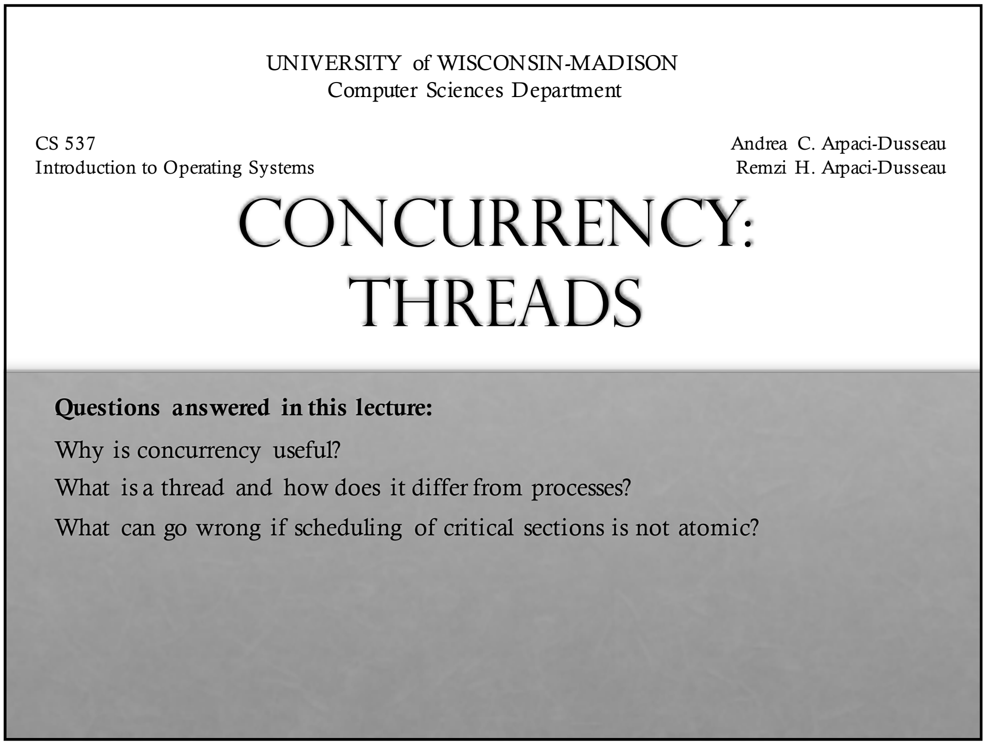


UNIVERSITY of WISCONSIN-MADISON
Computer Sciences Department

CS 537
Introduction to Operating Systems

Andrea C. Arpaci-Dusseau
Remzi H. Arpaci-Dusseau

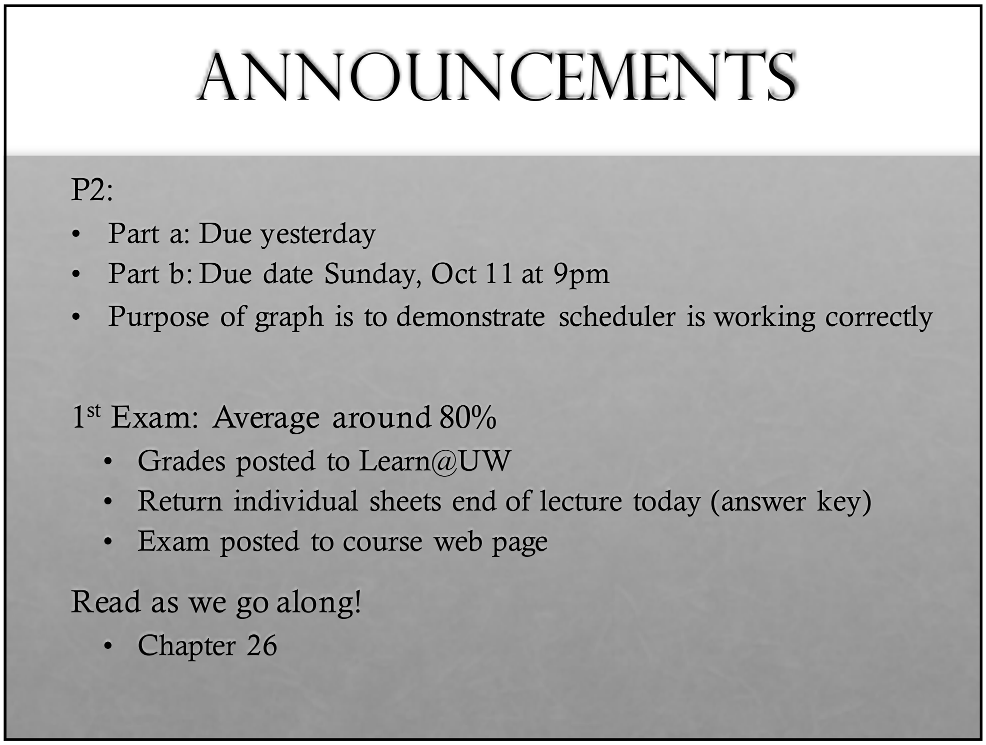
Concurrency: Threads

Questions answered in this lecture:

Why is concurrency useful?

What is a thread and how does it differ from processes?

What can go wrong if scheduling of critical sections is not atomic?



Announcements

P2:

- Part a: Due yesterday
- Part b: Due date Sunday, Oct 11 at 9pm
- Purpose of graph is to demonstrate scheduler is working correctly

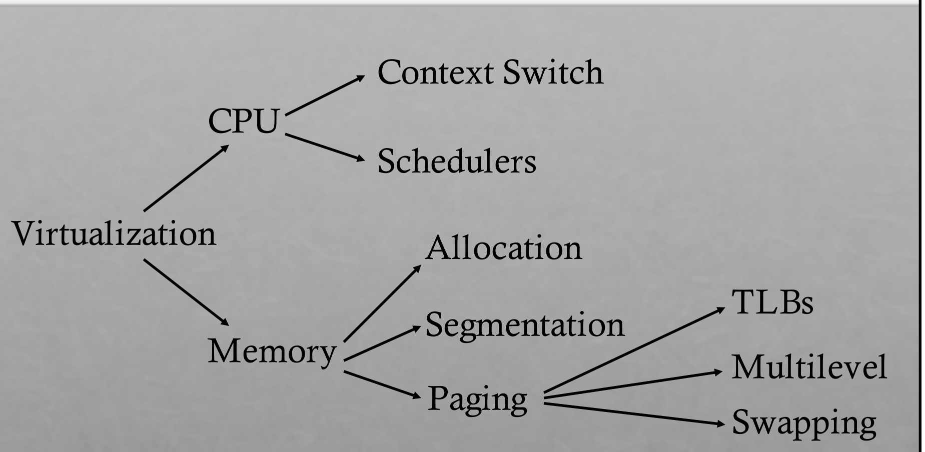
1st Exam: Average around 80%

- Grades posted to Learn@UW
- Return individual sheets end of lecture today (answer key)
- Exam posted to course web page

Read as we go along!

- Chapter 26

Review: Easy Piece 1


Virtualization

CPU

Context Switch

Schedulers

Memory

Allocation

Segmentation

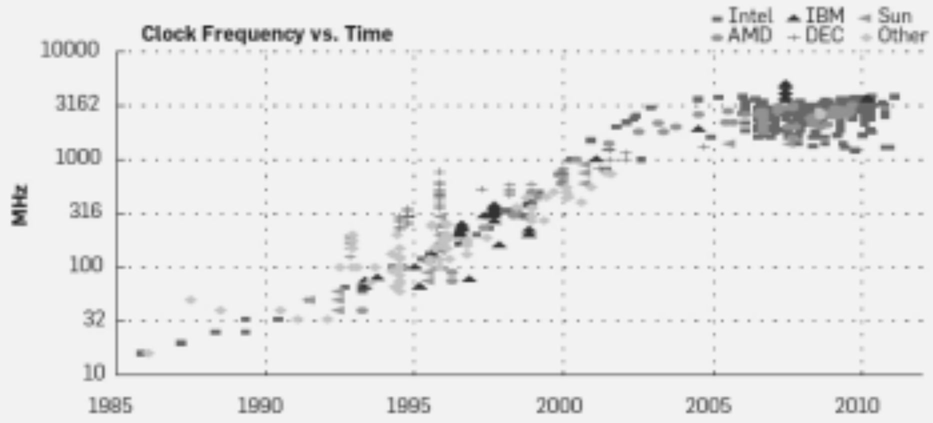
Paging

TLBs

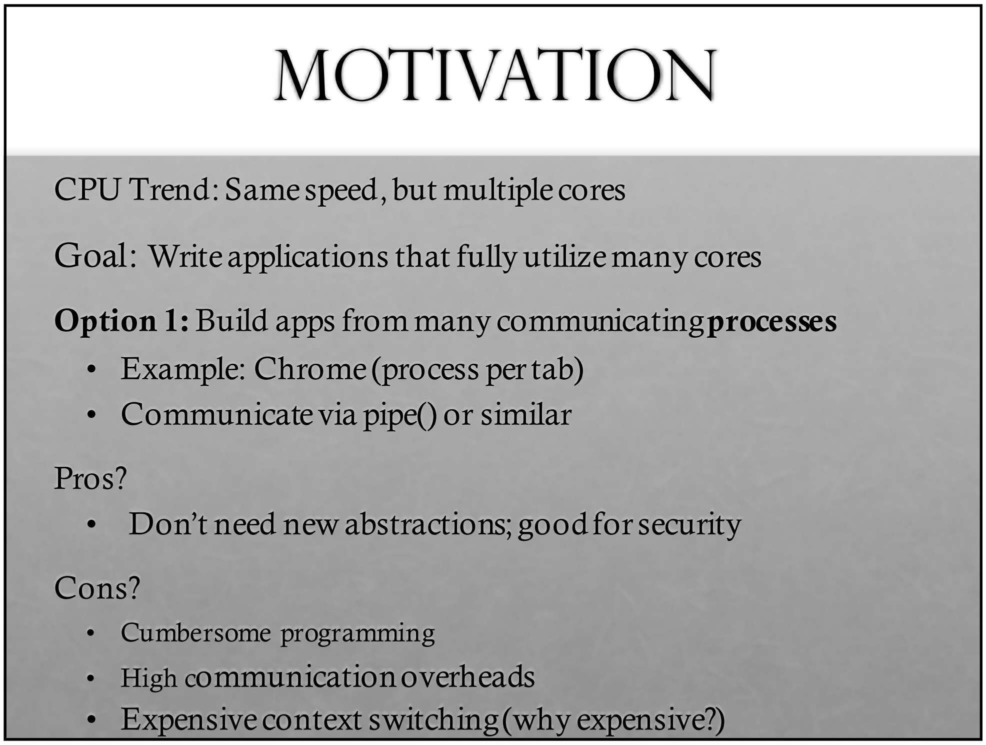
Multilevel

Swapping

Motivation for Concurrency



http://cacm.acm.org/magazines/2012/4/147359-cpu-db-recording-microprocessor-history/fulltext



Motivation

CPU Trend: Same speed, but multiple cores

Goal: Write applications that fully utilize many cores

Option 1: Build apps from many communicating **processes**

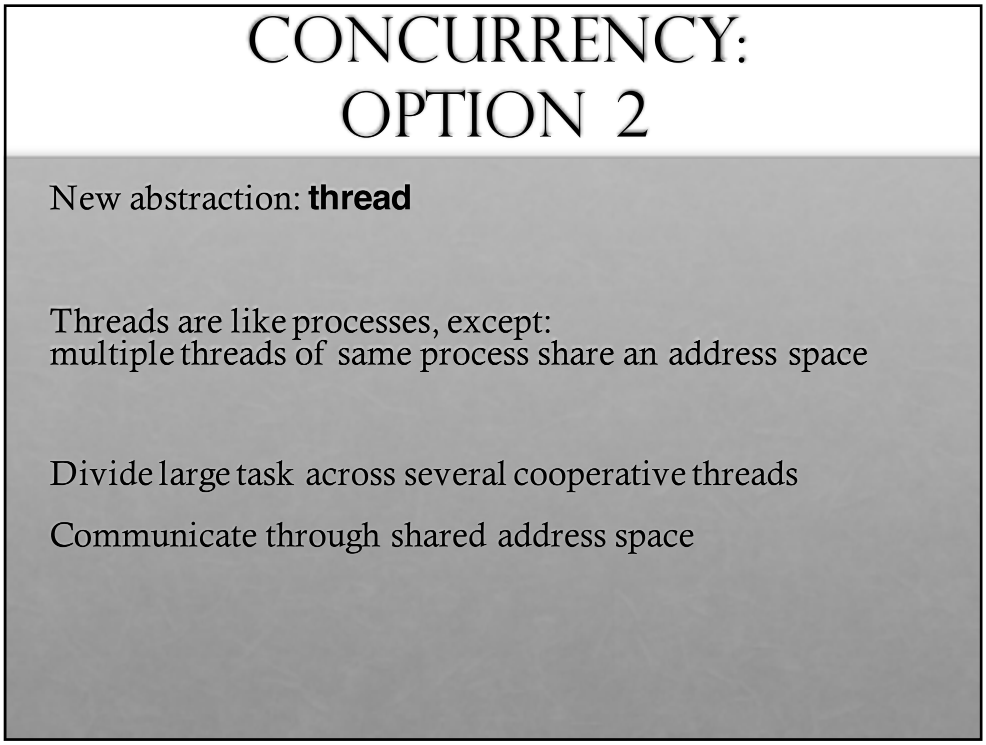
- Example: Chrome (process per tab)
- Communicate via pipe() or similar

Pros?

- Don't need new abstractions; good for security

Cons?

- Cumbersome programming
- High communication overheads
- Expensive context switching (why expensive?)



