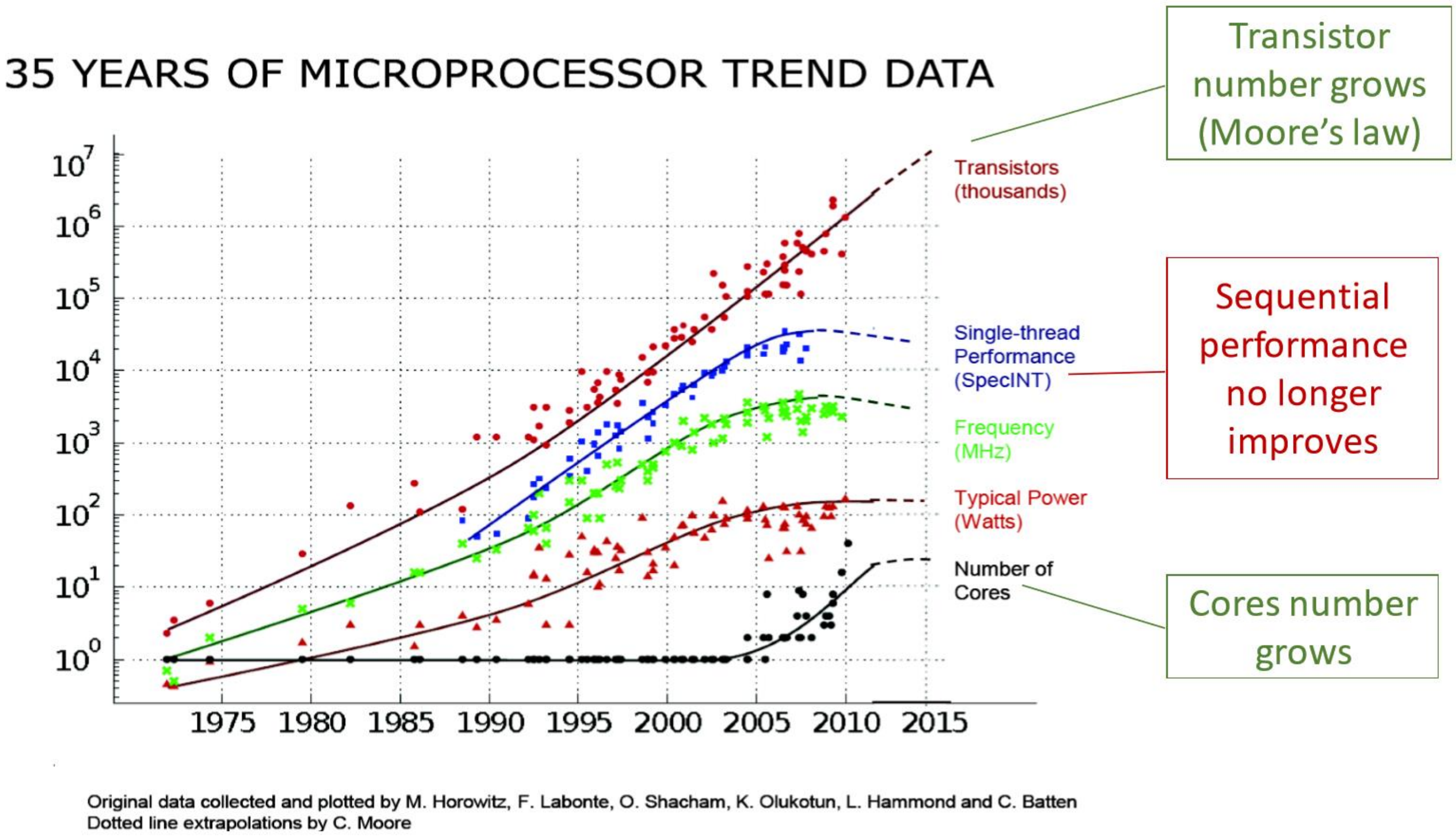
- Programming model
- Execution Model
- Performance/Efficiency
- Exposing parallelism

Free lunch…



Original data collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond and C. Batten
Dotted line extrapolations by C. Moore

Free lunch – is over ☹



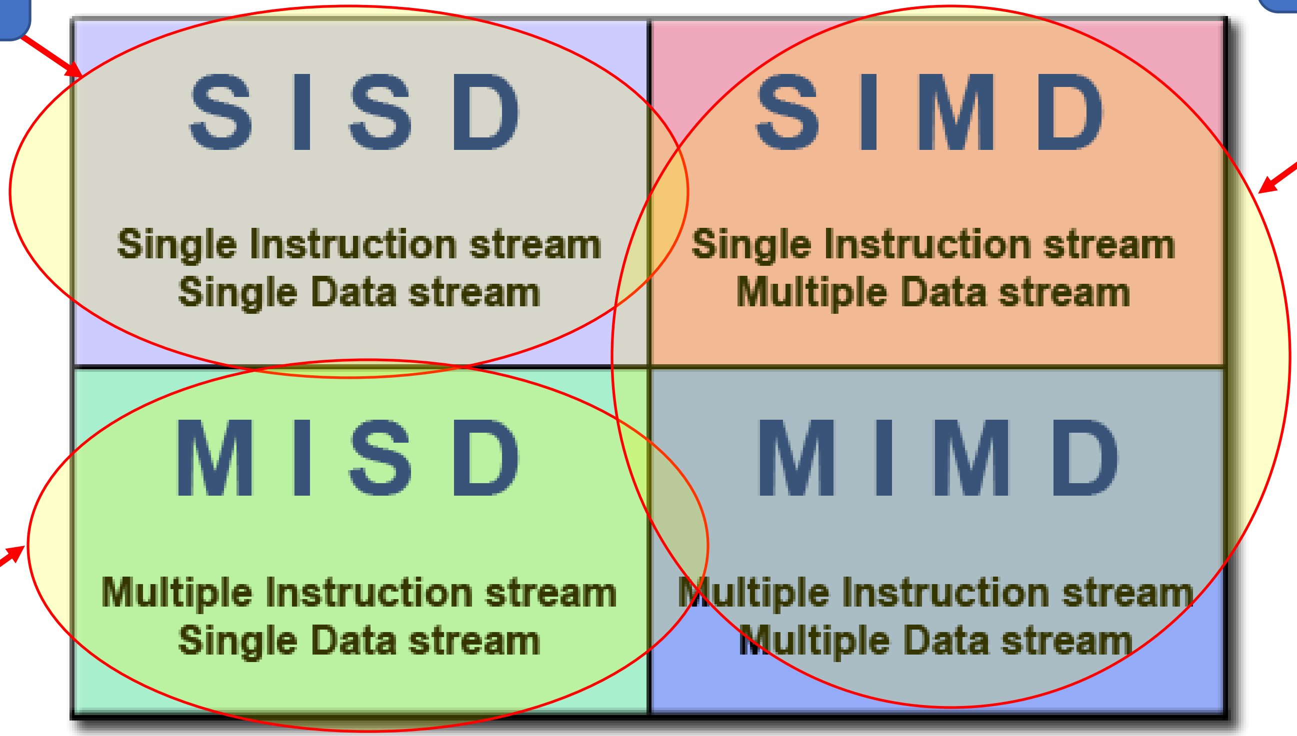
Flynn’s Taxonomy

SISD	SIMD
MISD	MIMD

Execution Models: Flynn’s Taxonomy

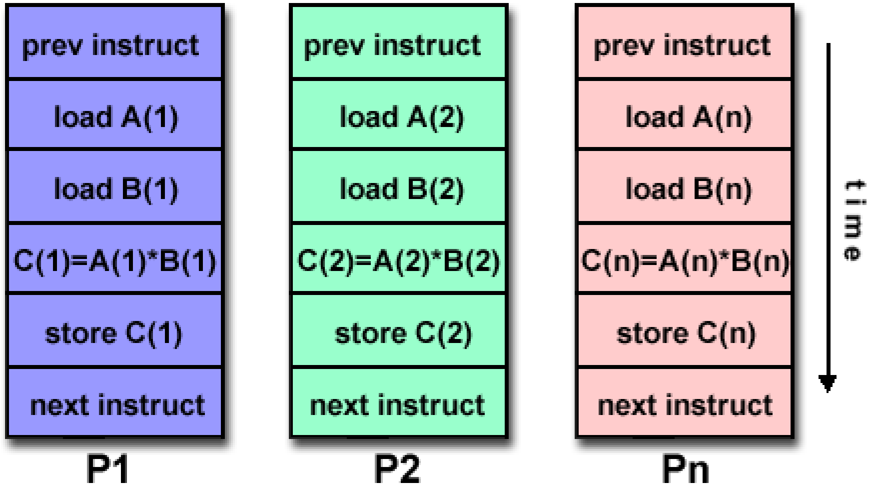
Normal Serial program

Our main focus

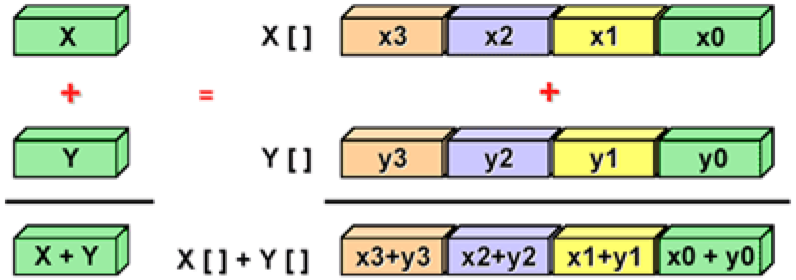


Fault – tolerance
Pipeline parallelism

SIMD

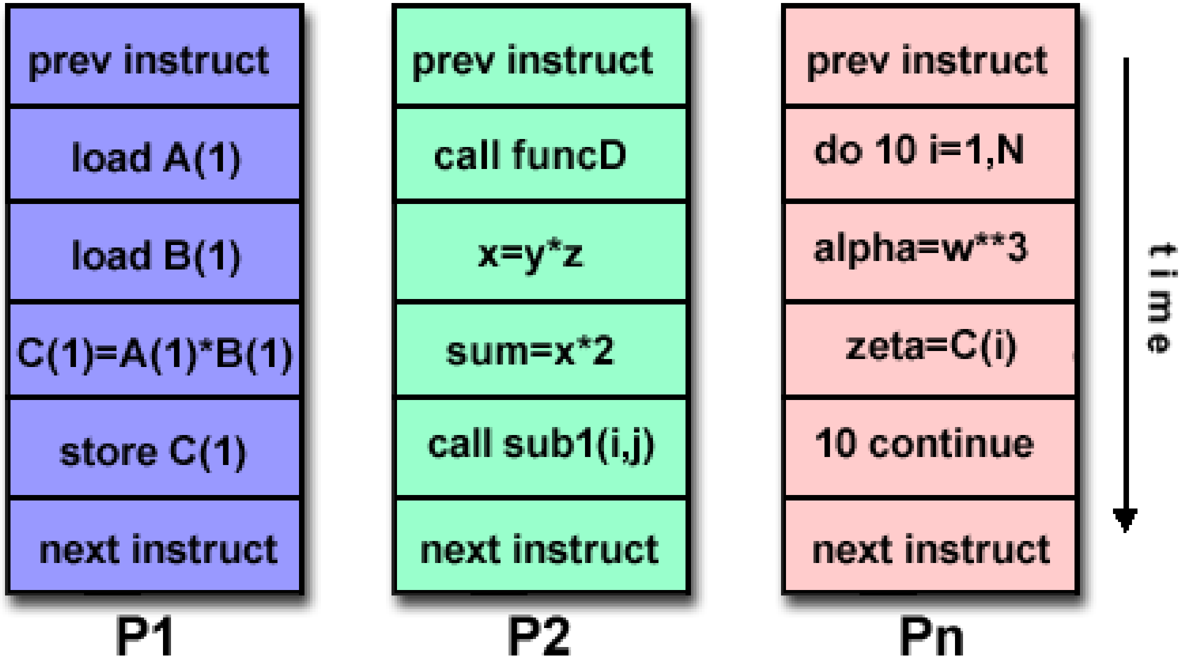


- Example: vector operations (e.g., Intel SSE/AVX, GPU)