Concurrency: Option 2

New abstraction: **thread**

Threads are like processes, except:
multiple threads of same process share an address space

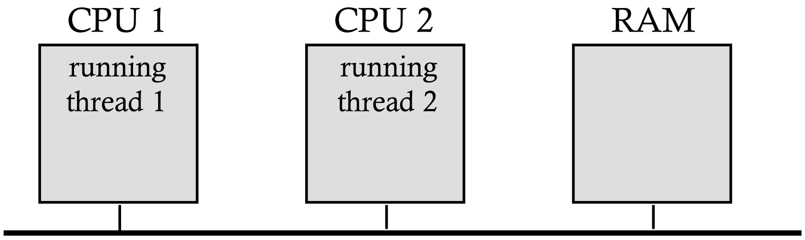
Divide large task across several cooperative threads

Communicate through shared address space

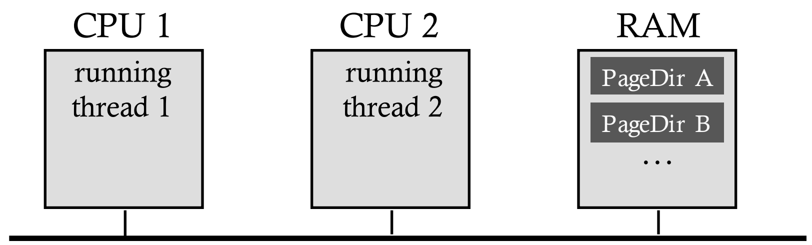
Common Programming Models

Multi-threaded programs tend to be structured as:

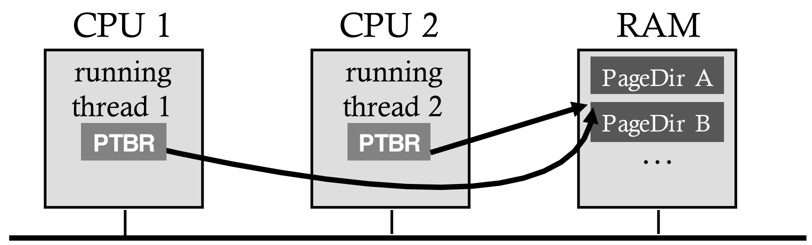
- **Producer/consumer**
  Multiple producer threads create data (or work) that is handled by one of the multiple consumer threads
- **Pipeline**
  Task is divided into series of subtasks, each of which is handled in series by a different thread
- **Defer work with background thread**
  One thread performs non-critical work in the background (when CPU idle)

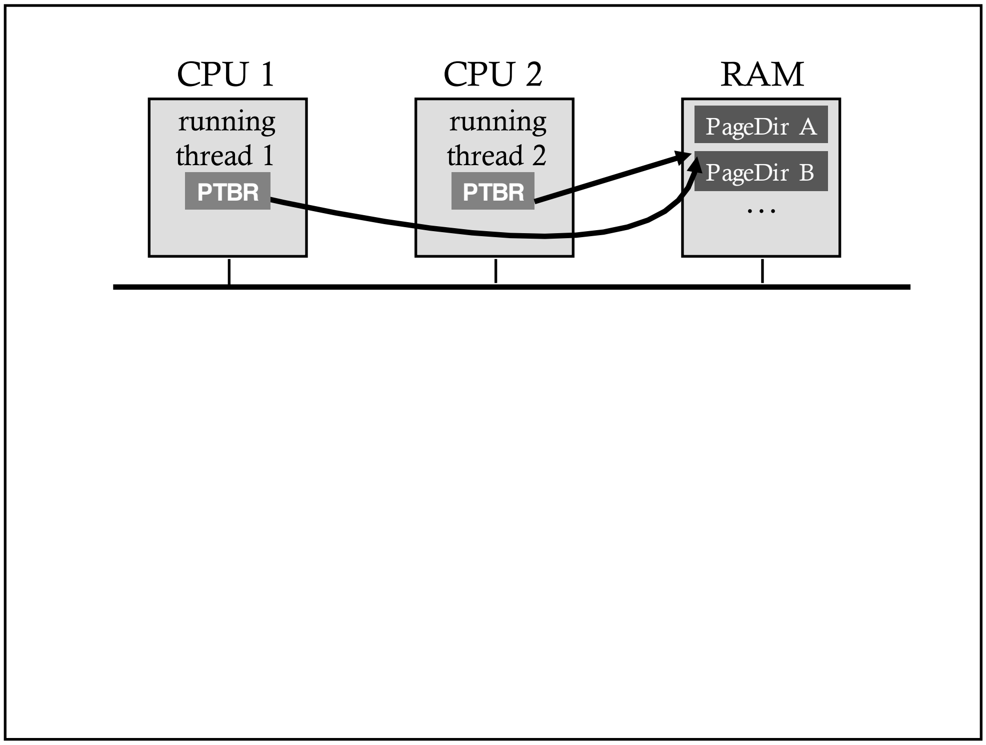


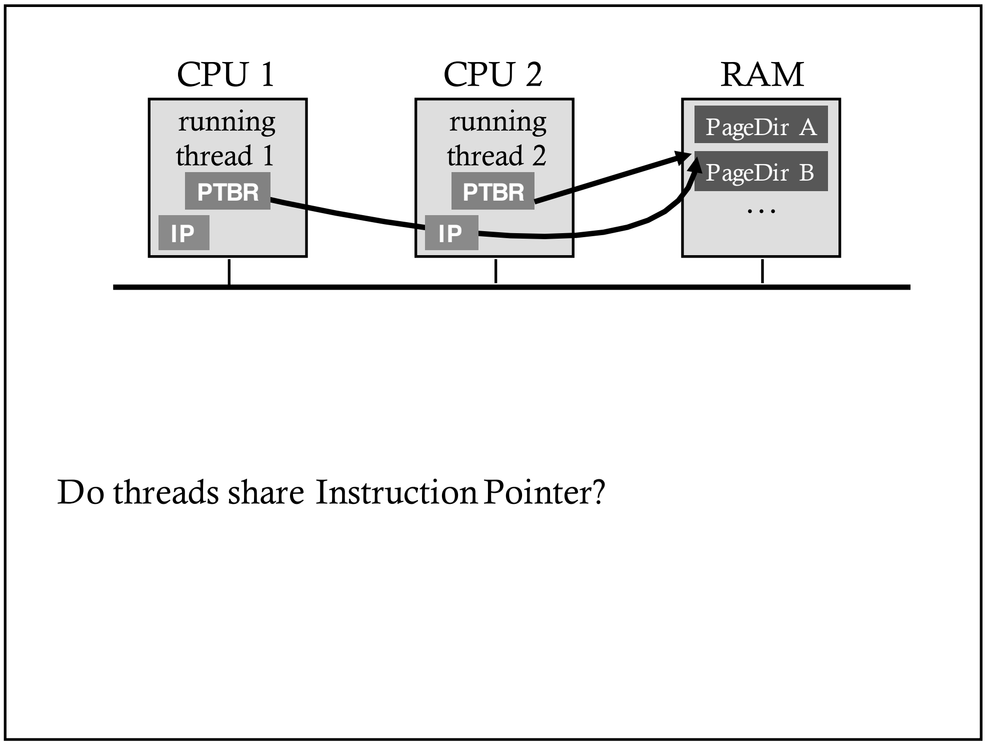
What state do threads share?



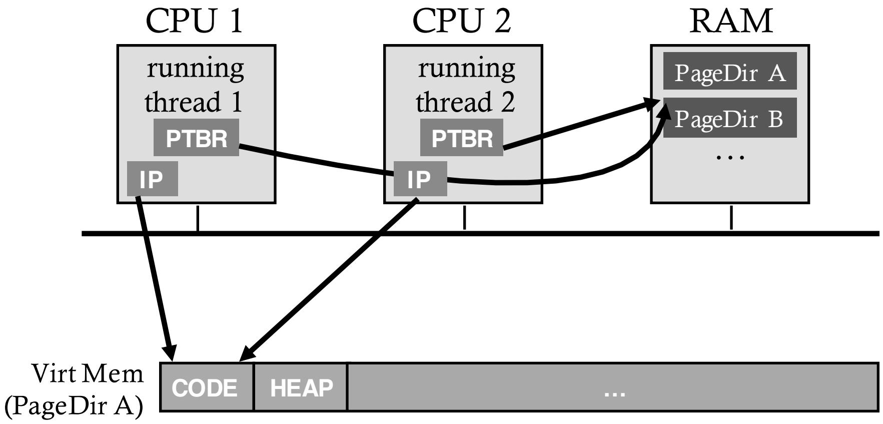
What threads share page directories?

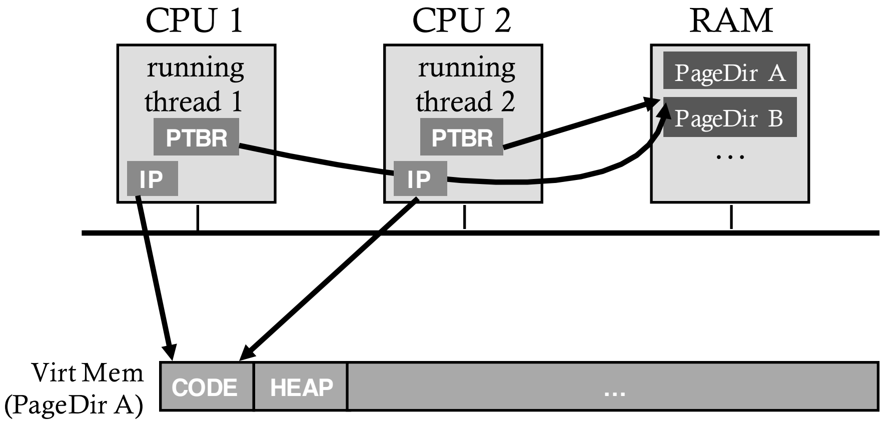






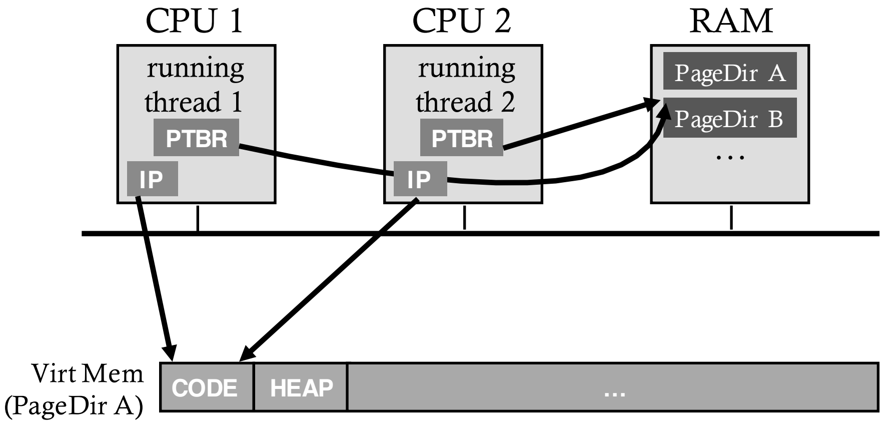
Do threads share Instruction Pointer?

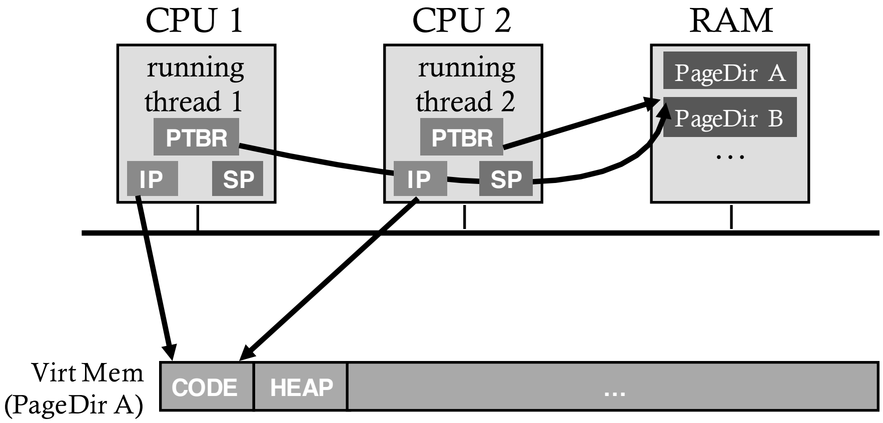




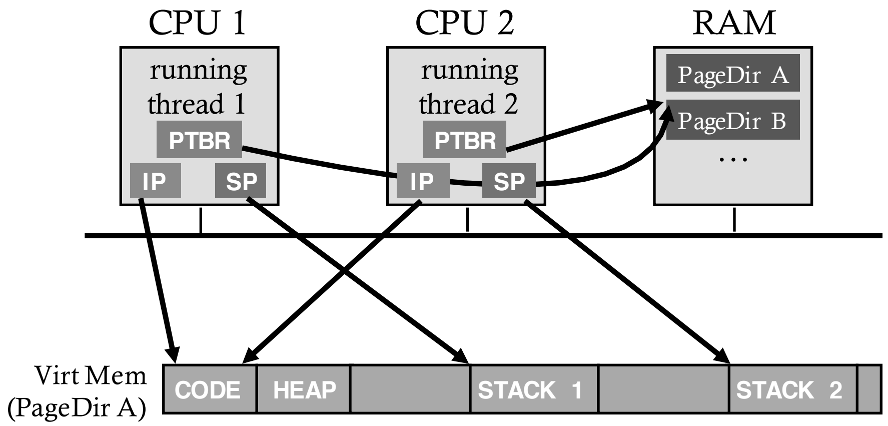
Share code, but each thread may be executing different code at the same time

→ Different Instruction Pointers





Do threads share stack pointer?



CPU 1

running thread 1

PTBR

IP

SP

CPU 2

running thread 2

PTBR

IP

SP

RAM

PageDir A

PageDir B

…

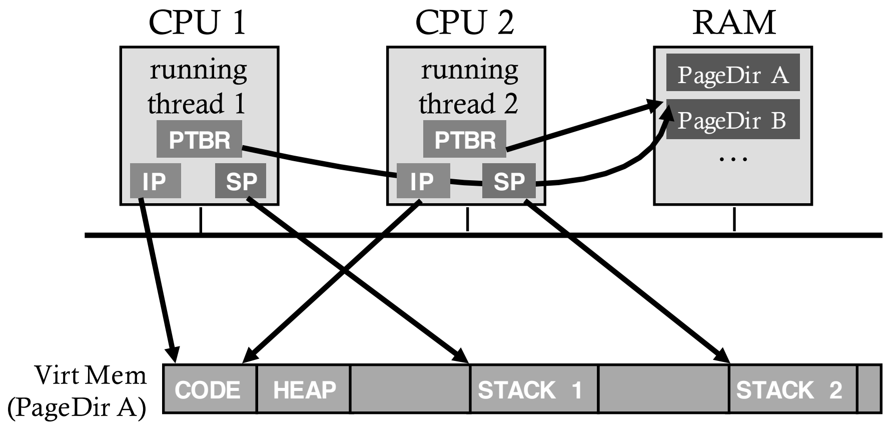
Virt Mem (PageDir A)

CODE

HEAP

STACK 1

STACK 2



CPU 1

running thread 1

PTBR

IP

SP

CPU 2

running thread 2

PTBR

IP

SP

RAM

PageDir A

PageDir B

…

Virt Mem (PageDir A)