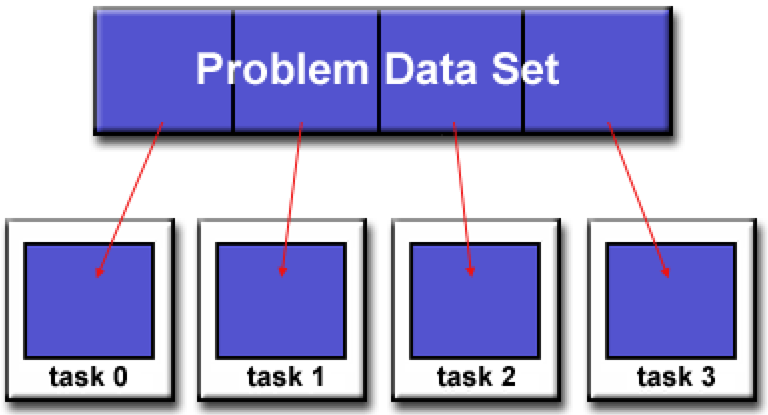
MIMD

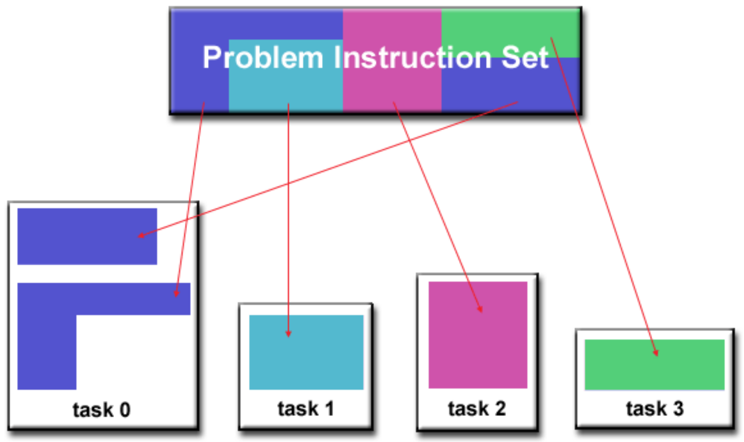
- Example: multi-core CPU



Problem Partitioning

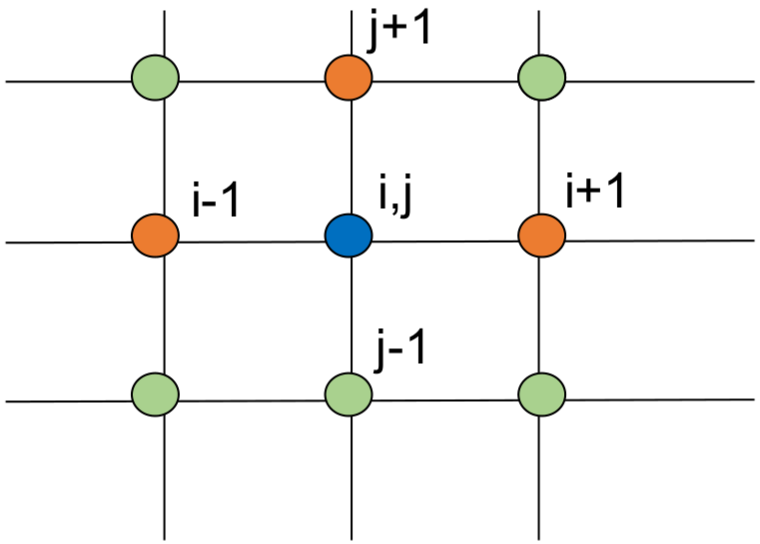
- Decomposition: Domain v. Functional
- Domain Decomposition
  - SPMD
  - Input domain
  - Output Domain
  - Both
- Functional Decomposition
  - MPMD
  - Independent Tasks
  - Pipelining



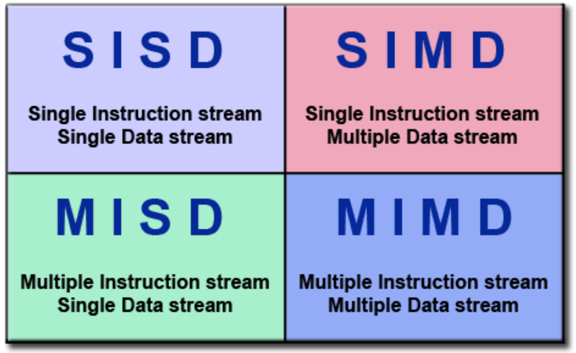


Game of Life

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

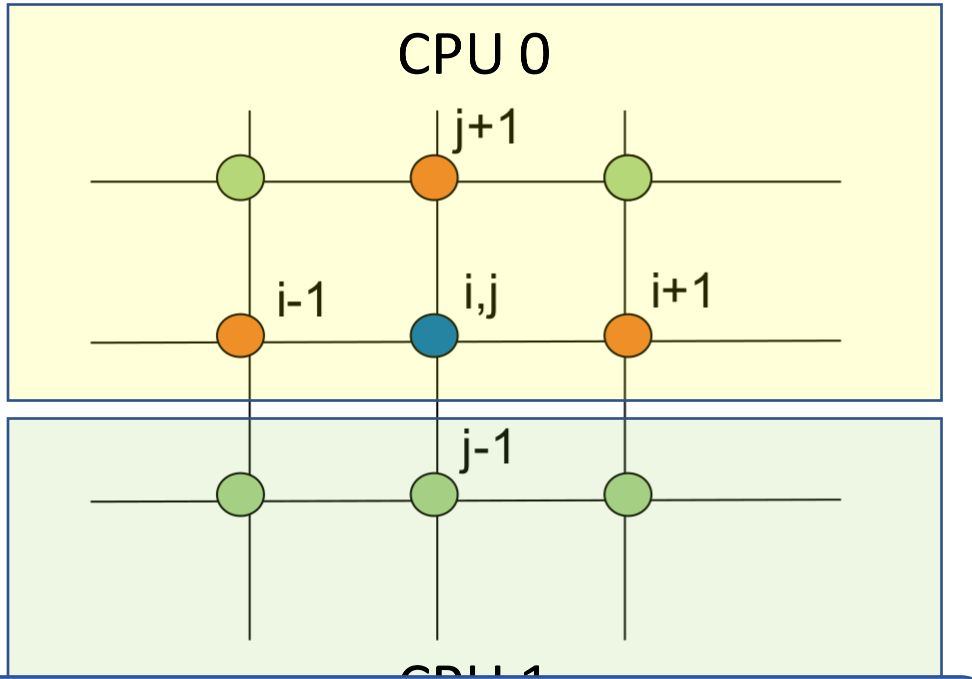


What model fits "best"?



Domain decomposition

- Each CPU gets part of the input



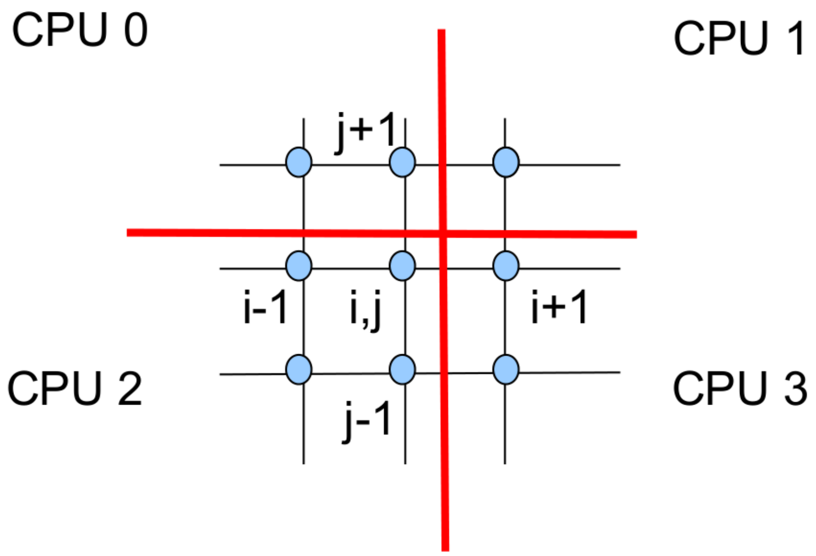
How could we do a functional decomposition?

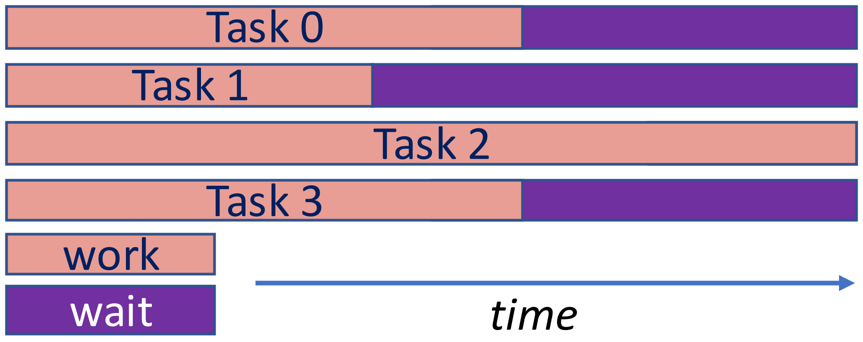
Issues?

- Accessing Data
  - Can we access v(i+1, j) from CPU 0
    - …as in a "normal" serial program?
    - Shared memory? Distributed?
  - Time to access v(i+1,j) == Time to access v(i-1,j) ?
  - *Scalability vs Latency*
- Control
  - Can we assign one vertex per CPU?
  - Can we assign one vertex per process/logical task?
  - *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

- Slowest task determines performance



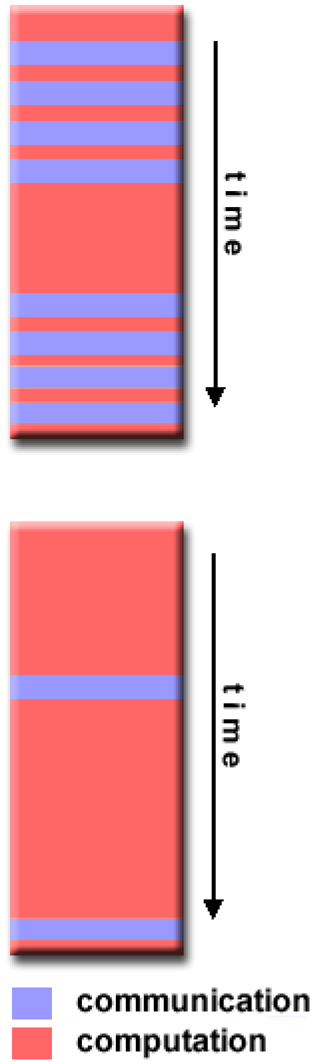


Granularity

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

- 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



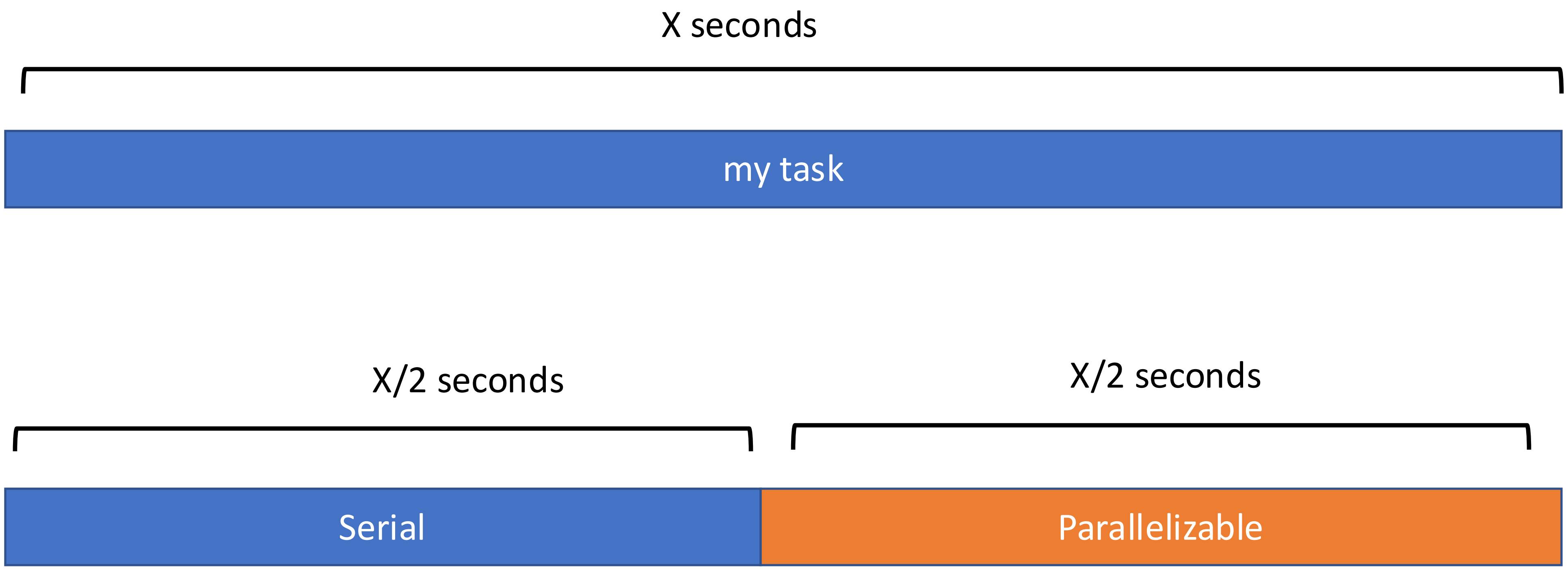
Performance: Amdahl's law

- Sp
- Sp

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

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

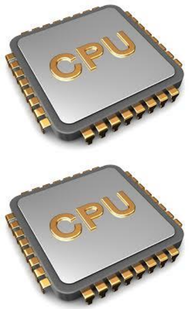
Amdahl's law

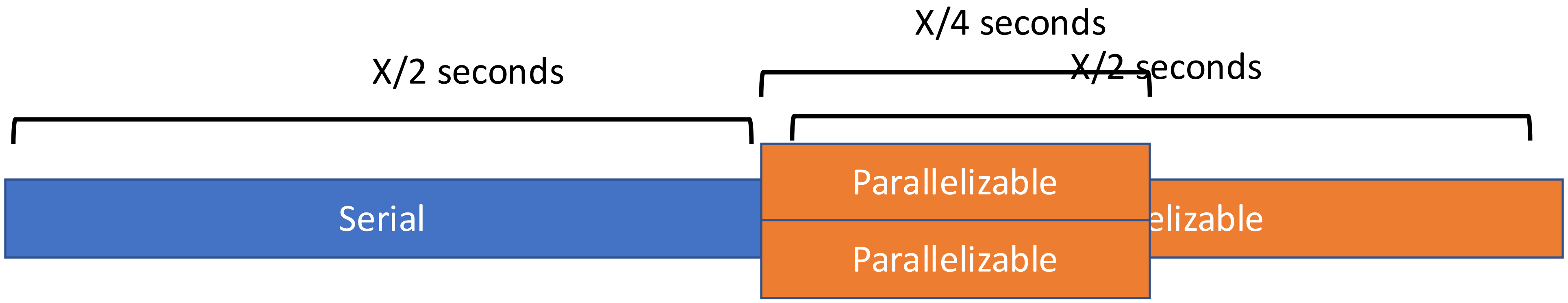


What makes something "serial" vs. parallelizable?

Amdahl's law

2 CPUs





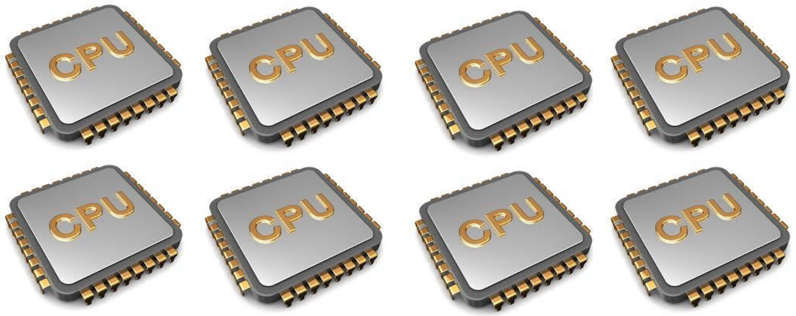
End to end time: (X/2 + X/4) = (3/4)X seconds

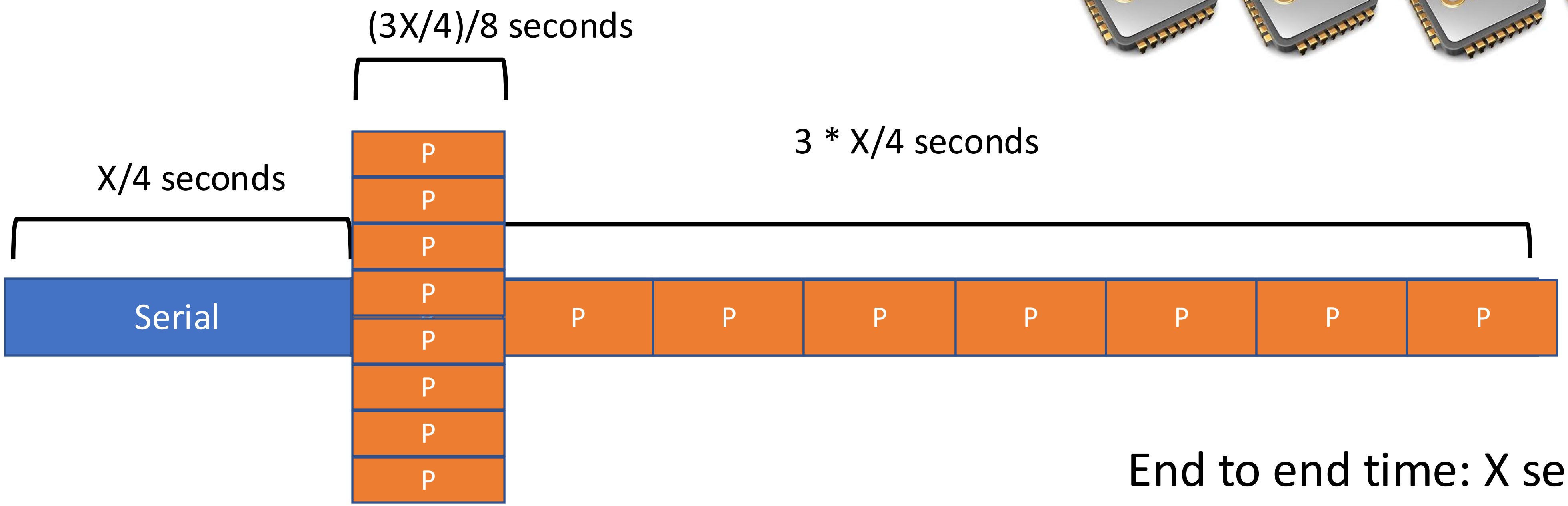
What is the "speedup" in this case?