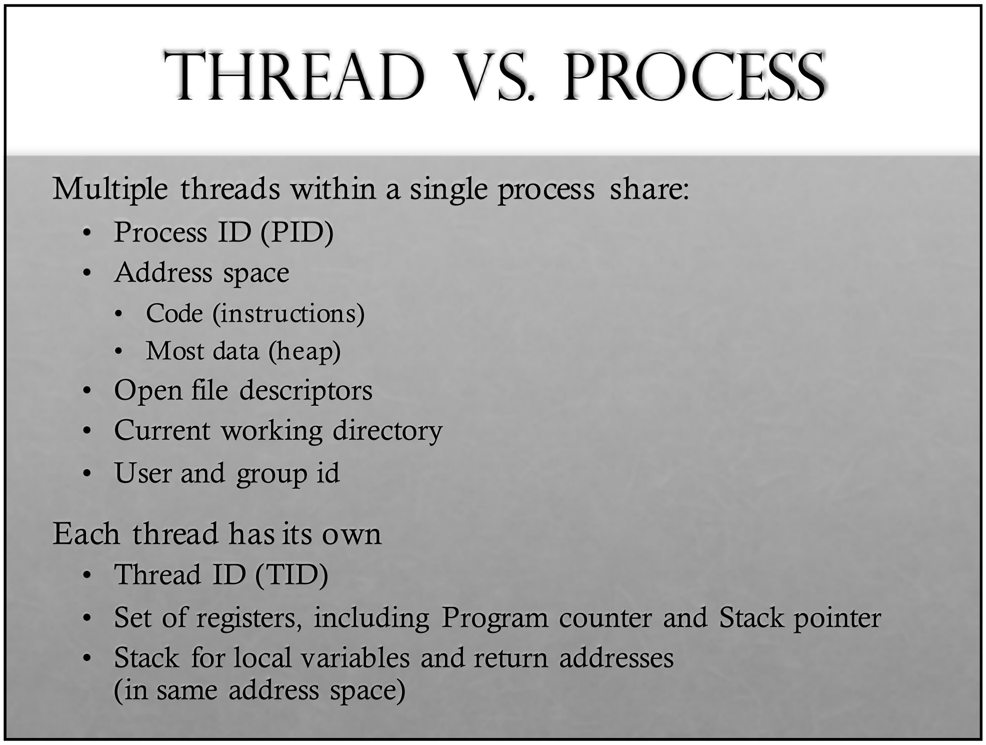
CODE

HEAP

STACK 1

STACK 2

threads executing different functions need different stacks



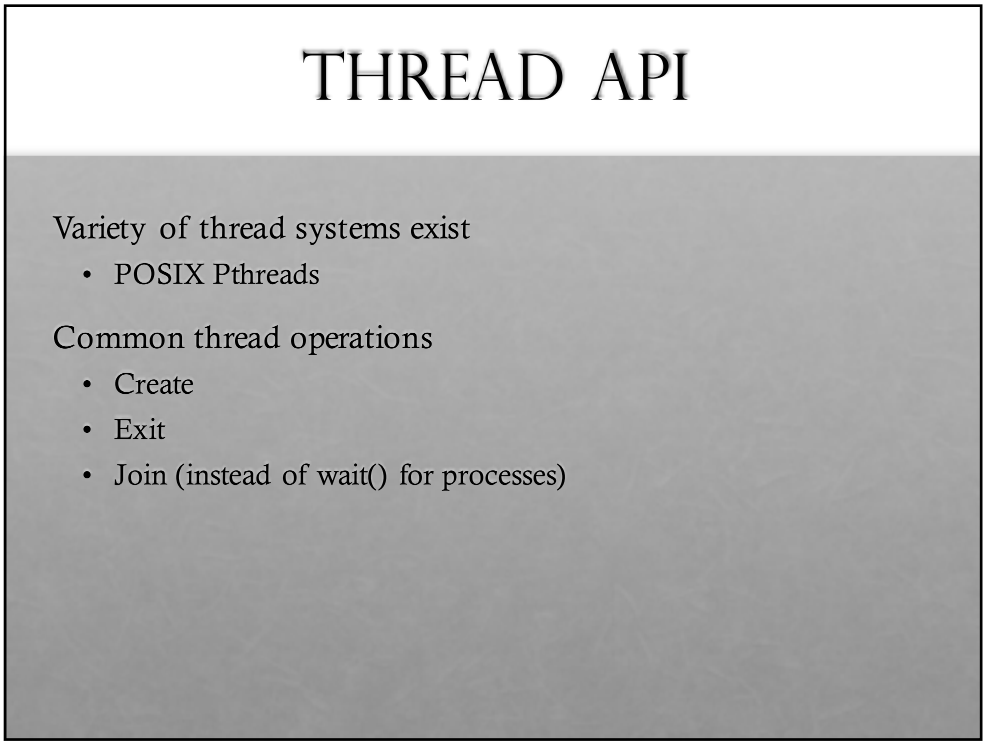
Thread vs. Process

Multiple threads within a single process share:

- Process ID (PID)
- Address space
  - Code (instructions)
  - Most data (heap)
- Open file descriptors
- Current working directory
- User and group id

Each thread has its own

- Thread ID (TID)
- Set of registers, including Program counter and Stack pointer
- Stack for local variables and return addresses (in same address space)



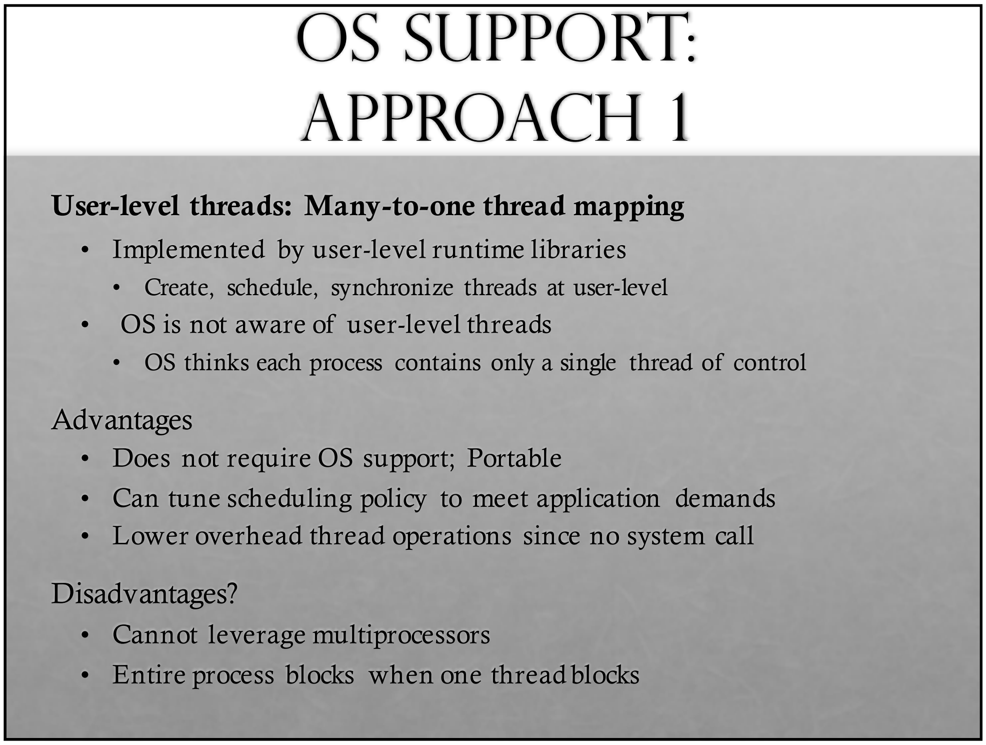
Thread API

Variety of thread systems exist

- POSIX Pthreads

Common thread operations

- Create
- Exit
- Join (instead of wait() for processes)



OS Support: Approach 1

User-level threads: Many-to-one thread mapping

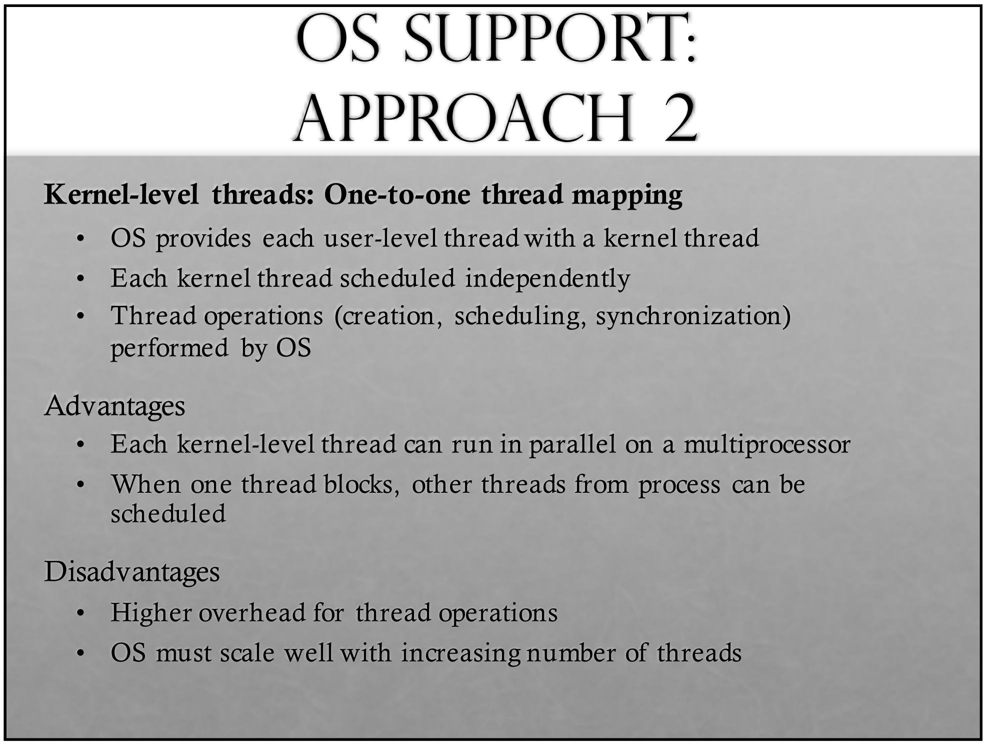
- Implemented by user-level runtime libraries
  - Create, schedule, synchronize threads at user-level
- OS is not aware of user-level threads
  - OS thinks each process contains only a single thread of control

Advantages

- Does not require OS support; Portable
- Can tune scheduling policy to meet application demands
- Lower overhead thread operations since no system call

Disadvantages?

- Cannot leverage multiprocessors
- Entire process blocks when one thread blocks



OS Support: Approach 2

Kernel-level threads: One-to-one thread mapping

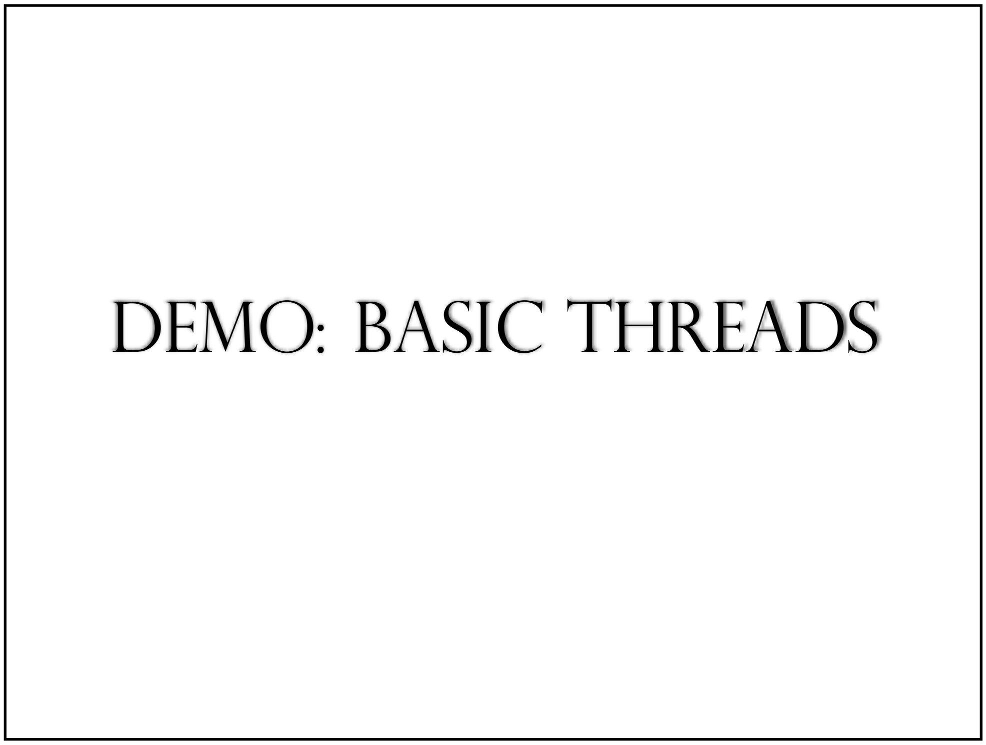
- OS provides each user-level thread with a kernel thread
- Each kernel thread scheduled independently
- Thread operations (creation, scheduling, synchronization) performed by OS

Advantages

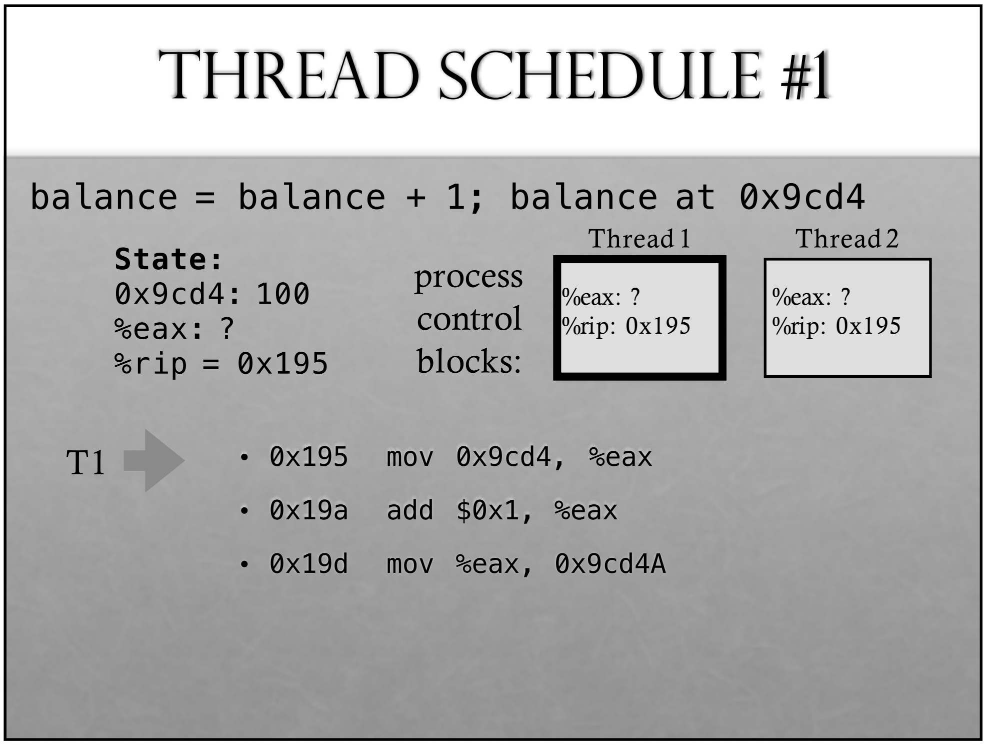
- Each kernel-level thread can run in parallel on a multiprocessor
- When one thread blocks, other threads from process can be scheduled

Disadvantages

- Higher overhead for thread operations
- OS must scale well with increasing number of threads



Demo: Basic Threads



Thread Schedule #1

`balance = balance + 1; balance at 0x9cd4`

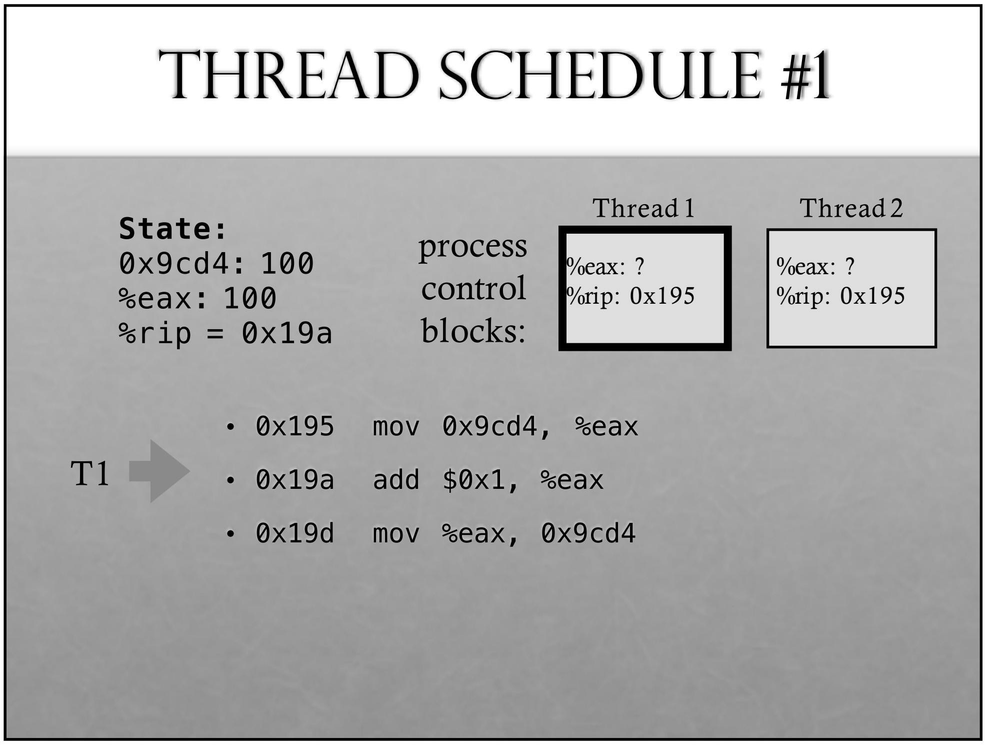
```
State:
0x9cd4: 100
%eax: ?
%rip = 0x195
```