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

Speedup exercise

8 CPUs



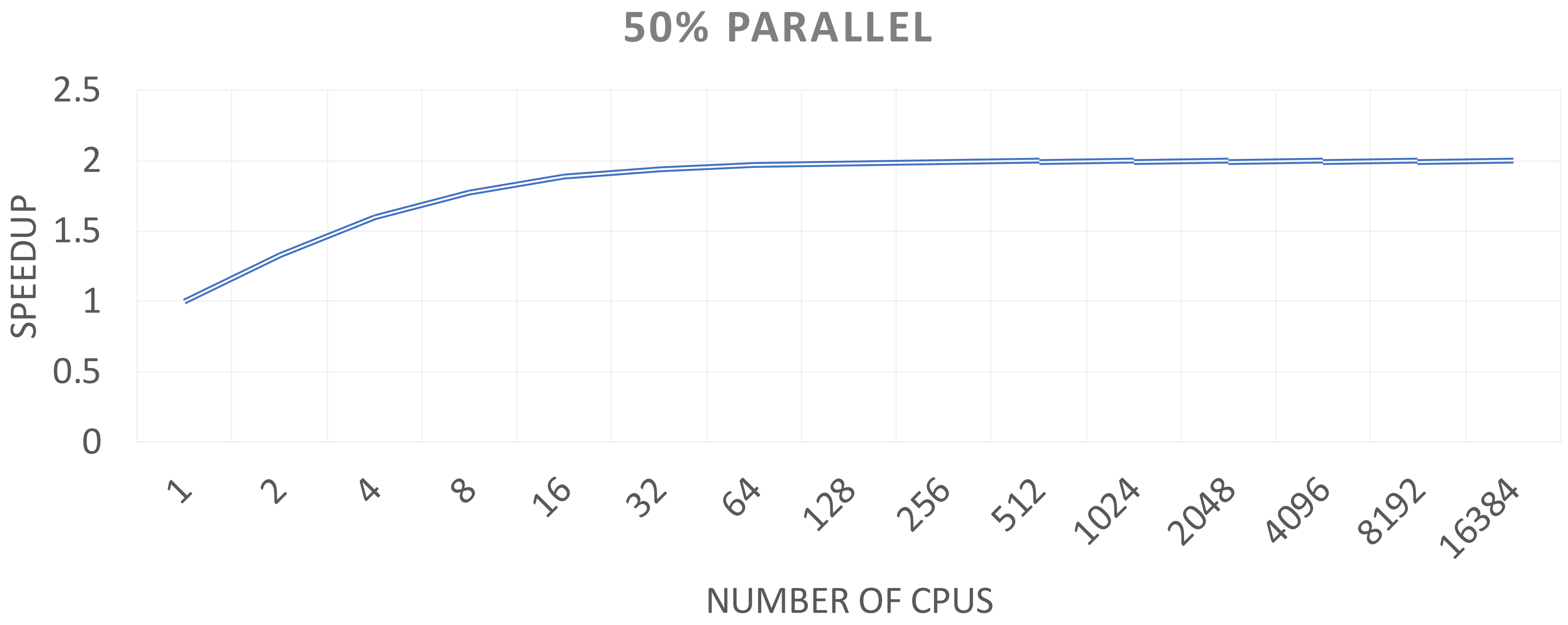


End to end time: X seconds

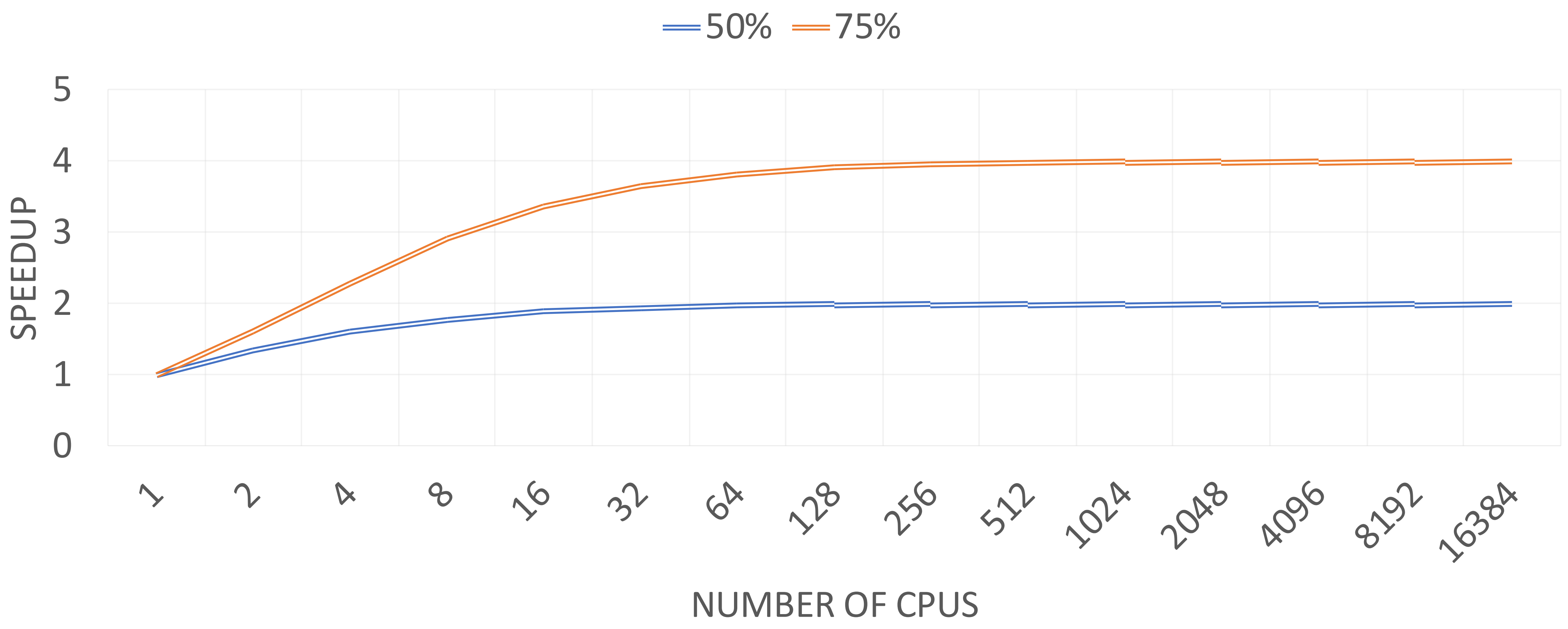
What is the “speedup” in this case?

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

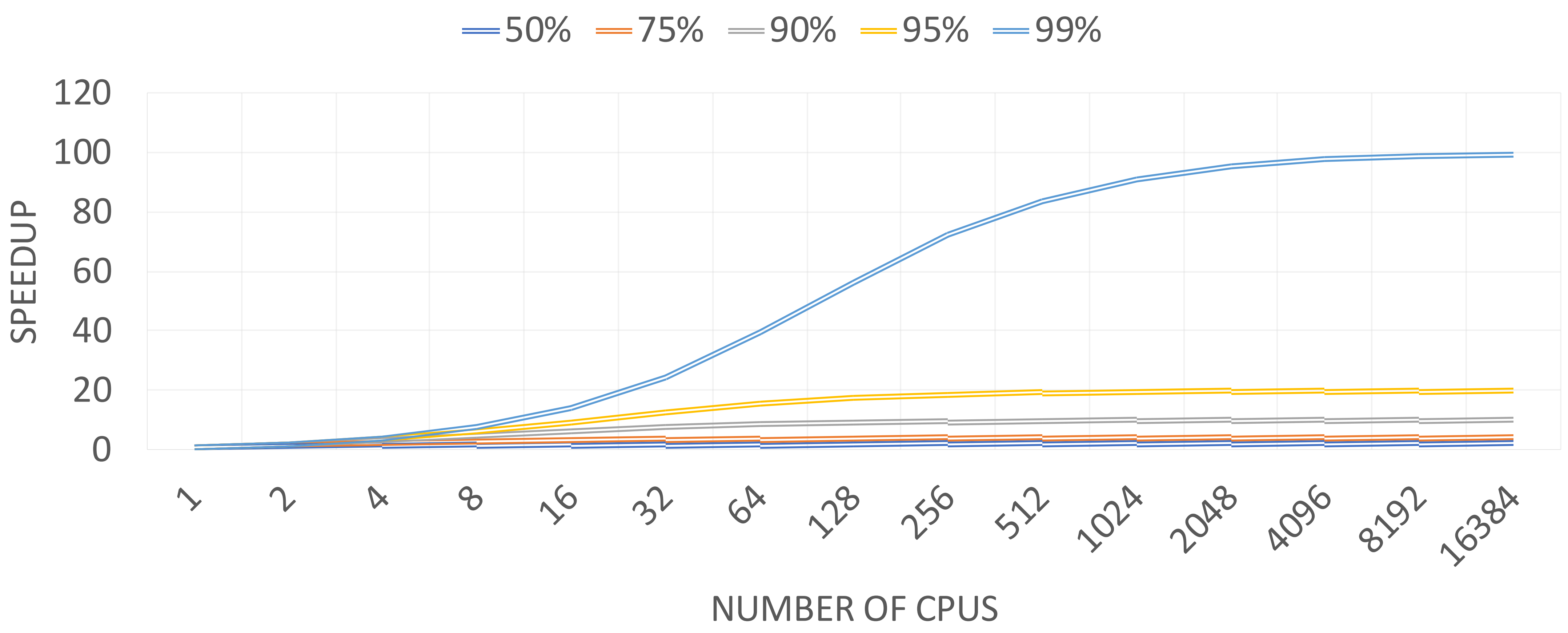
Amdahl Action Zone



Amdahl Action Zone



Amdahl Action Zone



Strong Scaling vs Weak Scaling

Amdahl vs. Gustafson

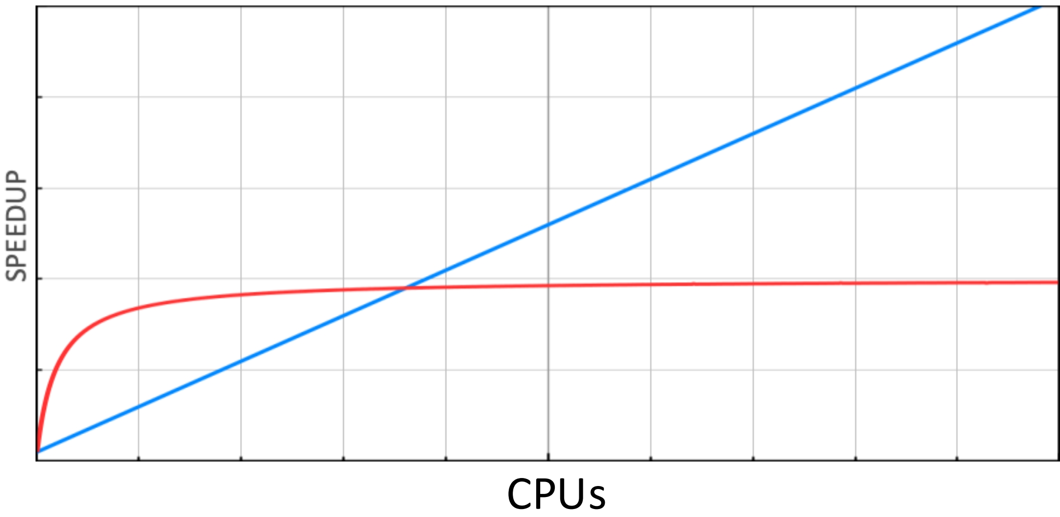
- $N = \#CPUs,\ S = serial\ portion = 1 - A$
- Amdahl's law: $Speedup(N) = \frac{1}{\frac{A}{N}+S}$
  - **Strong scaling:** $Speedup(N)$ calculated given total amount of work is fixed
  - Solve same problems faster when problem size is fixed and #CPU grows
  - Assuming parallel portion is fixed, speedup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

- Gustafson's law: *Speedup(N)* = S + (S-1)*N
  - **Weak scaling:** *Speedup(N) calculated given work per CPU is fixed*
  - Work/CPU fixed when adding more CPUs keeps granularity fixed
  - Problem size grows: solve larger problems
  - **Consequence:** speedup upper bound is much higher
  - Given work W on n CPUs, with α serial
    - Incremental work W' on (n+1) CPUs:

      $W' = \alpha W + (1-\alpha) nW$
    - Speedup based on case where (1-α) scales perfectly:

$$S(n) = \frac{\alpha W + (1-\alpha) nW}{\alpha W + \frac{(1-\alpha) nW}{n}}$$

$$S(n) = \alpha + (1-\alpha) n$$



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

Super-linear speedup

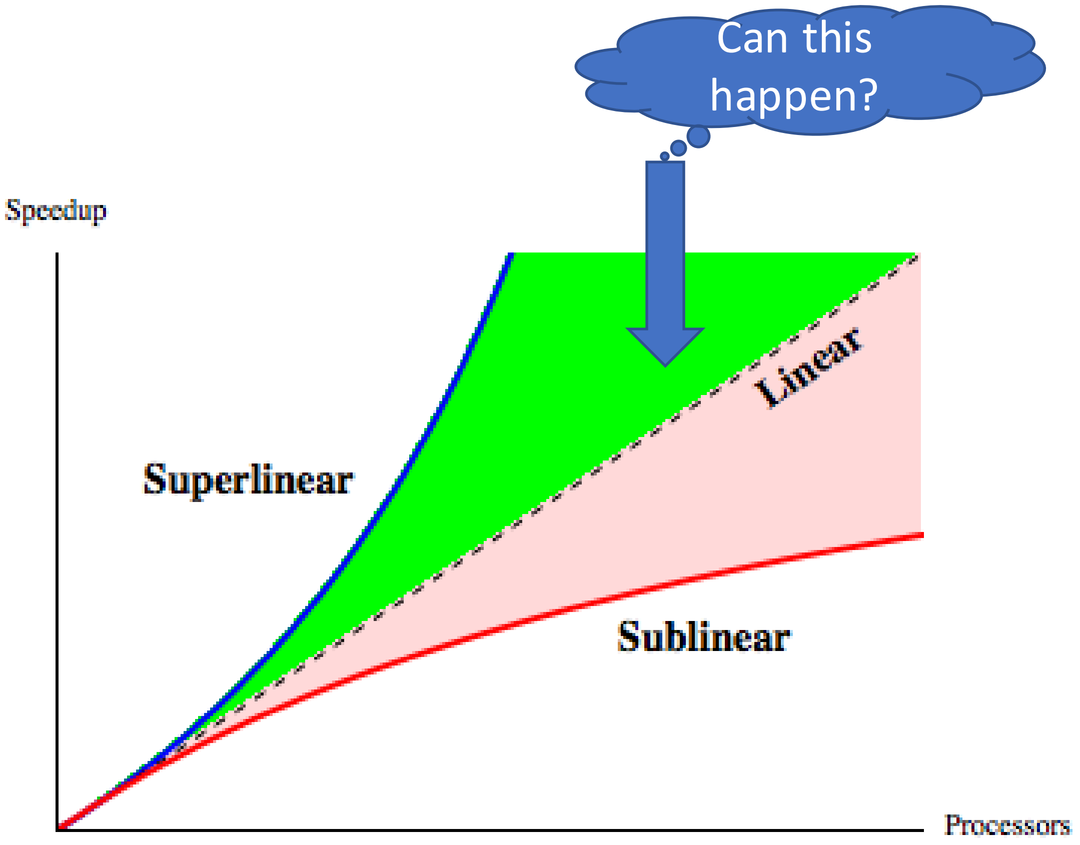
- Possible due to cache
- But usually just poor methodology
- Baseline: ***best*** serial algorithm
- Example:

Efficient **bubble sort**

- *Serial: 150s*
- *Parallel 40s*
- *Speedup:* $\frac{150}{40} = 3.75$?