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

T1 ➡

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4A
```



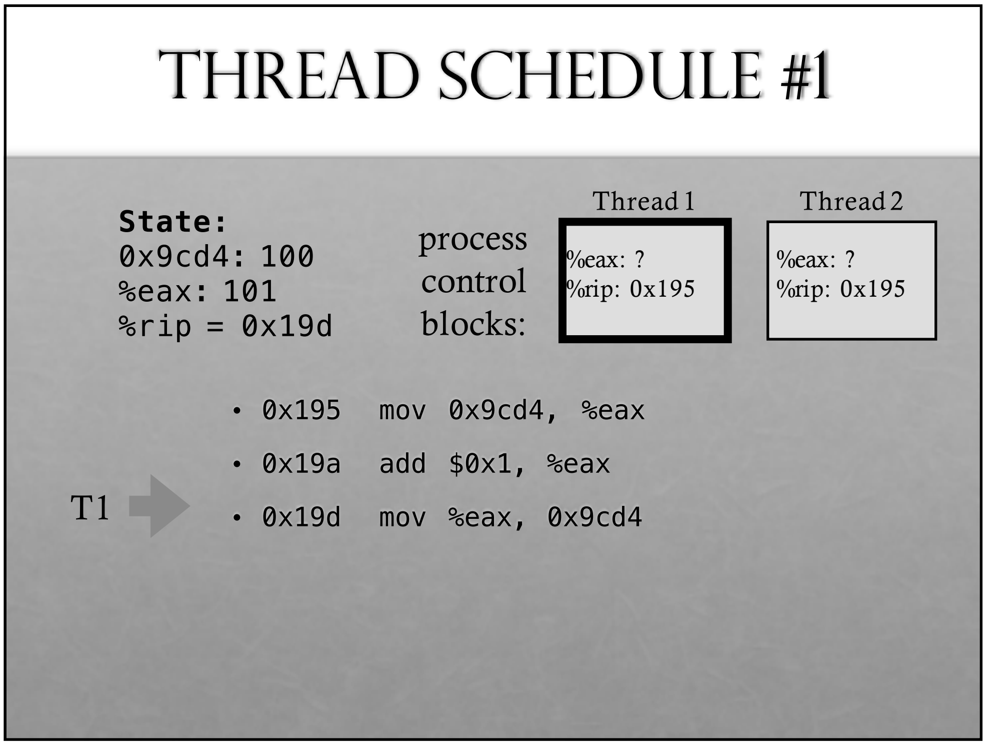
Thread Schedule #1

State:
0x9cd4: 100
%eax: 100
%rip = 0x19a

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

```
      • 0x195   mov  0x9cd4, %eax
T1 ➡  • 0x19a   add  $0x1, %eax
      • 0x19d   mov  %eax, 0x9cd4
```



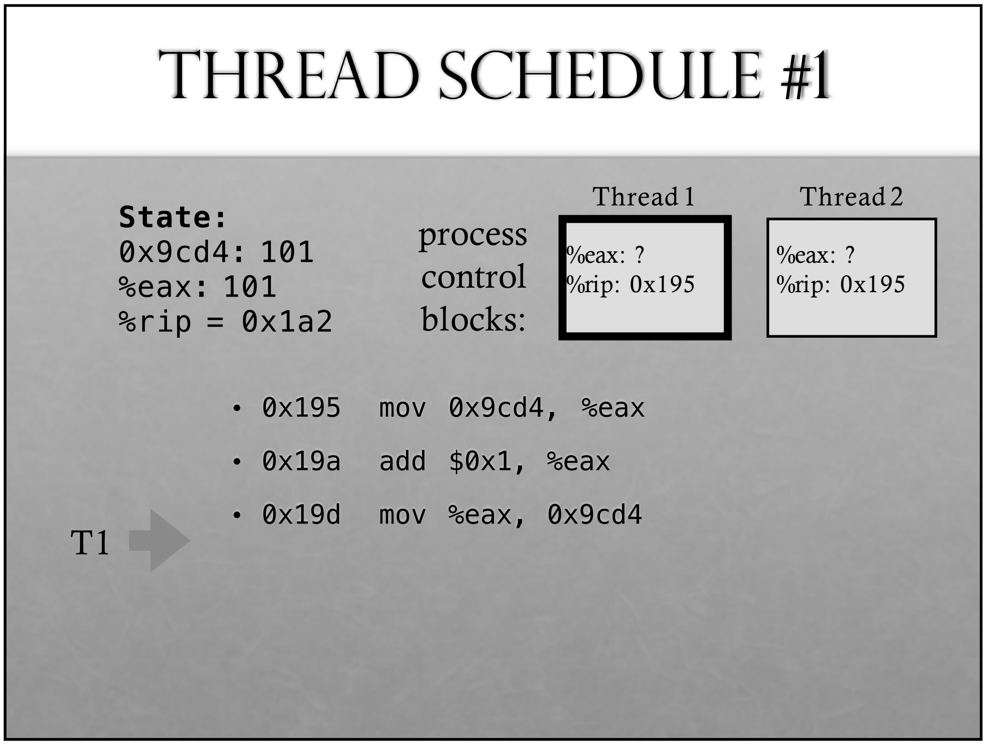
Thread Schedule #1

State:
0x9cd4: 100
%eax: 101
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

```
      • 0x195   mov  0x9cd4, %eax
      • 0x19a   add  $0x1, %eax
T1 ➡  • 0x19d   mov  %eax, 0x9cd4
```



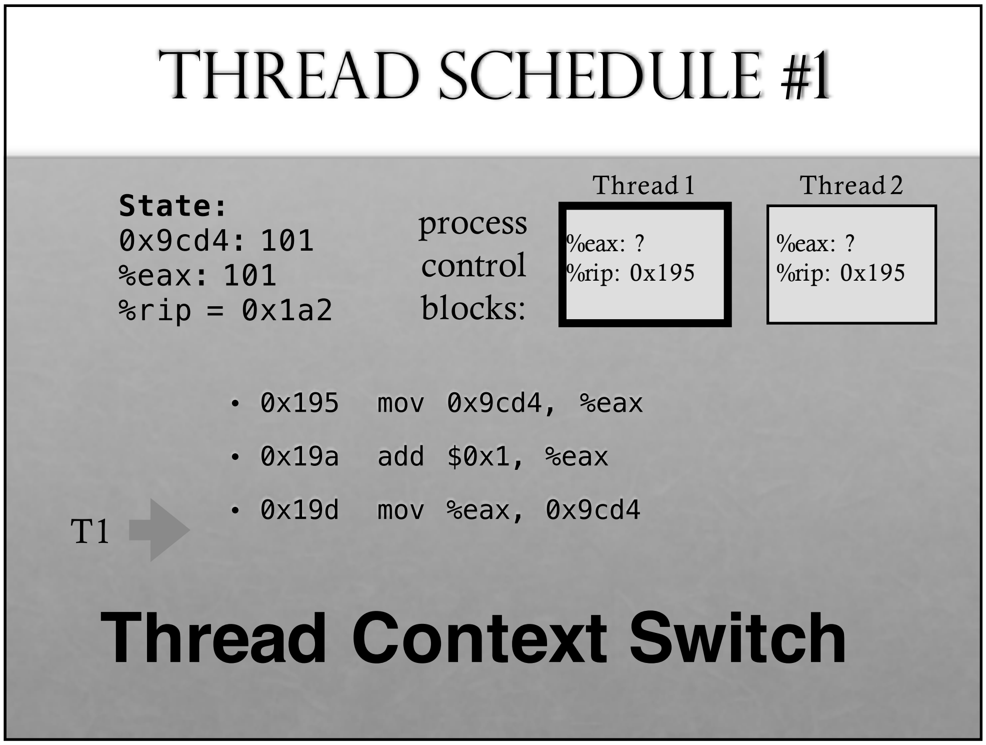
Thread Schedule #1

State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

process
control
blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```



Thread Schedule #1

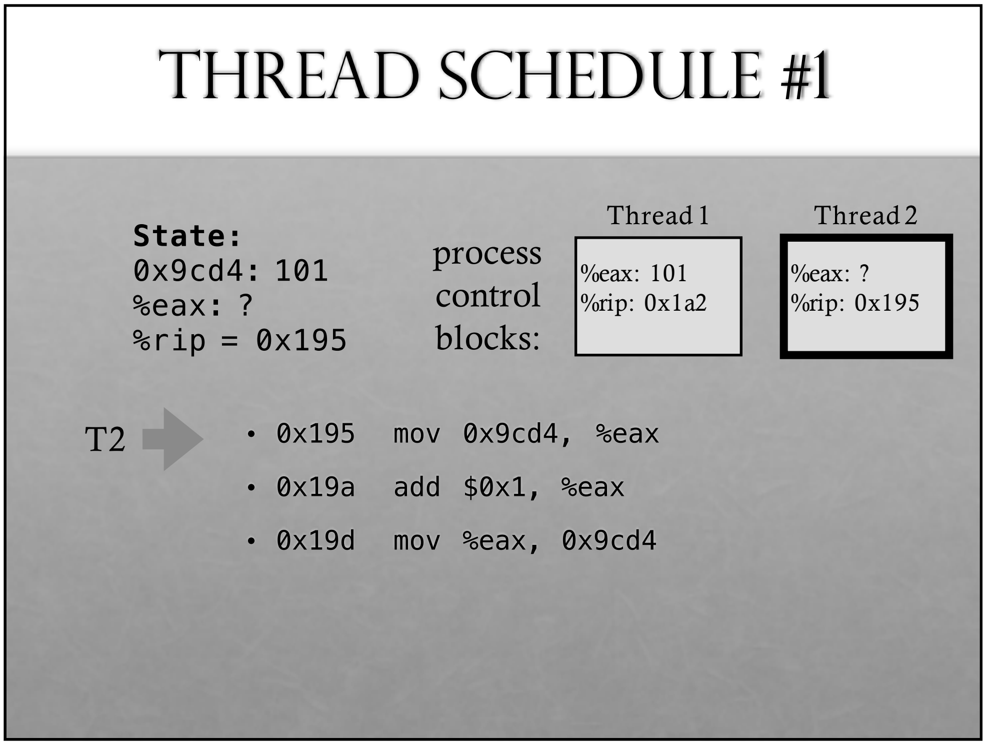
State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

process
control
blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```

Thread Context Switch



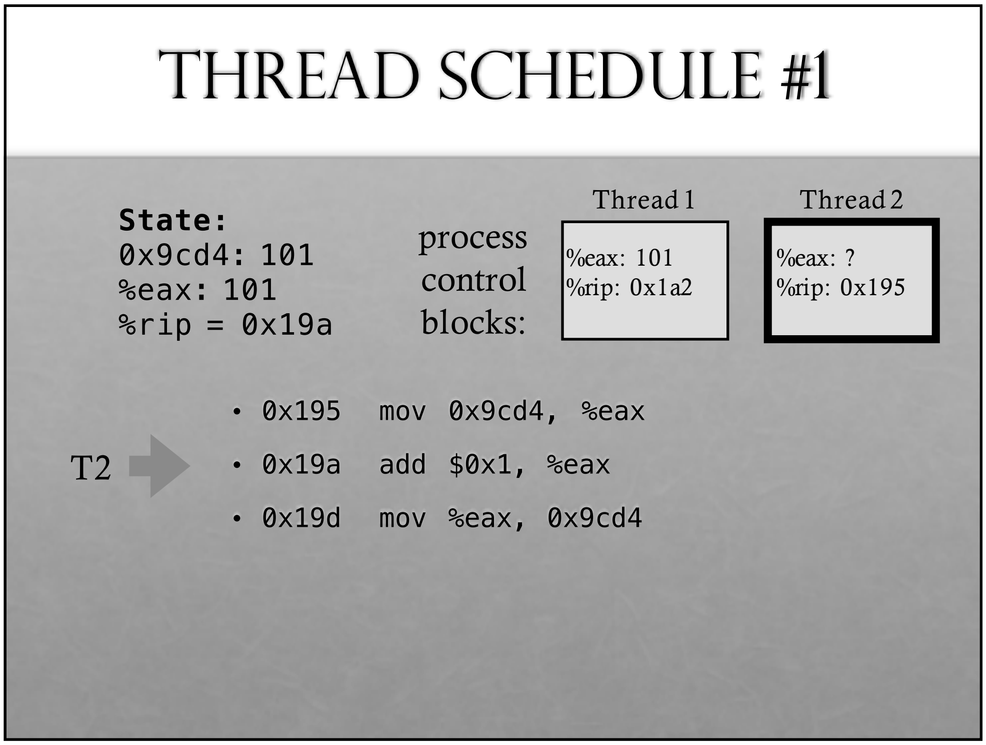
Thread Schedule #1

State:
0x9cd4: 101
%eax: ?
%rip = 0x195

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4



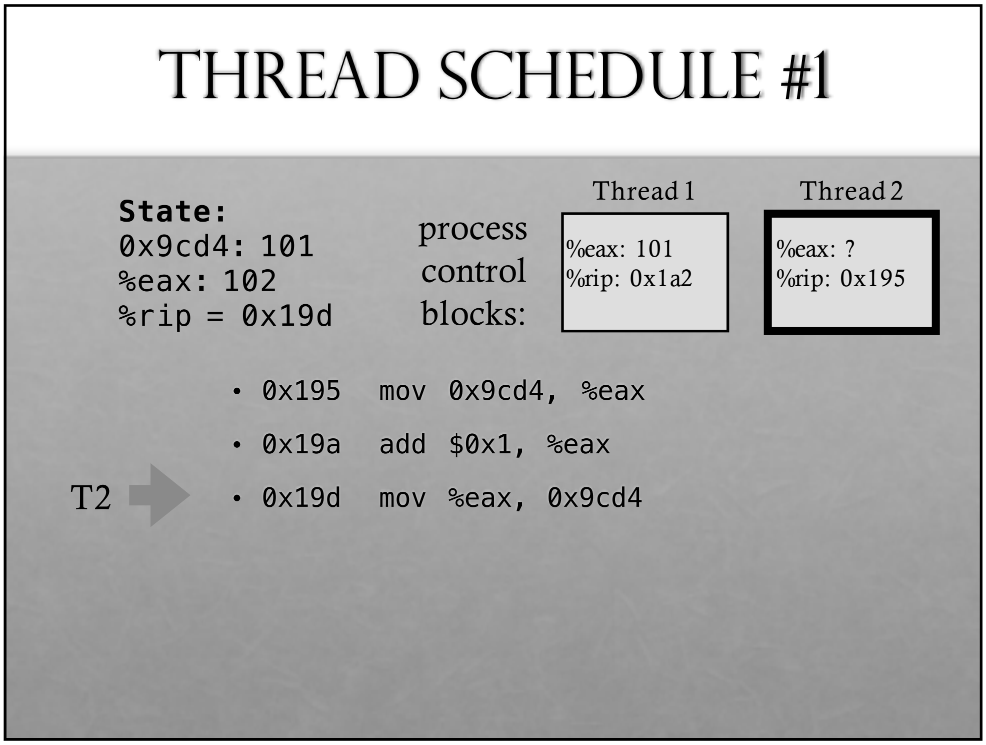
Thread Schedule #1

State:
0x9cd4: 101
%eax: 101
%rip = 0x19a

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4



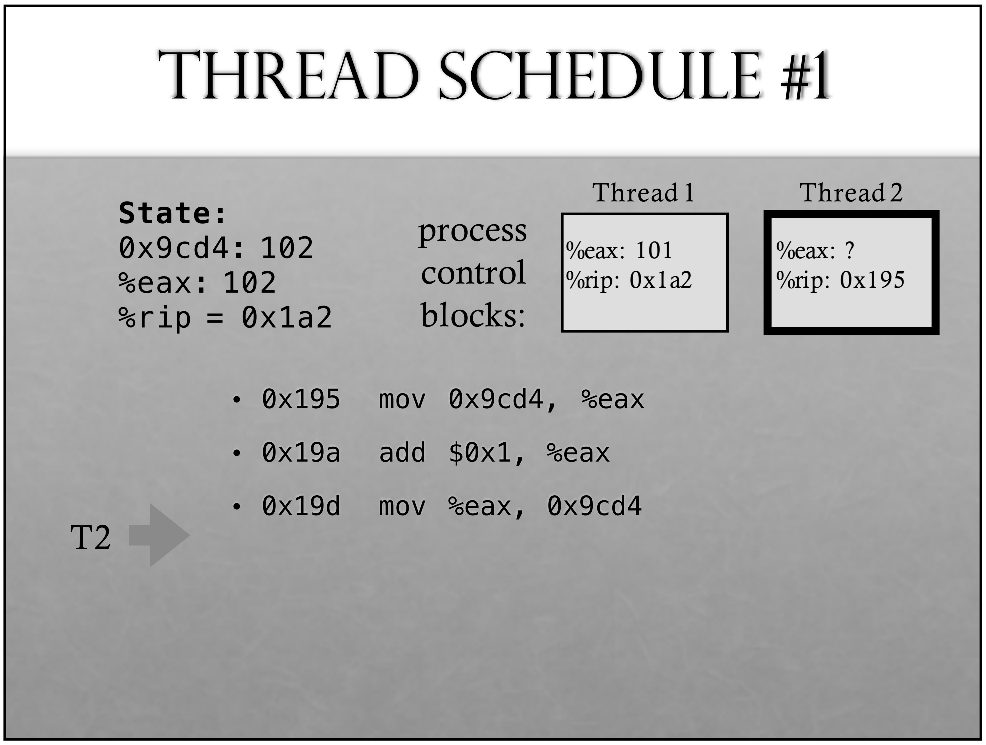
Thread Schedule #1

State:
0x9cd4: 101
%eax: 102
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4



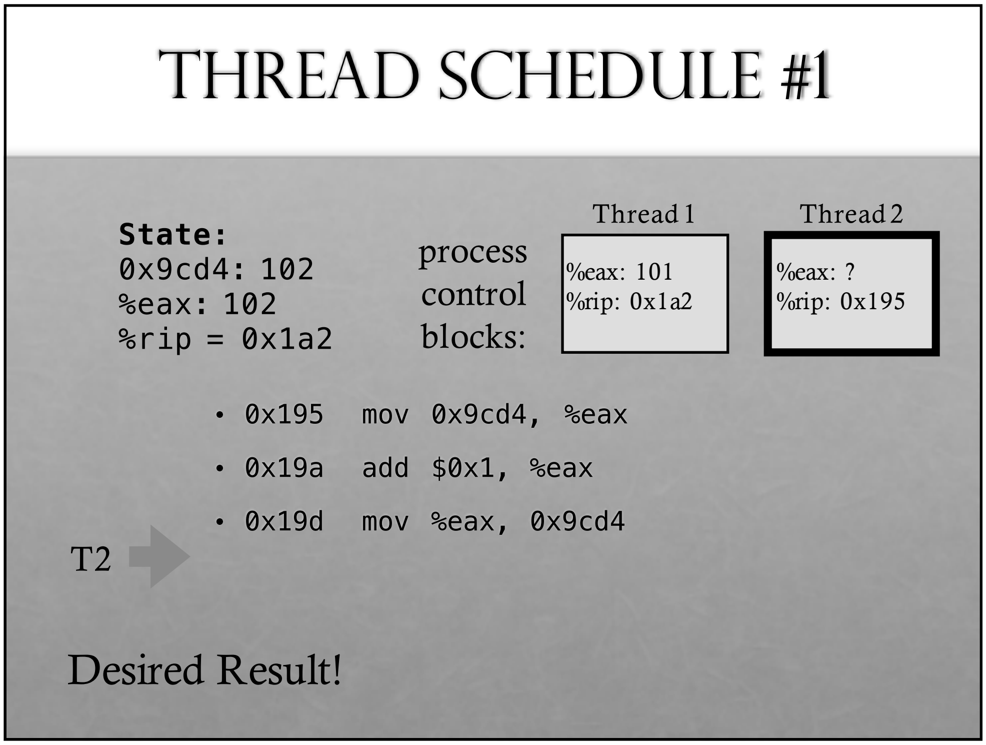
Thread Schedule #1

State:
0x9cd4: 102
%eax: 102
%rip = 0x1a2

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4



Thread Schedule #1

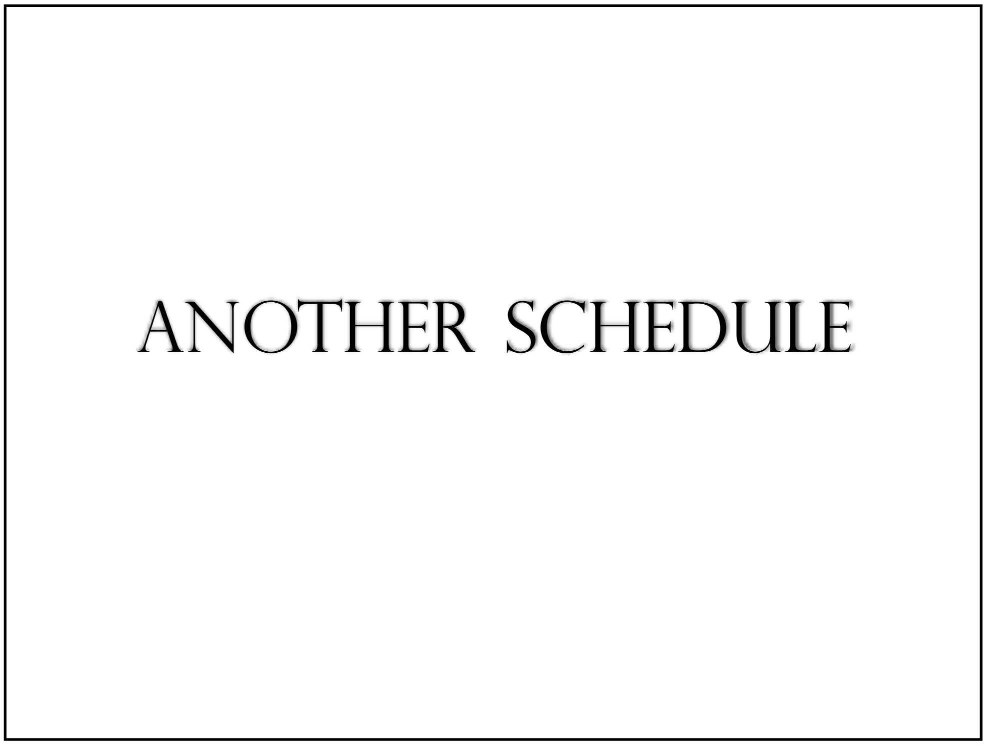
```
State:
0x9cd4: 102
%eax: 102
%rip = 0x1a2
```

process control blocks:

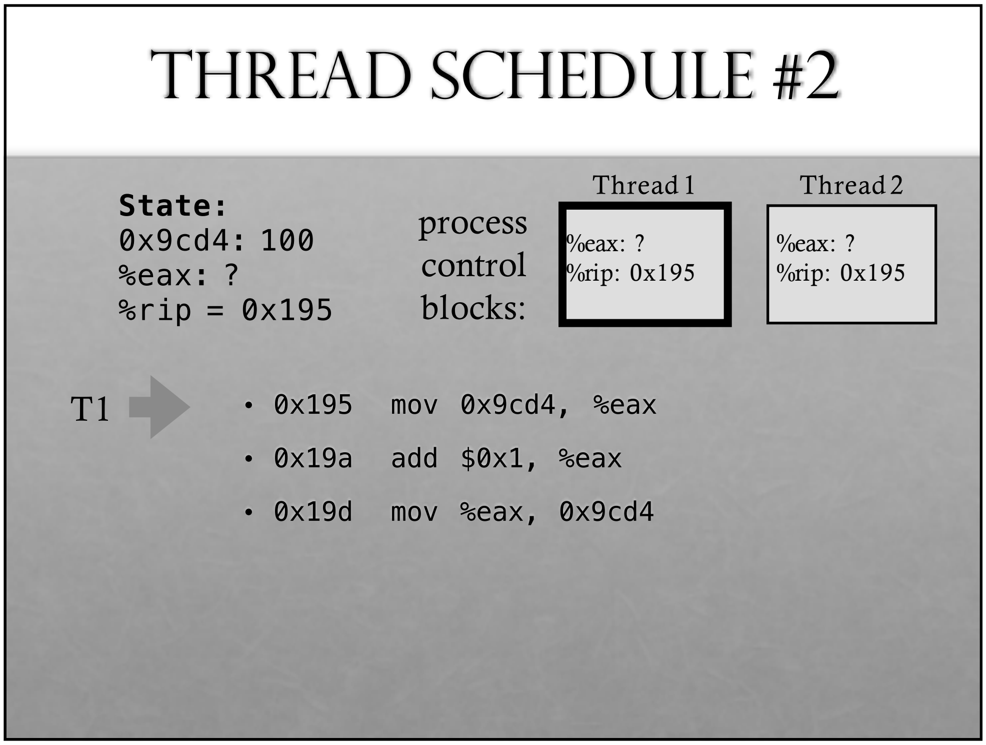
Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: ? %rip: 0x195

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```

Desired Result!



Another Schedule



Thread Schedule #2

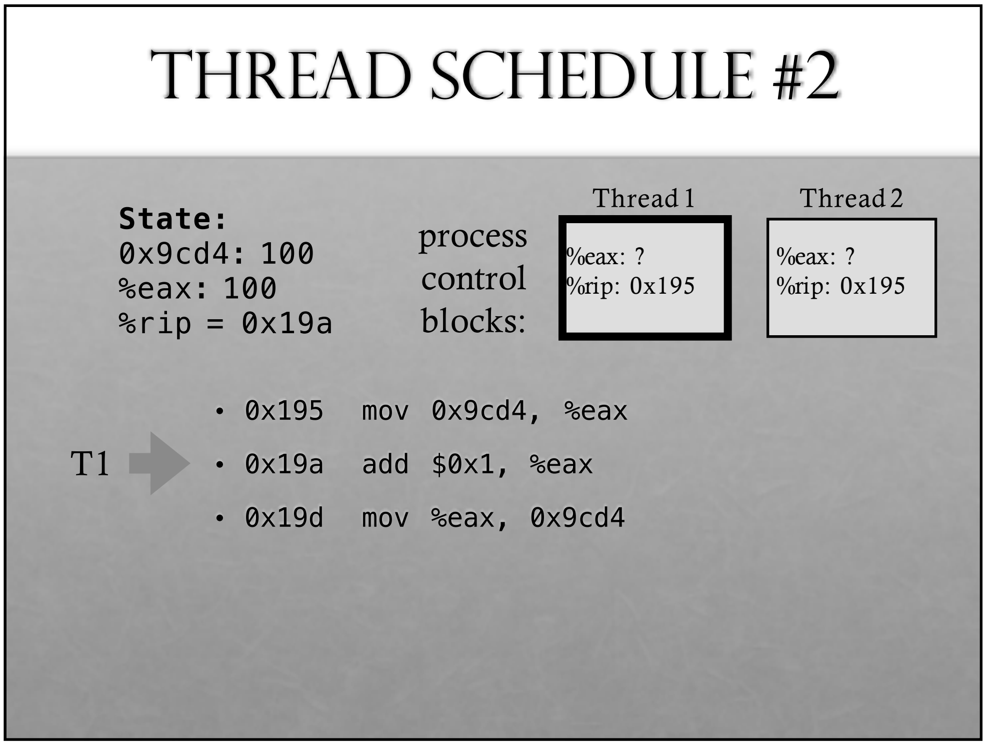
State:
0x9cd4: 100
%eax: ?
%rip = 0x195

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

T1 →

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```



Thread Schedule #2

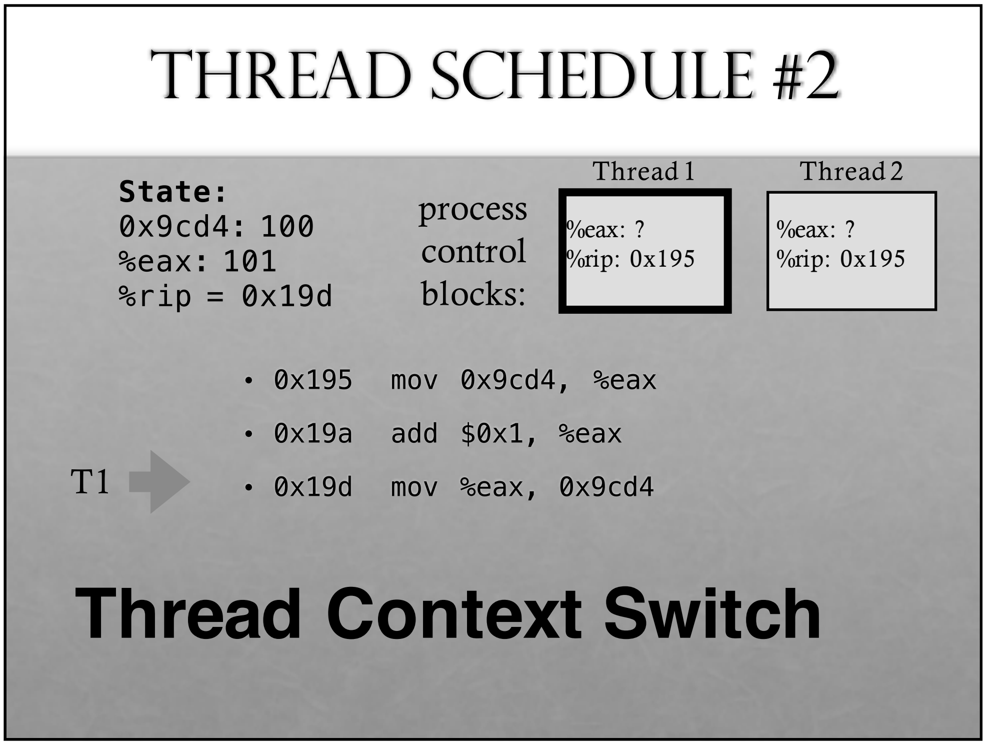
State:
0x9cd4: 100
%eax: 100
%rip = 0x19a

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

T1 → (next to 0x19a)

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```



Thread Schedule #2

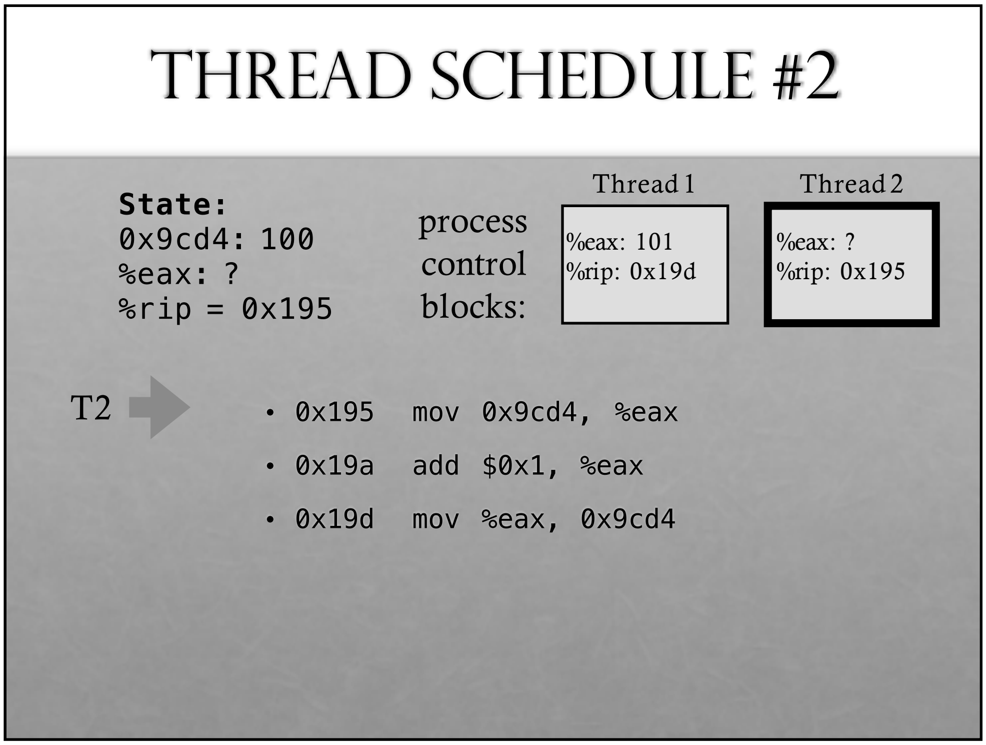
State:
0x9cd4: 100
%eax: 101
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: ? %rip: 0x195	%eax: ? %rip: 0x195