NO NO NO!

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



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;
}
```

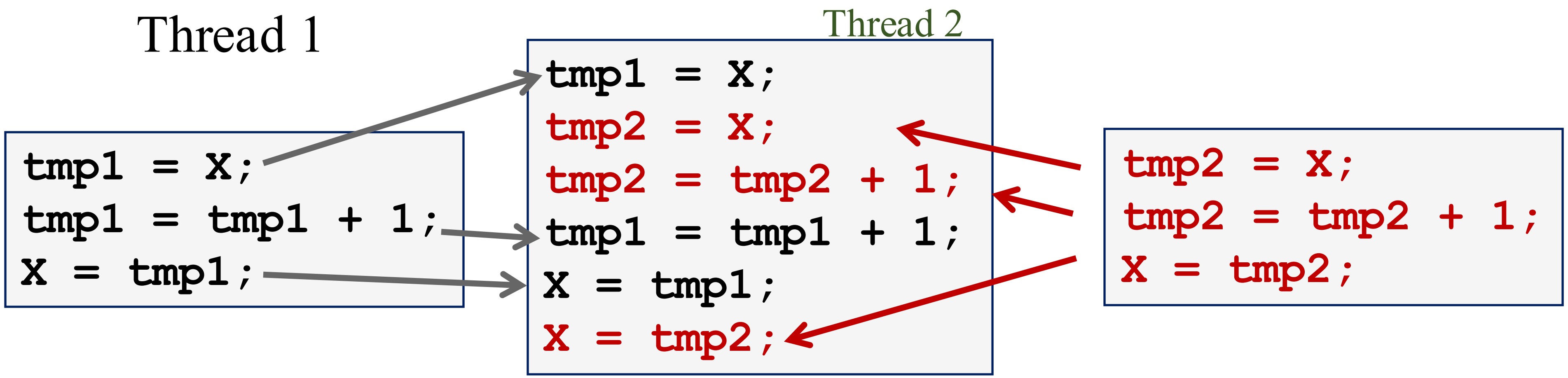
Answer:

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



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*

Is mutual exclusion a good abstraction?

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);
}
```

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

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

DEADLOCK!

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.~~
  - *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*

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

Mutex, spinlock, etc. are ways to implement

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

Did we get all the important conditions?

Why is correctness defined in terms of locks?

Implementing Locks

```
int lock_value = 0;
int* lock = &lock_value;
```

```
Lock::Acquire() {
  while (*lock == 1)
     ; //spin
  *lock = 1;
}
```

```
Lock::Release() {
    *lock = 0;
}
```

Completely and utterly broken.
How can we fix it?

What are the problem(s) with this?

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

HW Support for Read-Modify-Write (RMW)

IDEA: hardware implements something like:

```
bool rmw(addr, value) {
  atomic {
    tmp = *addr;
    newval = modify(tmp);
    *addr = newval;
   }
}
```

Why is that hard?
How can we do it?

Preview of Techniques:

- Bus locking
- Single Instruction ISA extensions
  - Test&Set
  - CAS: Compare & swap
  - Exchange, locked increment, locked decrement (x86)
- Multi-instruction ISA extensions:
  - LLSC: (PowerPC,Alpha, MIPS)
  - Transactional Memory (x86, PowerPC)

More on this later…

Implementing Locks with Test&set

```
int lock_value = 0;
int* lock = &lock_value;
```

```
Lock::Acquire() {
while (test&set(lock) == 1)
   ; //spin
}
```

(test & set ~= CAS ~= LLSC)

TST: ***Test&set***

- Reads a value from memory
- Write "1" back to memory location

```
Lock::Release() {
   *lock = 0;
}
```

What are the problem(s) with this?

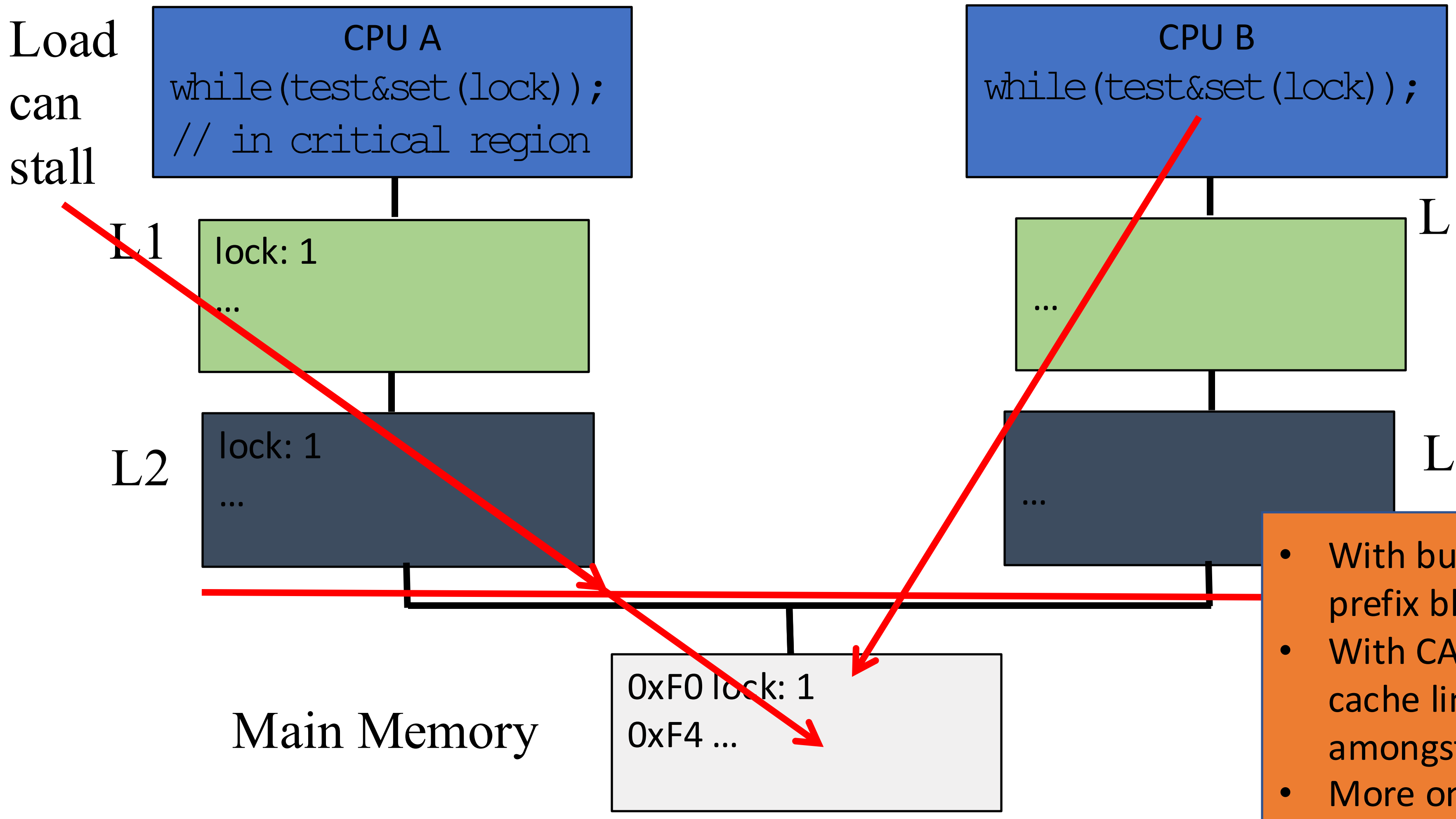
- A. CPU usage
- B. Memory usage
- C. Lock::Acquire() latency
- D. Memory bus usage
- E. Does not work

More on this later…

Test & Set with Memory Hierarchies

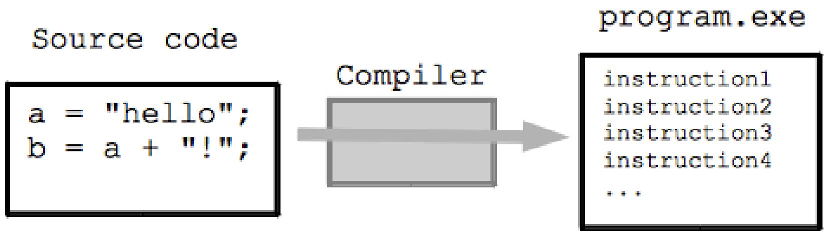
Initially, lock already held by some other CPU—A, B busy-waiting

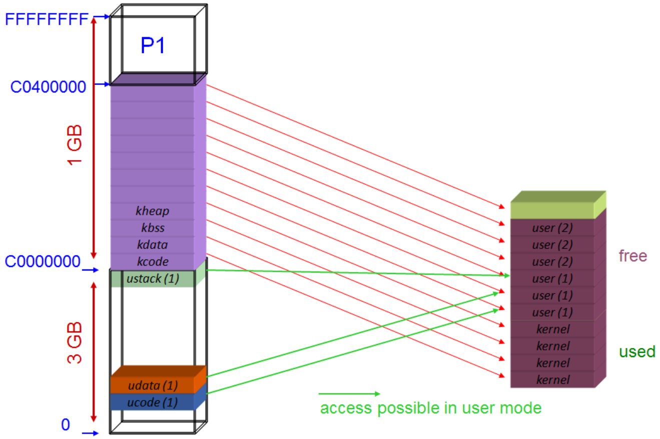
What happens to lock variable's cache line when different cpu's contend?