```
   • 0x195  mov  0x9cd4, %eax
   • 0x19a  add  $0x1, %eax
T1 • 0x19d  mov  %eax, 0x9cd4
```

Thread Context Switch



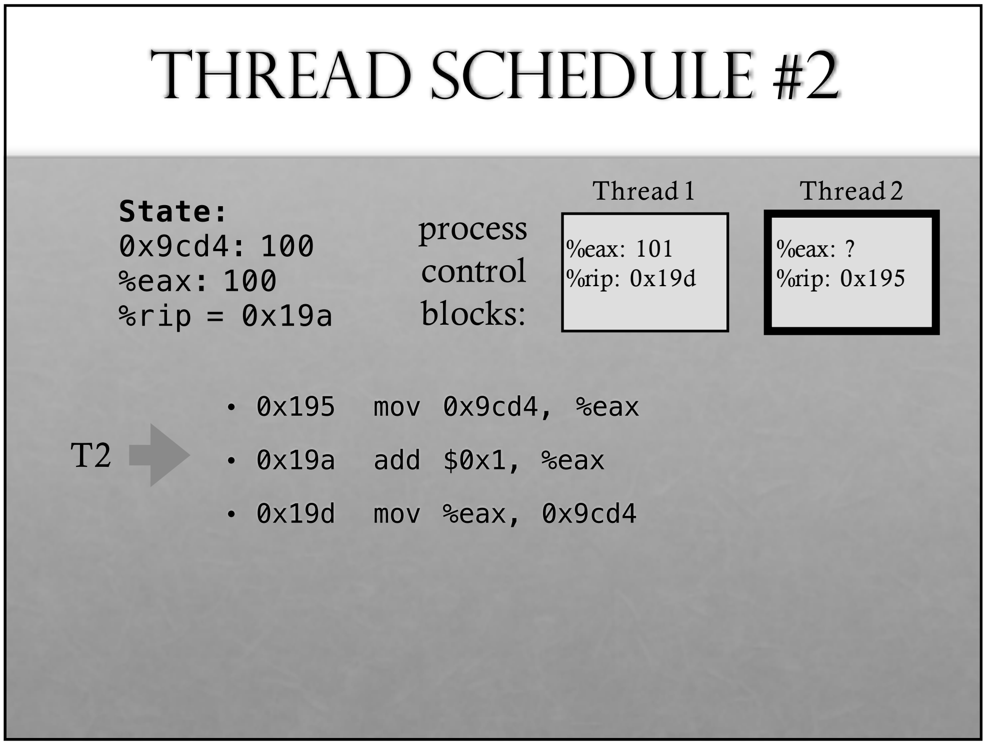
Thread Schedule #2

State:
0x9cd4: 100
%eax: ?
%rip = 0x195

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: ? %rip: 0x195

```
T2 • 0x195  mov  0x9cd4, %eax
   • 0x19a  add  $0x1, %eax
   • 0x19d  mov  %eax, 0x9cd4
```



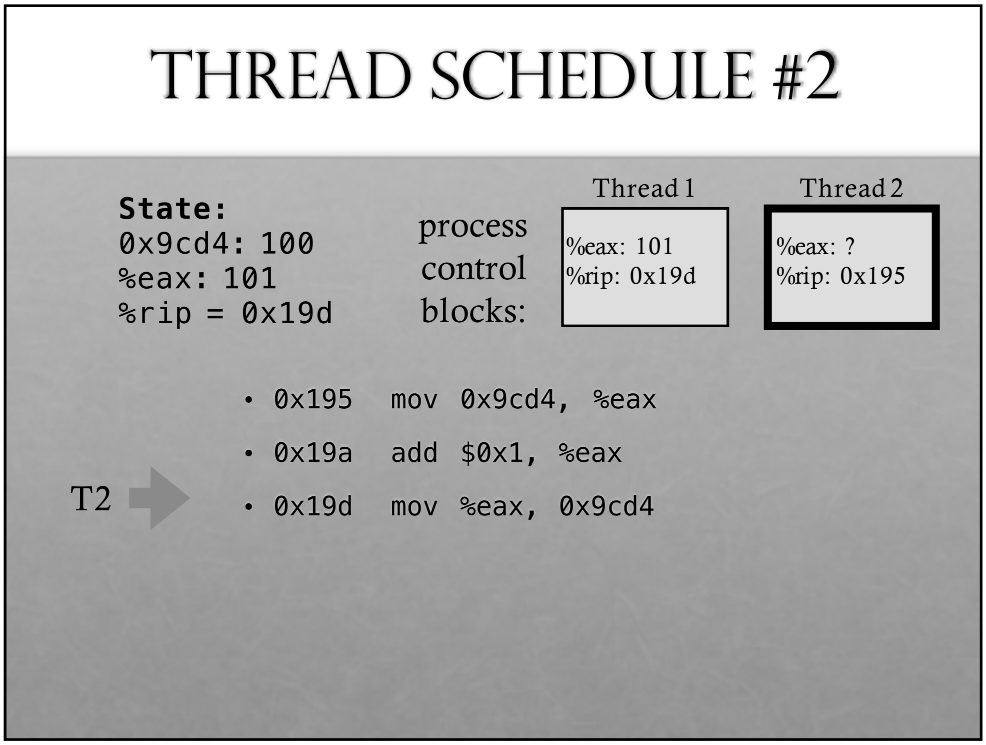
Thread Schedule #2

State:
0x9cd4: 100
%eax: 100
%rip = 0x19a

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: ? %rip: 0x195

```
     • 0x195   mov  0x9cd4, %eax
T2 → • 0x19a   add  $0x1, %eax
     • 0x19d   mov  %eax, 0x9cd4
```



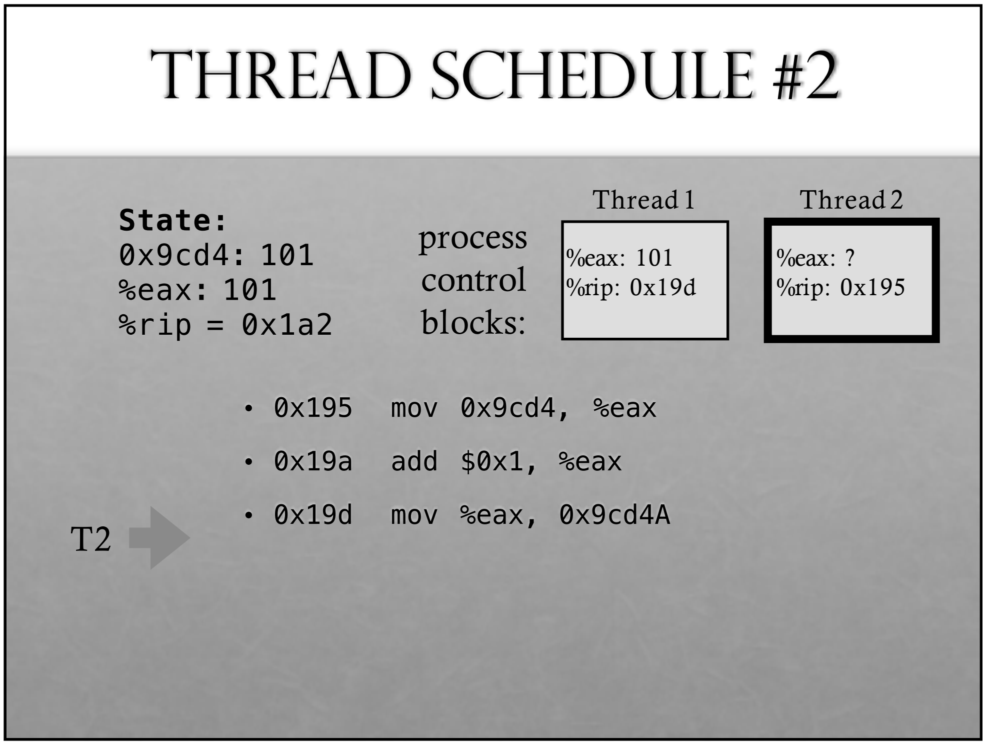
Thread Schedule #2

State:
0x9cd4: 100
%eax: 101
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: ? %rip: 0x195

```
     • 0x195   mov  0x9cd4, %eax
     • 0x19a   add  $0x1, %eax
T2 → • 0x19d   mov  %eax, 0x9cd4
```



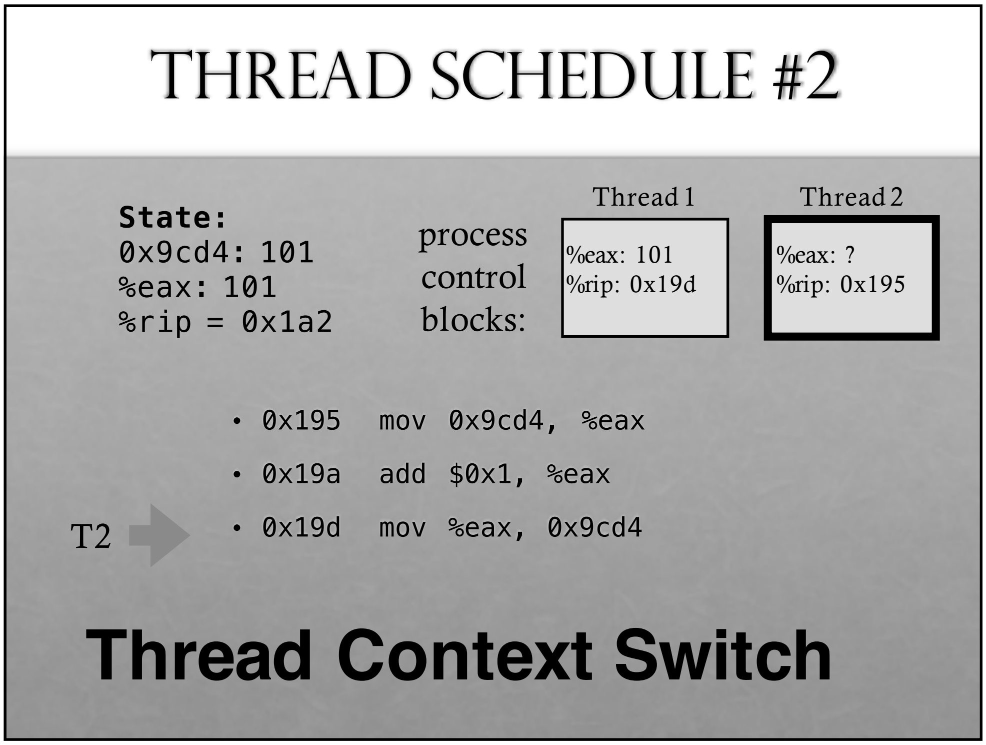
Thread Schedule #2

State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

process
control
blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4A



Thread Schedule #2

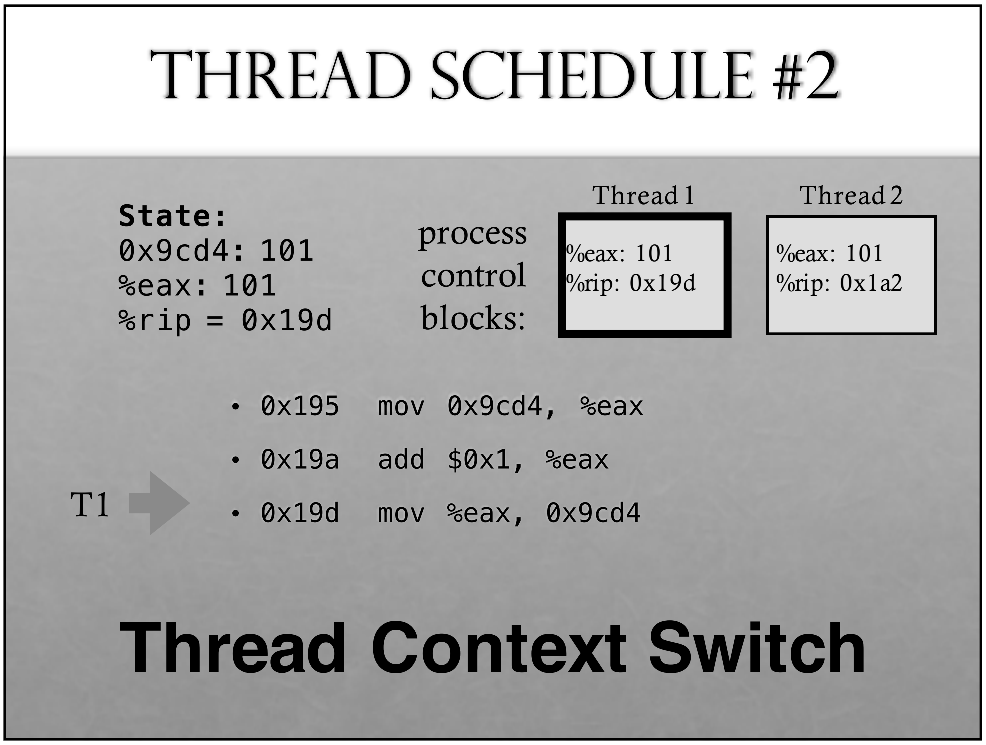
State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

process
control
blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: ? %rip: 0x195

- 0x195 mov 0x9cd4, %eax
- 0x19a add $0x1, %eax
- 0x19d mov %eax, 0x9cd4

Thread Context Switch



Thread Schedule #2

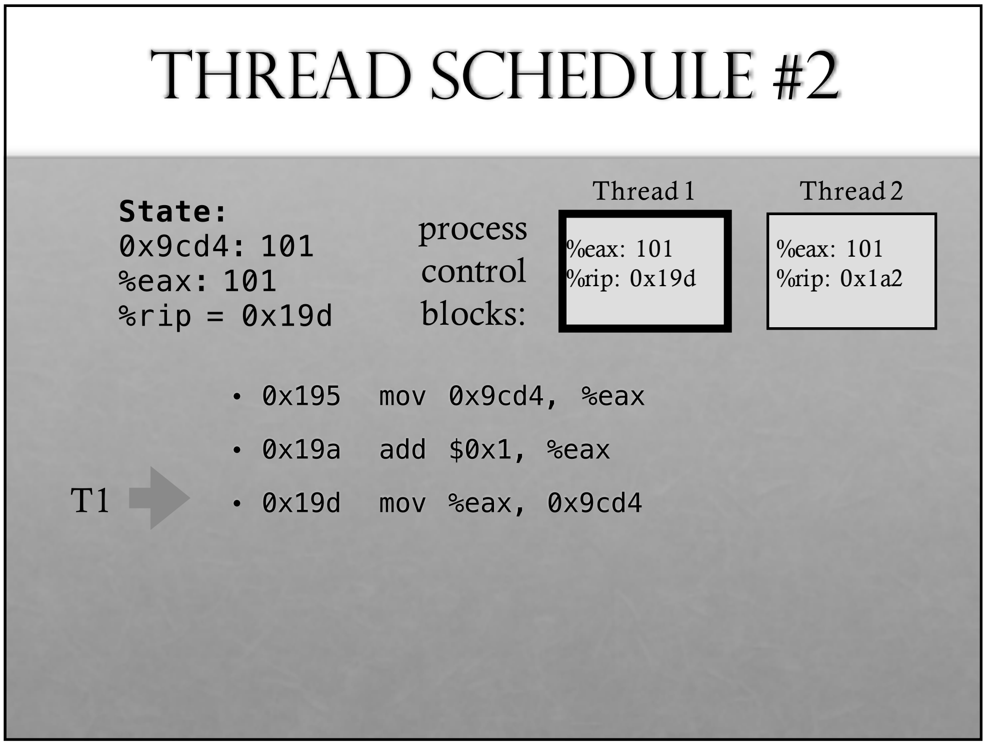
State:
0x9cd4: 101
%eax: 101
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: 101 %rip: 0x1a2

```
   • 0x195   mov  0x9cd4, %eax
   • 0x19a   add  $0x1, %eax
T1 • 0x19d   mov  %eax, 0x9cd4
```

Thread Context Switch



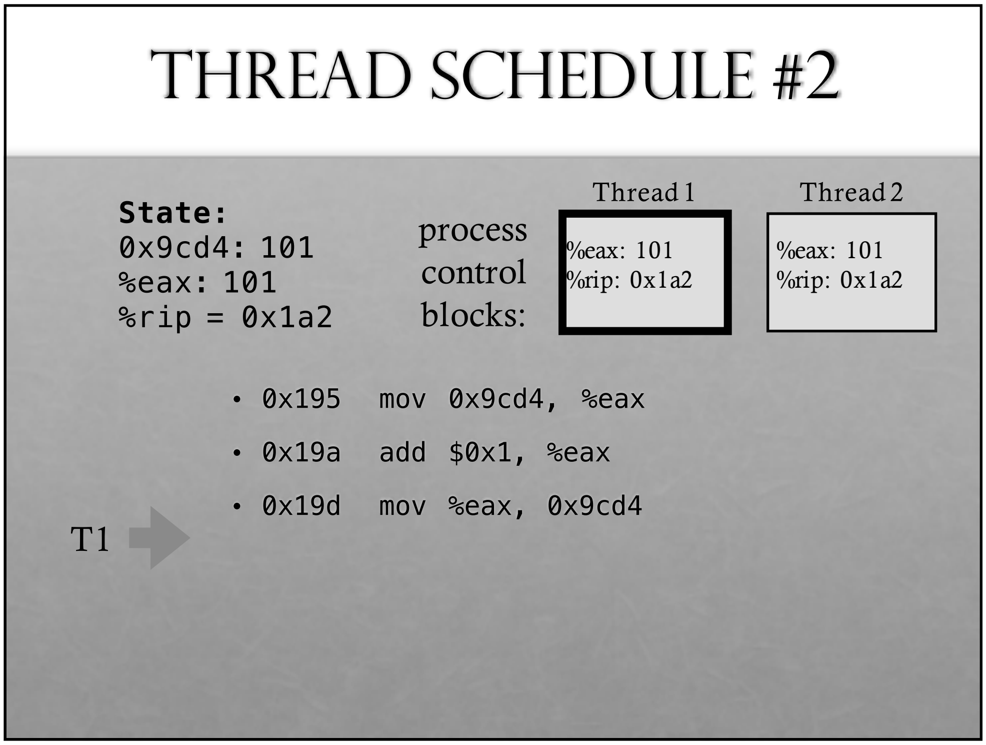
Thread Schedule #2

State:
0x9cd4: 101
%eax: 101
%rip = 0x19d

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x19d	%eax: 101 %rip: 0x1a2

```
   • 0x195   mov  0x9cd4, %eax
   • 0x19a   add  $0x1, %eax
T1 • 0x19d   mov  %eax, 0x9cd4
```



Thread Schedule #2

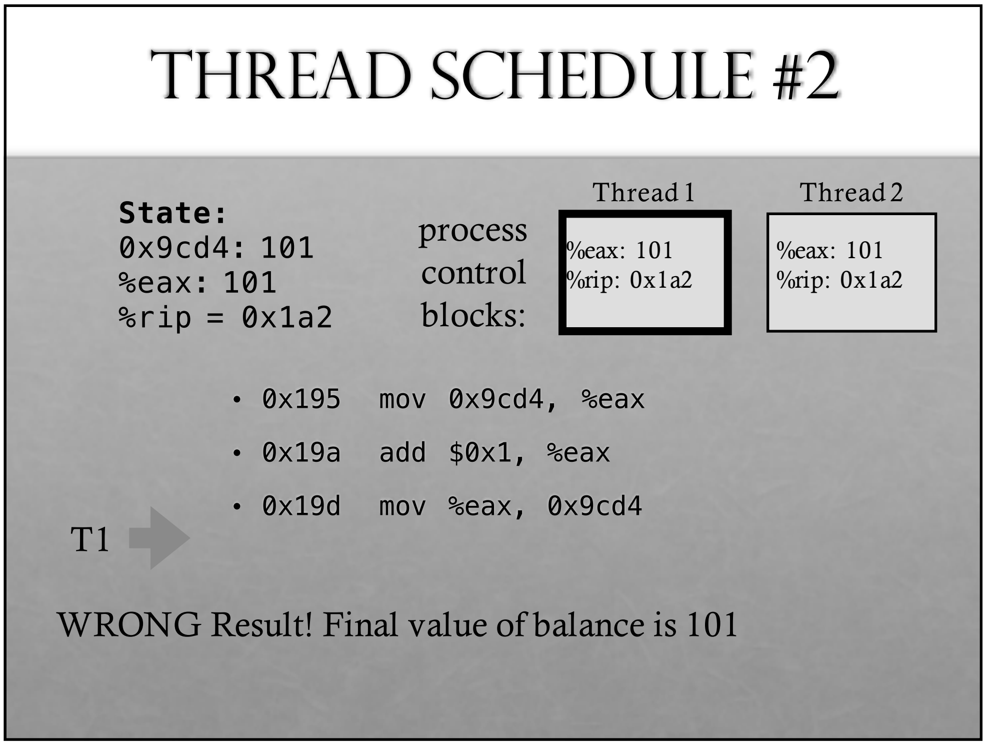
State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: 101 %rip: 0x1a2

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```

T1



Thread Schedule #2

State:
0x9cd4: 101
%eax: 101
%rip = 0x1a2

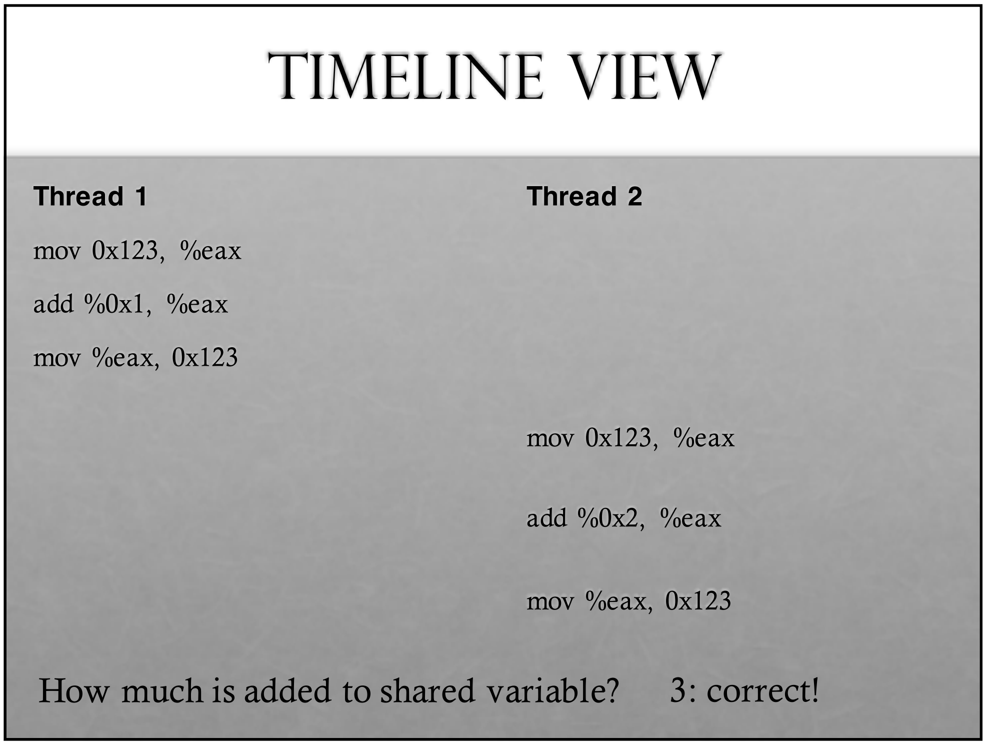
process control blocks:

Thread 1	Thread 2
%eax: 101 %rip: 0x1a2	%eax: 101 %rip: 0x1a2