- With bus-locking, lock prefix blocks *everyone*
- With CAS, LL-SC, cache line cache line "ping pongs" amongst contenders
- More on this next time…

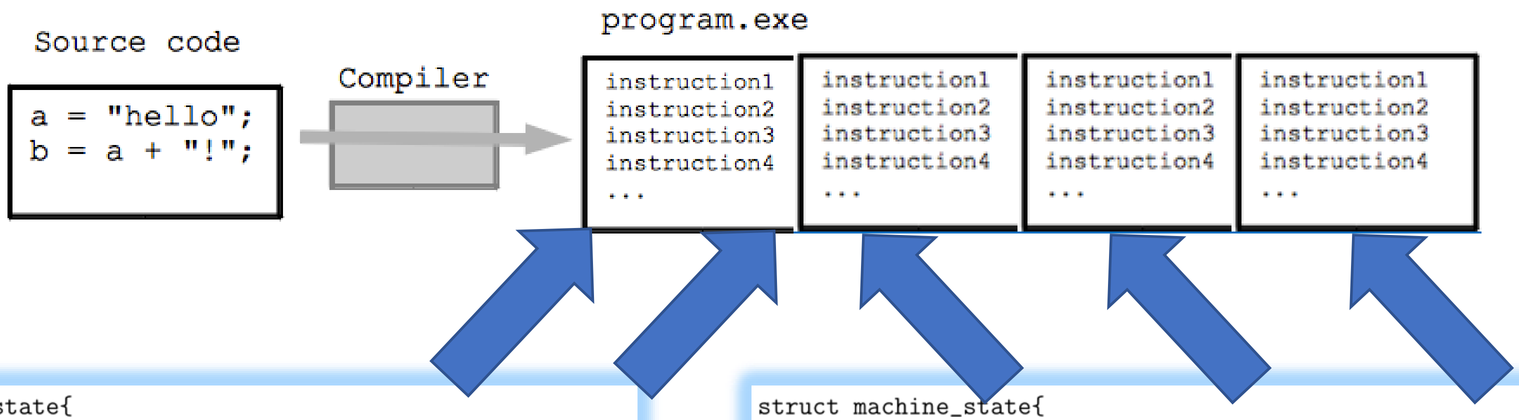
Programming and Machines: a mental model






```
struct machine_state{
  uint64 pc;
  uint64 Registers[16];
  uint64 cr[6]; // control registers cr0-cr4 and EFER on AMD
...
} machine;
while(1) {
  fetch_instruction(machine.pc);
  decode_instruction(machine.pc);
  execute_instruction(machine.pc);
}
void execute_instruction(i) {
  switch(opcode) {
  case add_rr:
   machine.Registers[i.dst] += machine.Registers[i.src];
   break;
}
```