```
• 0x195   mov  0x9cd4, %eax
• 0x19a   add  $0x1, %eax
• 0x19d   mov  %eax, 0x9cd4
```

T1

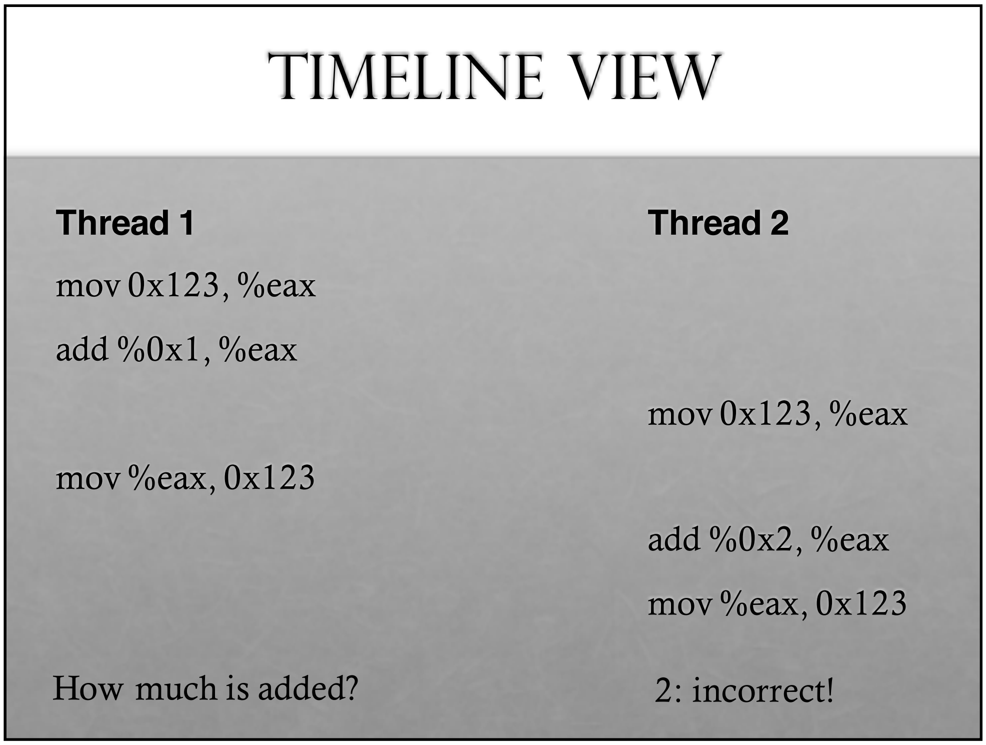
WRONG Result! Final value of balance is 101



Timeline View

Thread 1	Thread 2
mov 0x123, %eax	
add %0x1, %eax	
mov %eax, 0x123	
	mov 0x123, %eax
	add %0x2, %eax
	mov %eax, 0x123

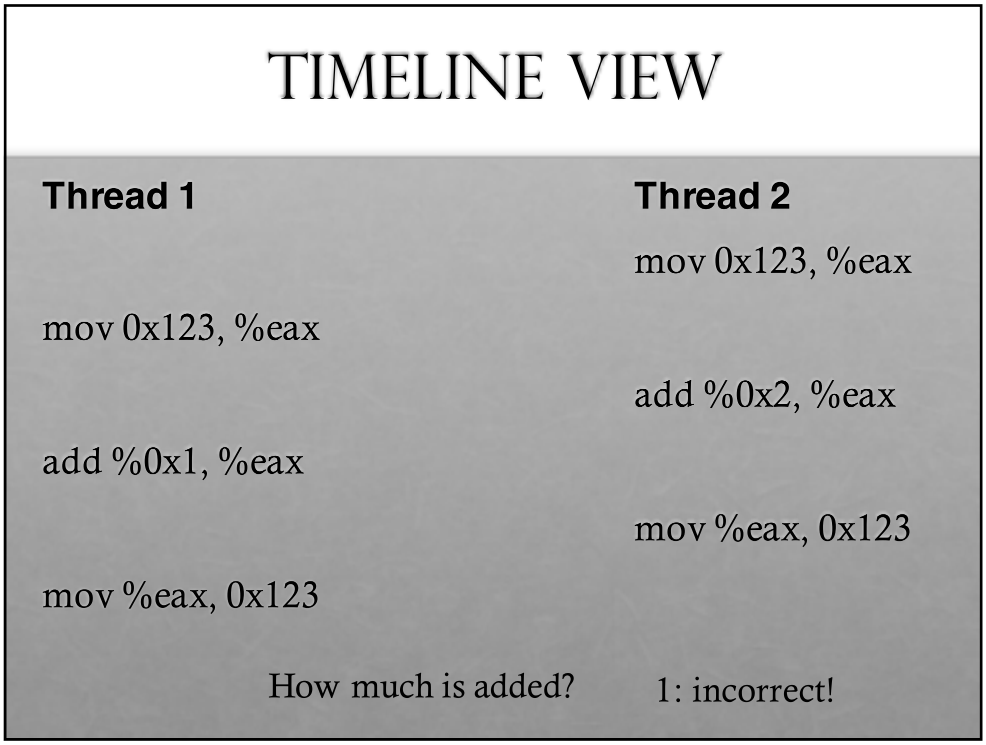
How much is added to shared variable? 3: correct!



Timeline View

Thread 1	Thread 2
mov 0x123, %eax	
add %0x1, %eax	
	mov 0x123, %eax
mov %eax, 0x123	
	add %0x2, %eax
	mov %eax, 0x123

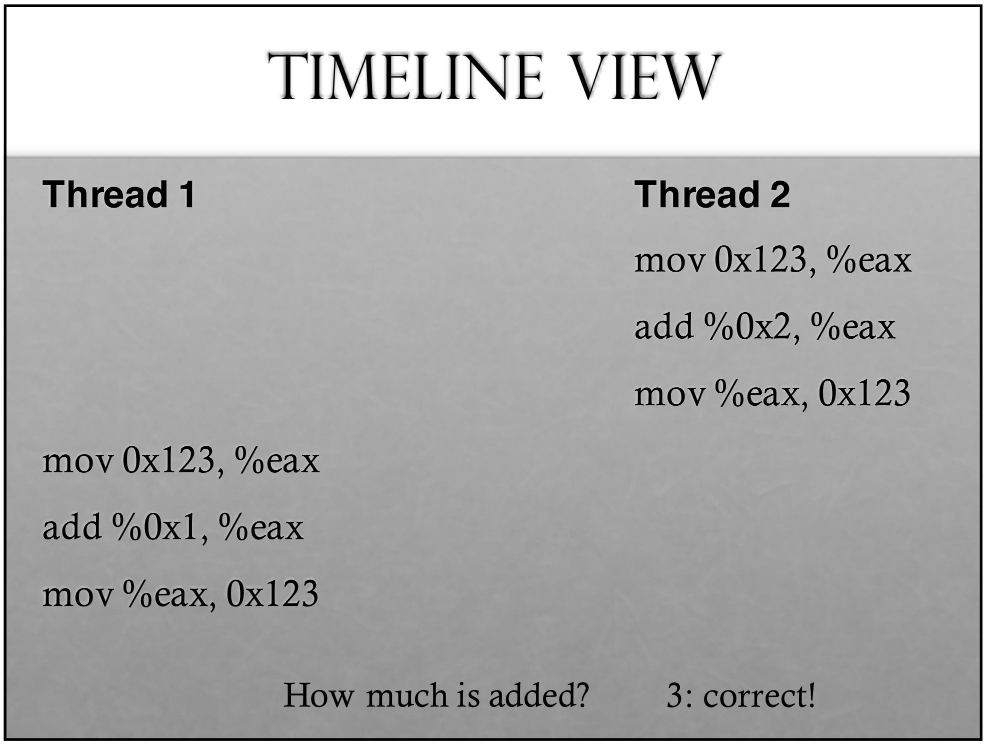
How much is added? 2: incorrect!



Timeline View

Thread 1	Thread 2
	mov 0x123, %eax
mov 0x123, %eax	
	add %0x2, %eax
add %0x1, %eax	
	mov %eax, 0x123
mov %eax, 0x123	

How much is added? 1: incorrect!



Timeline View

Thread 1	Thread 2
	mov 0x123, %eax
	add %0x2, %eax
	mov %eax, 0x123
mov 0x123, %eax	
add %0x1, %eax	
mov %eax, 0x123	

How much is added? 3: correct!

Timeline View

Thread 1	**Thread 2**
	mov 0x123, %eax
	add %0x2, %eax
mov 0x123, %eax	
add %0x1, %eax	
mov %eax, 0x123	
	mov %eax, 0x123

How much is added? 2: incorrect!

Non-Determinism

Concurrency leads to non-deterministic results

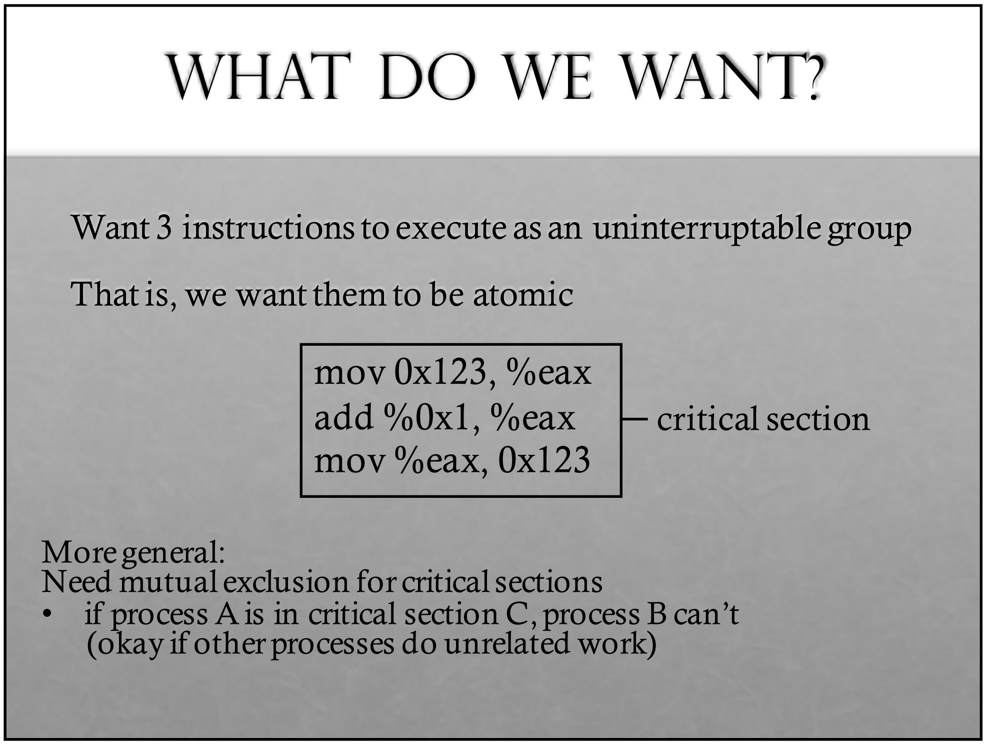
- Not deterministic result: different results even with same inputs
- race conditions

Whether bug manifests depends on CPU schedule!

Passing tests means little

How to program: imagine scheduler is malicious

Assume scheduler will pick bad ordering at some point…



What do we want?

Want 3 instructions to execute as an uninterruptable group

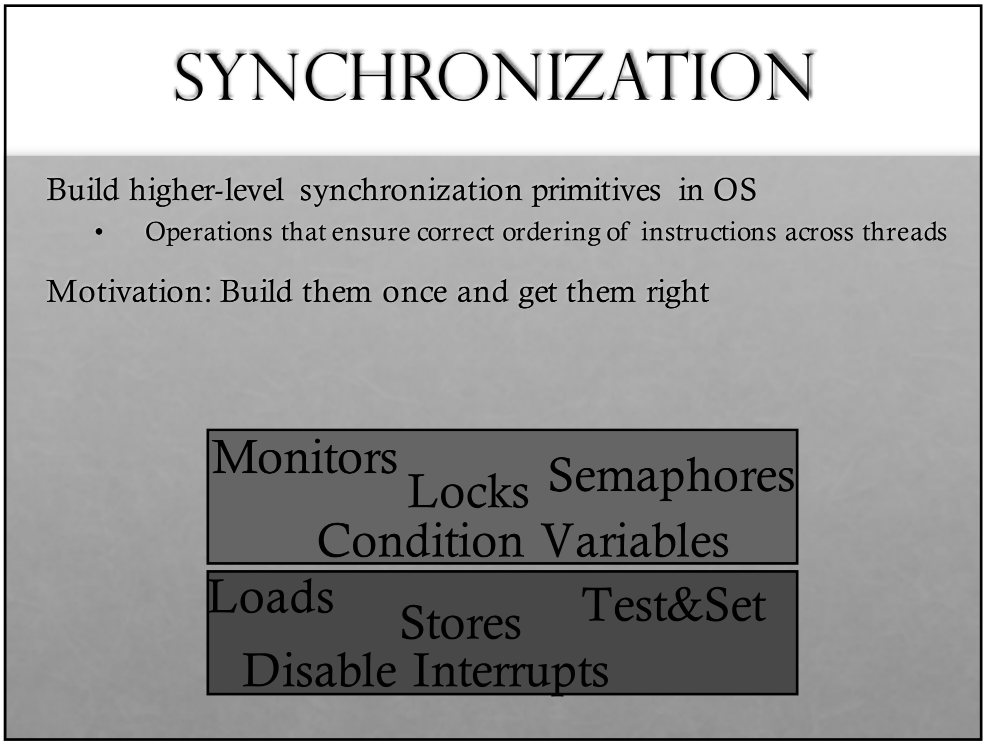
That is, we want them to be atomic

```
mov 0x123, %eax
add %0x1, %eax
mov %eax, 0x123
```

critical section

More general:
Need mutual exclusion for critical sections

- if process A is in critical section C, process B can't (okay if other processes do unrelated work)



Synchronization

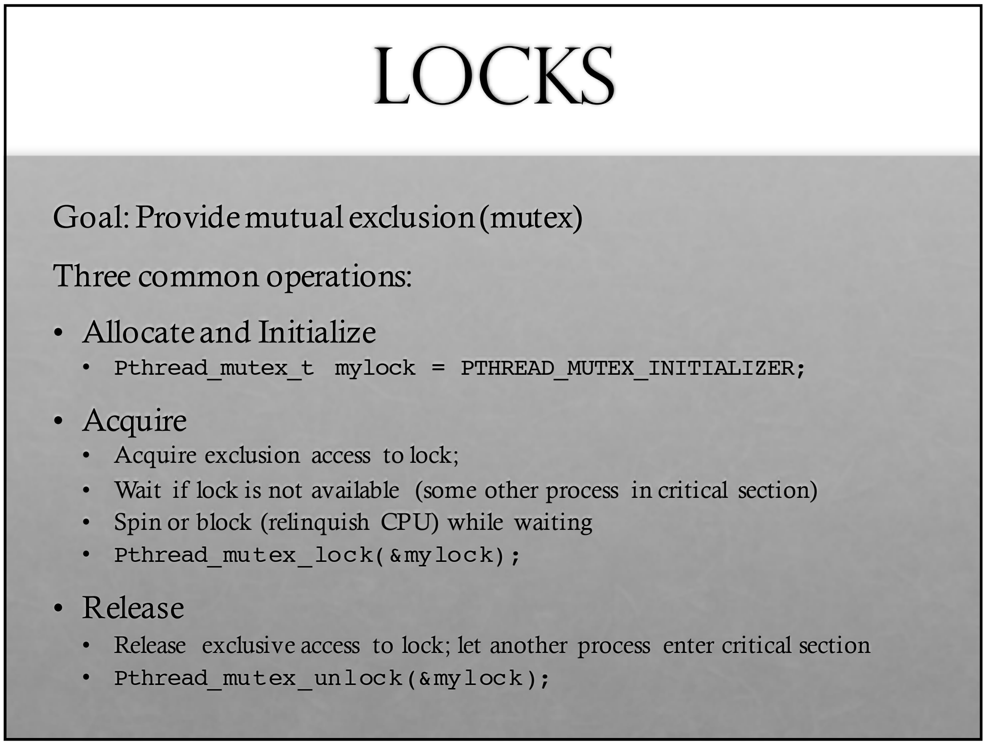
Build higher-level synchronization primitives in OS

- Operations that ensure correct ordering of instructions across threads

Motivation: Build them once and get them right

Monitors Locks Semaphores
Condition Variables

Loads Stores Test&Set
Disable Interrupts



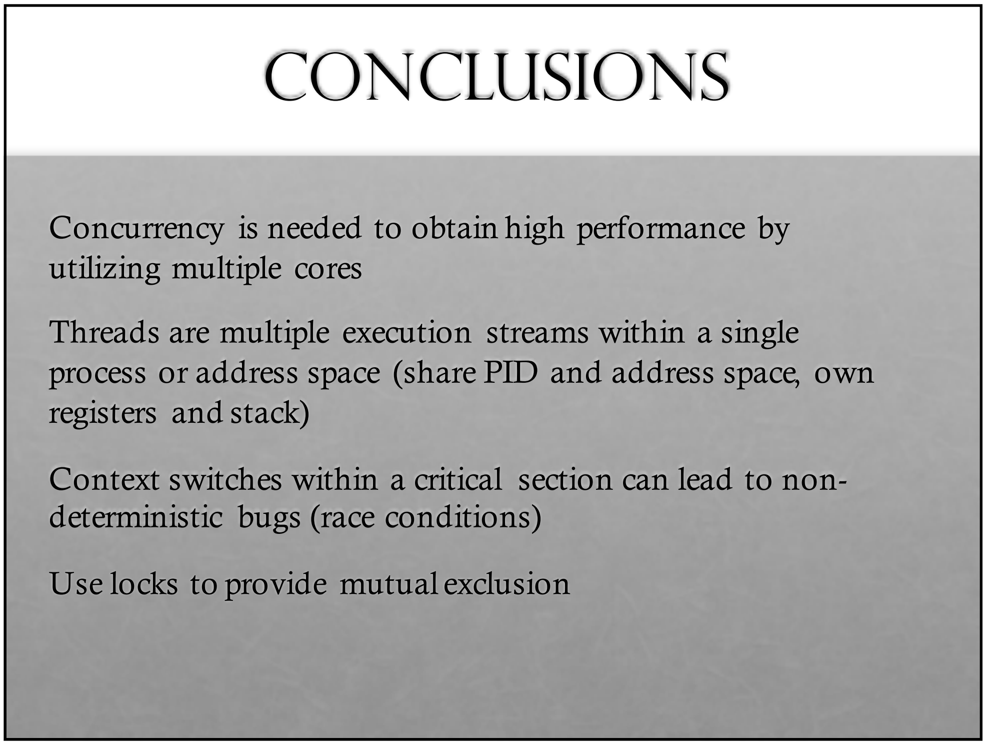
Locks

Goal: Provide mutual exclusion (mutex)

Three common operations:

- Allocate and Initialize
  - `Pthread_mutex_t mylock = PTHREAD_MUTEX_INITIALIZER;`
- Acquire
  - Acquire exclusion access to lock;
  - Wait if lock is not available (some other process in critical section)
  - Spin or block (relinquish CPU) while waiting
  - `Pthread_mutex_lock(&mylock);`
- Release
  - Release exclusive access to lock; let another process enter critical section
  - `Pthread_mutex_unlock(&mylock);`

More Demos



CONCLUSIONS

Concurrency is needed to obtain high performance by utilizing multiple cores

Threads are multiple execution streams within a single process or address space (share PID and address space, own registers and stack)

Context switches within a critical section can lead to non-deterministic bugs (race conditions)

Use locks to provide mutual exclusion