Parallel Machines: a mental model

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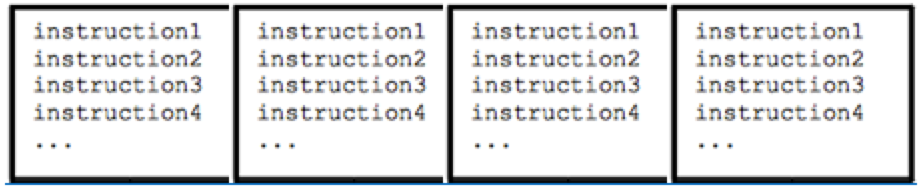
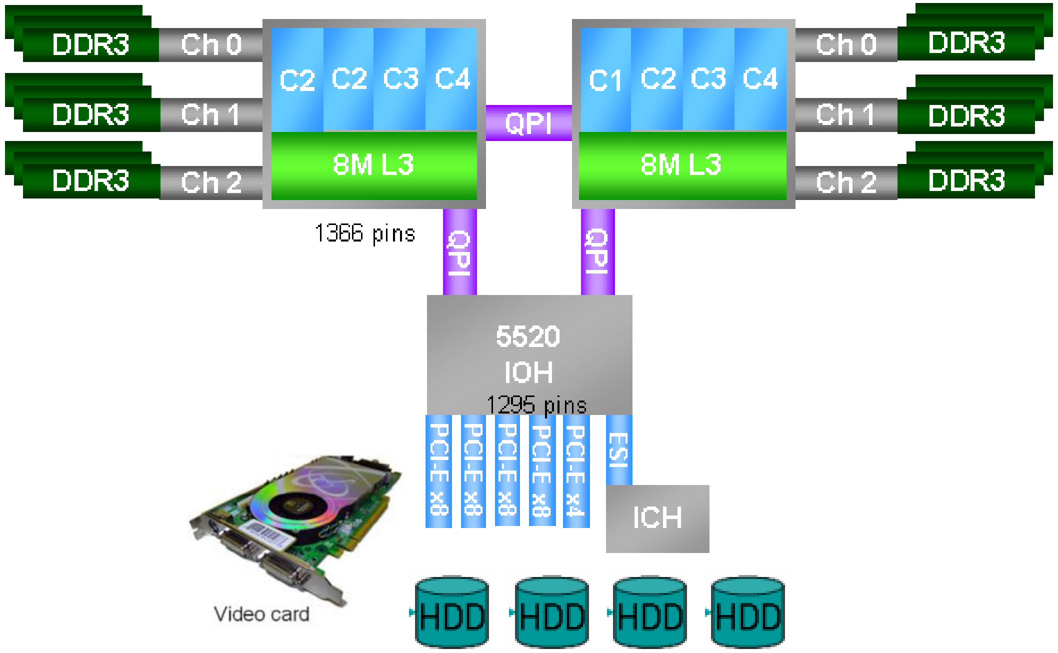
}
```

Processes and Threads

- Abstractions
- Containers
- State
  - Where is shared state?
  - How is it accessed?
  - Is it mutable?

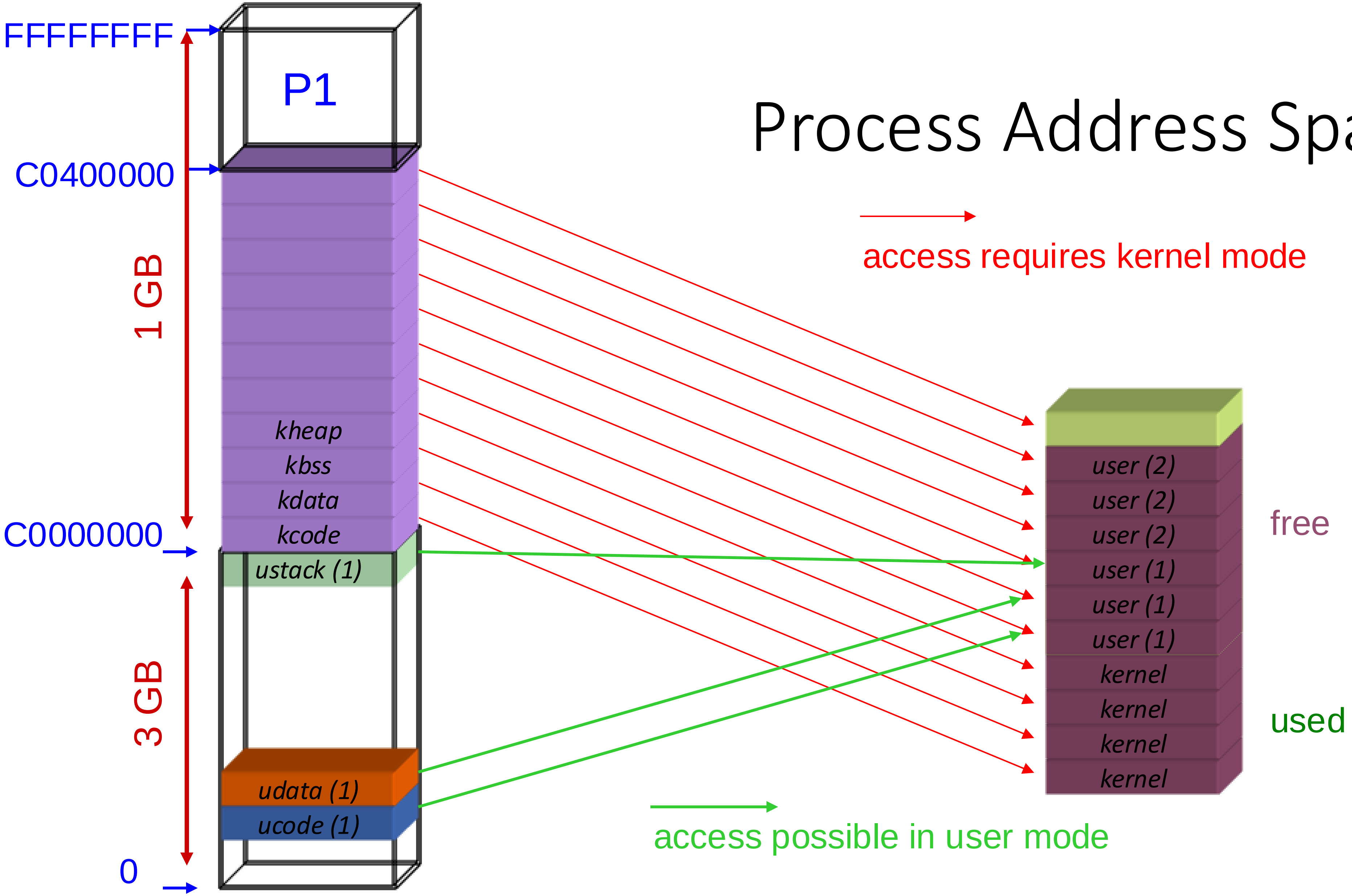




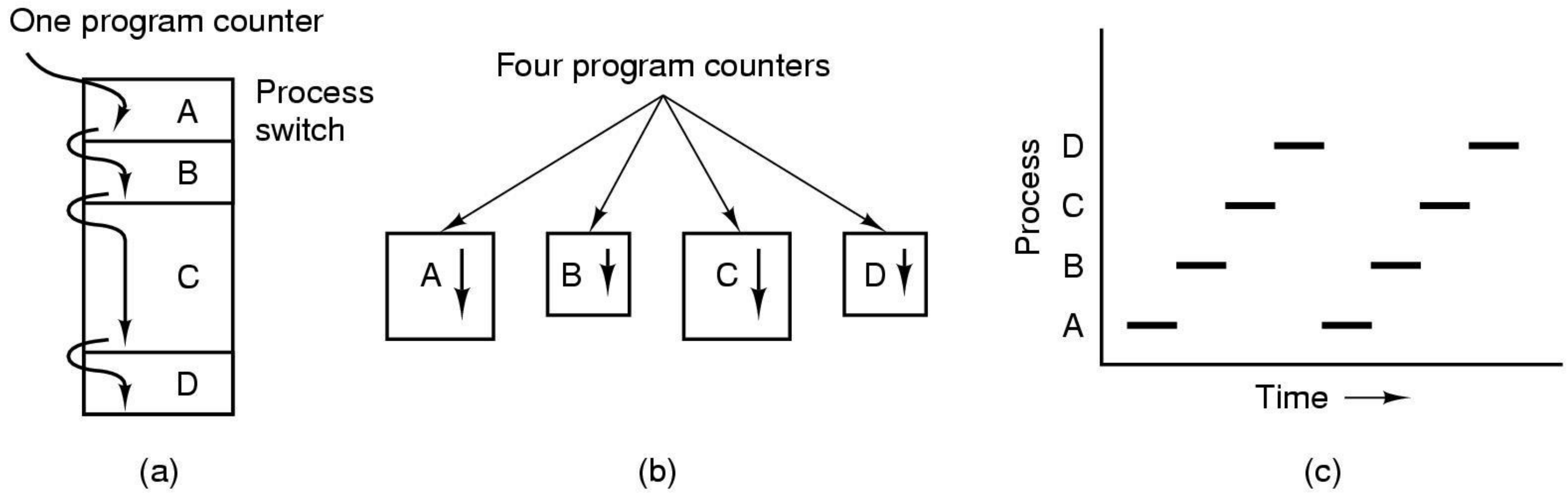
Processes & Virtual Memory

- Virtual Memory: Goals…what are they again?
- Abstraction: contiguous, isolated memory
    - Remember overlays?
- Prevent illegal operations
    - Access to others/OS memory
    - Fail fast (e.g. segv on *(NULL))
    - Prevent exploits that try to execute program data
- **Sharing mechanism/IPC substrate**

Process Address Space



Processes
The Process Model



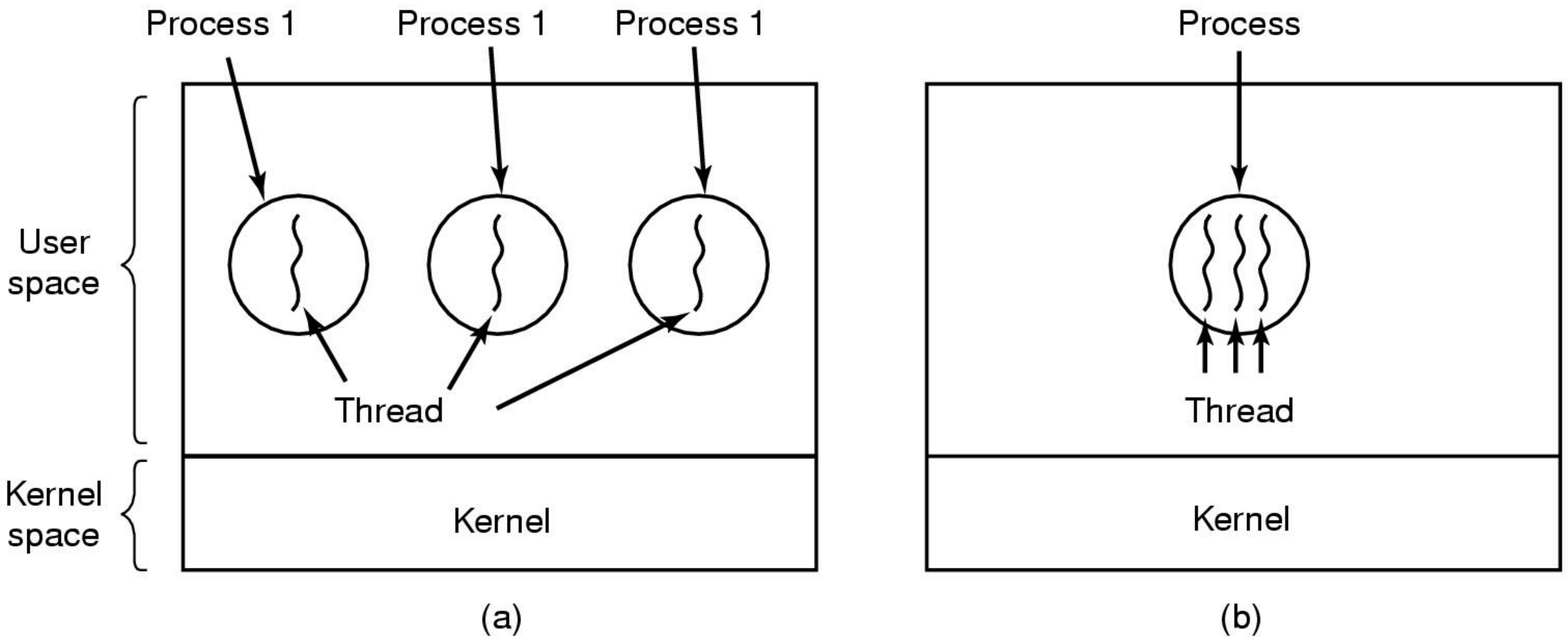
- Multiprogramming of four programs
- Conceptual model of 4 independent, sequential processes
- Only one program active at any instant

Implementation of Processes

Process management	Memory management	File management
Registers Program counter Program status word Stack pointer Process state Priority Scheduling parameters Process ID Parent process Process group Signals Time when process started CPU time used Children's CPU time Time of next alarm	Pointer to text segment Pointer to data segment Pointer to stack segment	Root directory Working directory File descriptors User ID Group ID

Fields of a process table entry

Threads
The Thread Model (1)



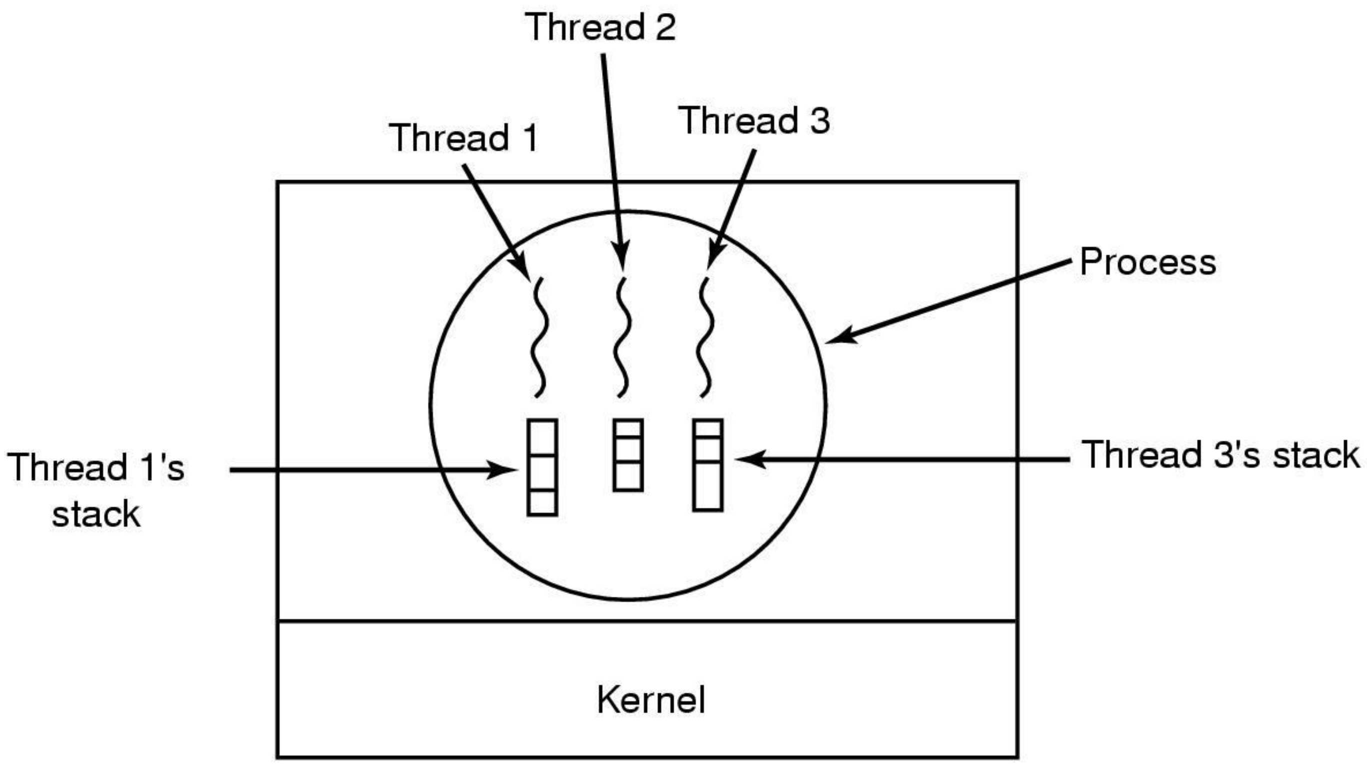
(a) Three processes each with one thread
(b) One process with three threads

The Thread Model

Per process items	Per thread items
Address space	Program counter
Global variables	Registers
Open files	Stack
Child processes	State
Pending alarms	
Signals and signal handlers	
Accounting information	

- Items shared by all threads in a process
- Items private to each thread

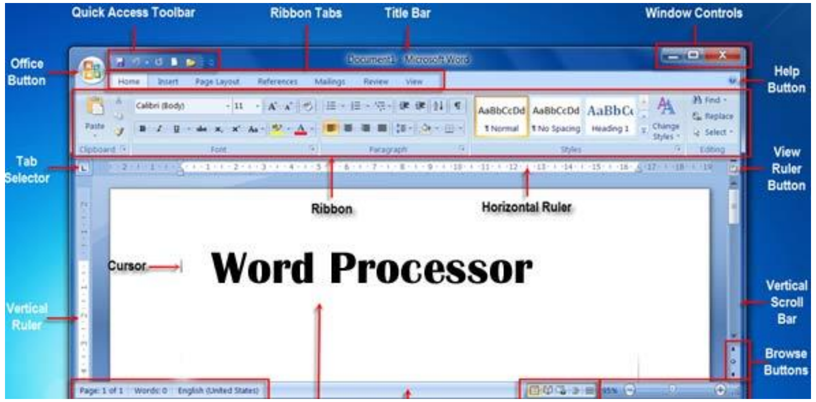
The Thread Model

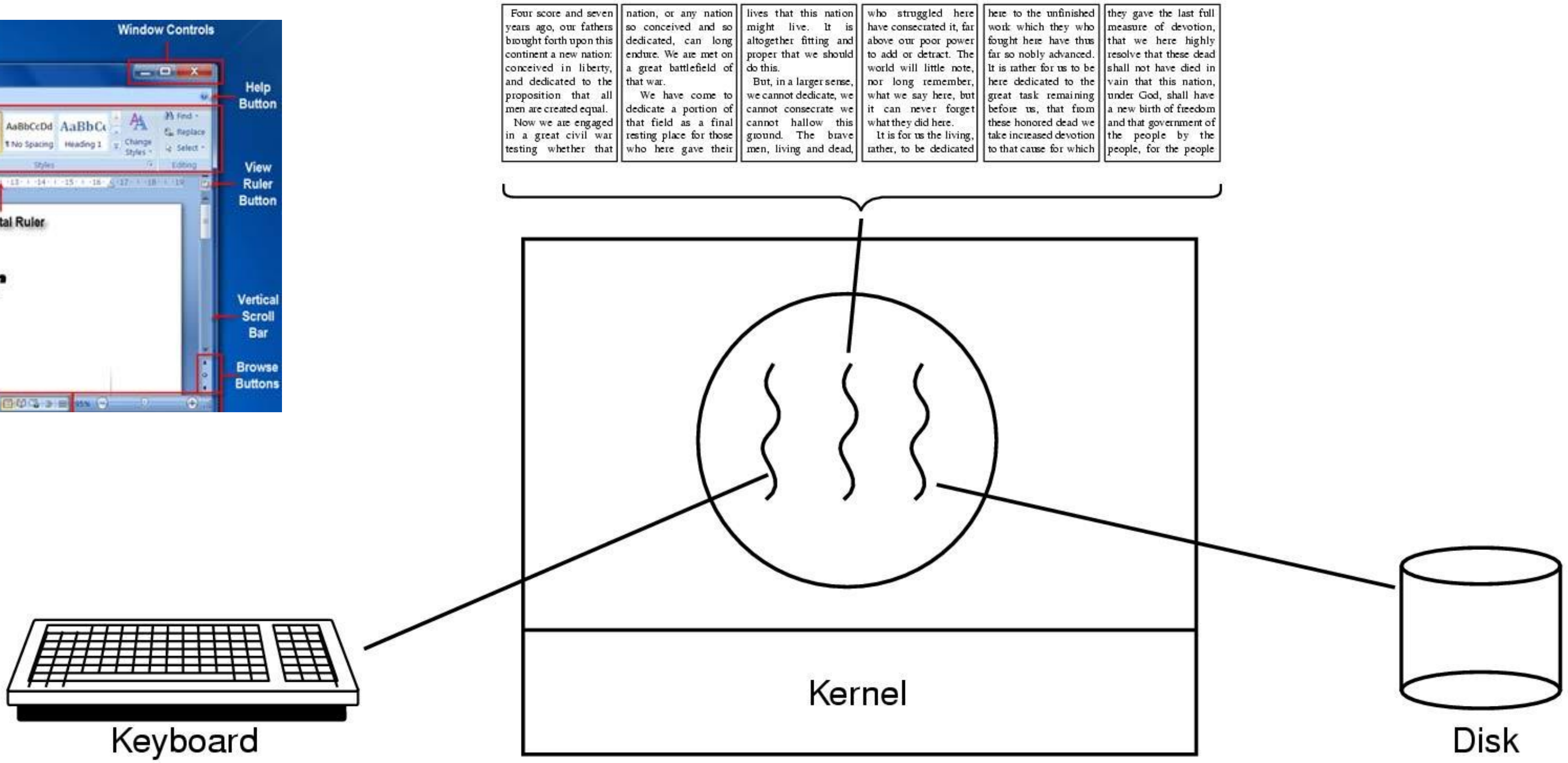


Each thread has its own stack

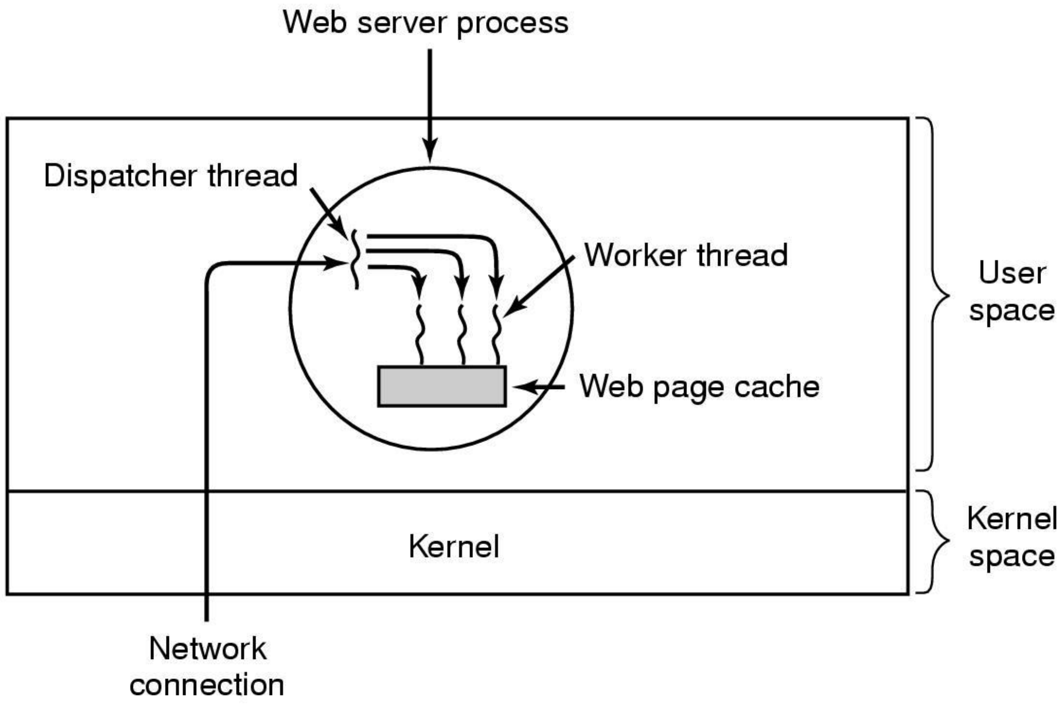
Using threads

Ex. How might we use threads in a word processor program?





Thread Usage




```
while (TRUE) {
  get_next_request(&buf);
  handoff_work(&buf);
}
```

(a)

```
while (TRUE) {
  wait_for_work(&buf)
  look_for_page_in_cache(&buf, &page);
  if (page_not_in_cache(&page)
      read_page_from_disk(&buf, &page);
  return_page(&page);
}
```

(b)

(a) Dispatcher thread

(b) Worker thread

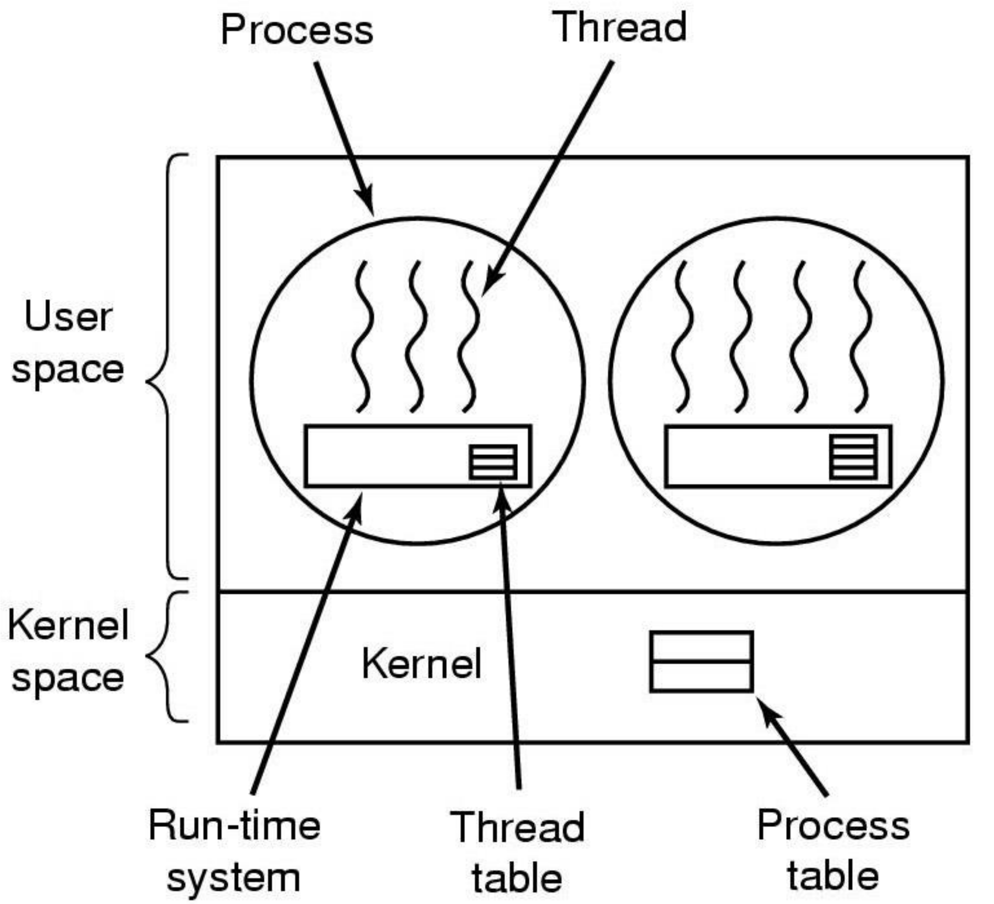
A multithreaded Web server

Thread Usage

Model	Characteristics
Threads	Parallelism, blocking system calls
Single-threaded process	No parallelism, blocking system calls
Finite-state machine	Parallelism, nonblocking system calls, interrupts

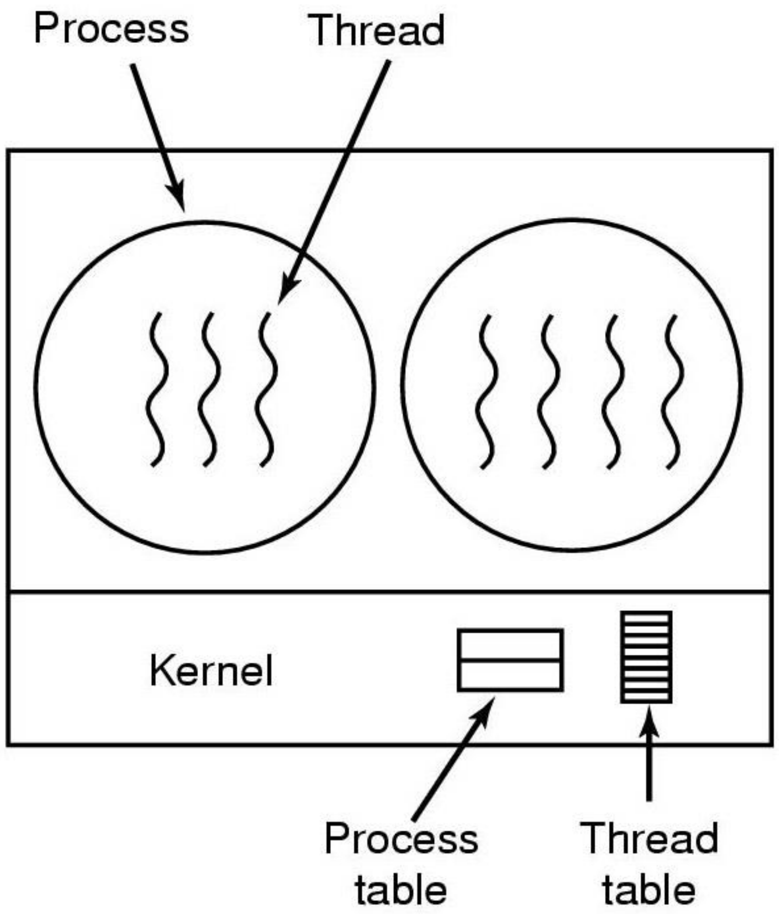
Three ways to construct a server

Implementing Threads in User Space



A user-level threads package

Implementing Threads in the Kernel



A threads package managed by the kernel

Pthreads

- POSIX standard thread model,
- Specifies the API and call semantics.
- Popular – most thread libraries are Pthreads-compatible

Preliminaries

- Include `pthread.h` in the main file
- Compile program with `-lpthread`
  - `gcc -o test test.c -lpthread`
  - may not report compilation errors otherwise but calls will fail
- Good idea to check return values on common functions

Thread creation

- Types: `pthread_t` – type of a thread
- Some calls:

```
int pthread_create(pthread_t *thread,
                   const pthread_attr_t *attr,
                   void * (*start_routine)(void *),
                   void *arg);
int pthread_join(pthread_t thread, void **status);
int pthread_detach();
void pthread_exit();
```

- No explicit parent/child model, except main thread holds process info
- Call `pthread_exit` in main, don't just fall through;
- Most likely you wouldn't need `pthread_join`
  - `status` = exit value returned by joinable thread
- Detached threads are those which cannot be joined (can also set this at creation)

Creating multiple threads

```
#include <stdio.h>
#include <pthread.h>
#define NUM_THREADS 4

void *hello (void *arg) {
      printf("Hello Thread\n");
}

main() {
  pthread_t tid[NUM_THREADS];
  for (int i = 0; i < NUM_THREADS; i++)
    pthread_create(&tid[i], NULL, hello, NULL);

  for (int i = 0; i < NUM_THREADS; i++)
    pthread_join(tid[i], NULL);
}
```

Can you find the bug here?

What is printed for myNum?

```
void *threadFunc(void *pArg) {
  int* p = (int*)pArg;
  int myNum = *p;
  printf( "Thread number %d\n", myNum);
}
. . .
// from main():
for (int i = 0; i < numThreads; i++) {
   pthread_create(&tid[i], NULL, threadFunc, &i);
}
```

Pthread Mutexes

- Type: `pthread_mutex_t`

```
int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *attr);
int pthread_mutex_destroy(pthread_mutex_t *mutex);
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
```

- Attributes: for shared mutexes/condition vars among processes, for priority inheritance, etc.
  - use defaults
- Important: Mutex scope must be visible to all threads!

Pthread Spinlock

- Type: `pthread_spinlock_t`

```
int pthread_spinlock_init(pthread_spinlock_t *lock);
int pthread_spinlock_destroy(pthread_spinlock_t *lock);
int pthread_spin_lock(pthread_spinlock_t *lock);
int pthread_spin_unlock(pthread_spinlock_t *lock);
int pthread_spin_trylock(pthread_spinlock_t *lock);
```


```
int pthread_mutex_init(pthread_mutex_t *mutex,…);
int pthread_mutex_destroy(pthread_mutex_t *mutex);
int pthread_mutex_lock(pthread_mutex_t *mutex);
int pthread_mutex_unlock(pthread_mutex_t *mutex);
int pthread_mutex_trylock(pthread_mutex_t *mutex);
```

Lab #1

- Basic synchronization
- http://www.cs.utexas.edu/~rossbach/cs378/lab/locking.html

- ***Start early!!!***

Questions?