CPSC 410

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Content from OSTEP

CONCURRENCY: THREADS

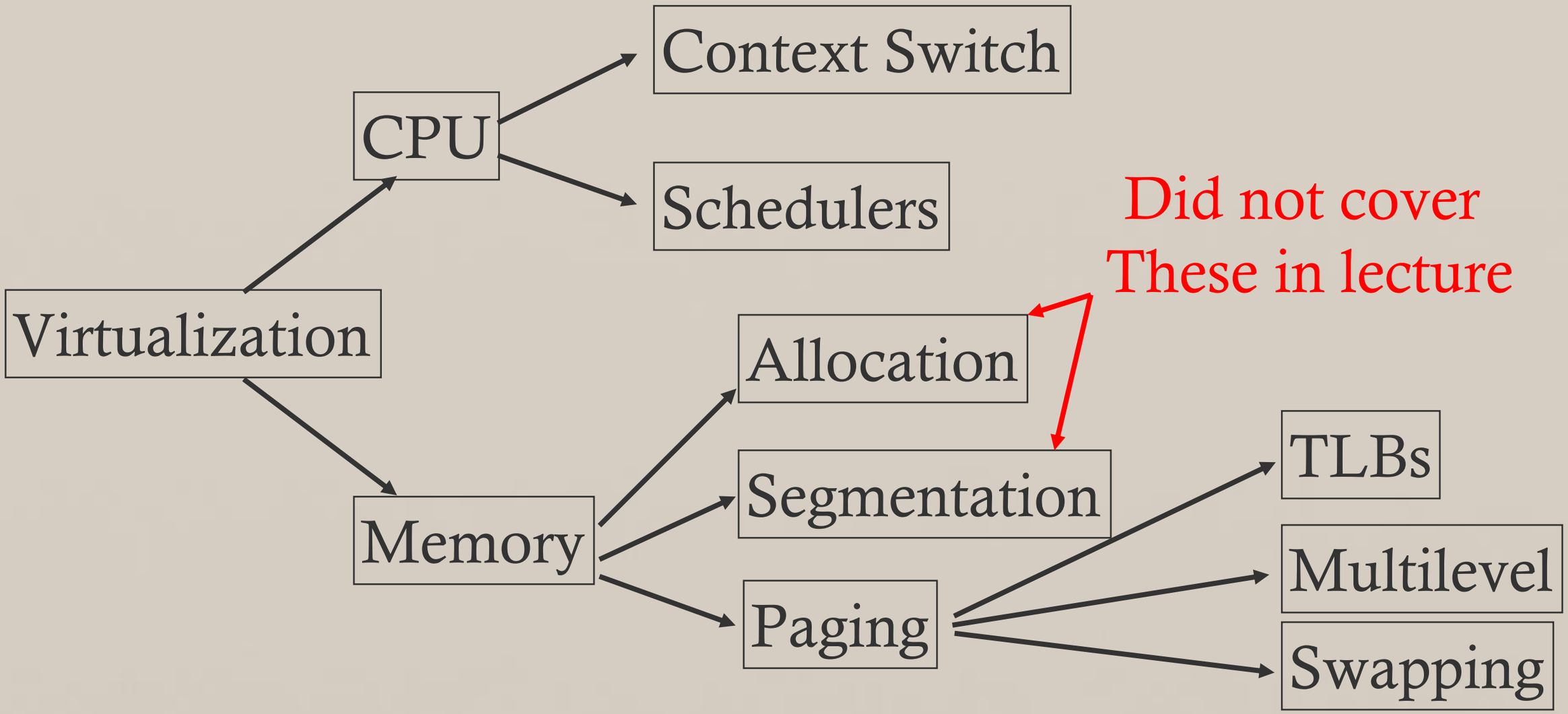
Questions answered in this lecture:

Why is concurrency useful?

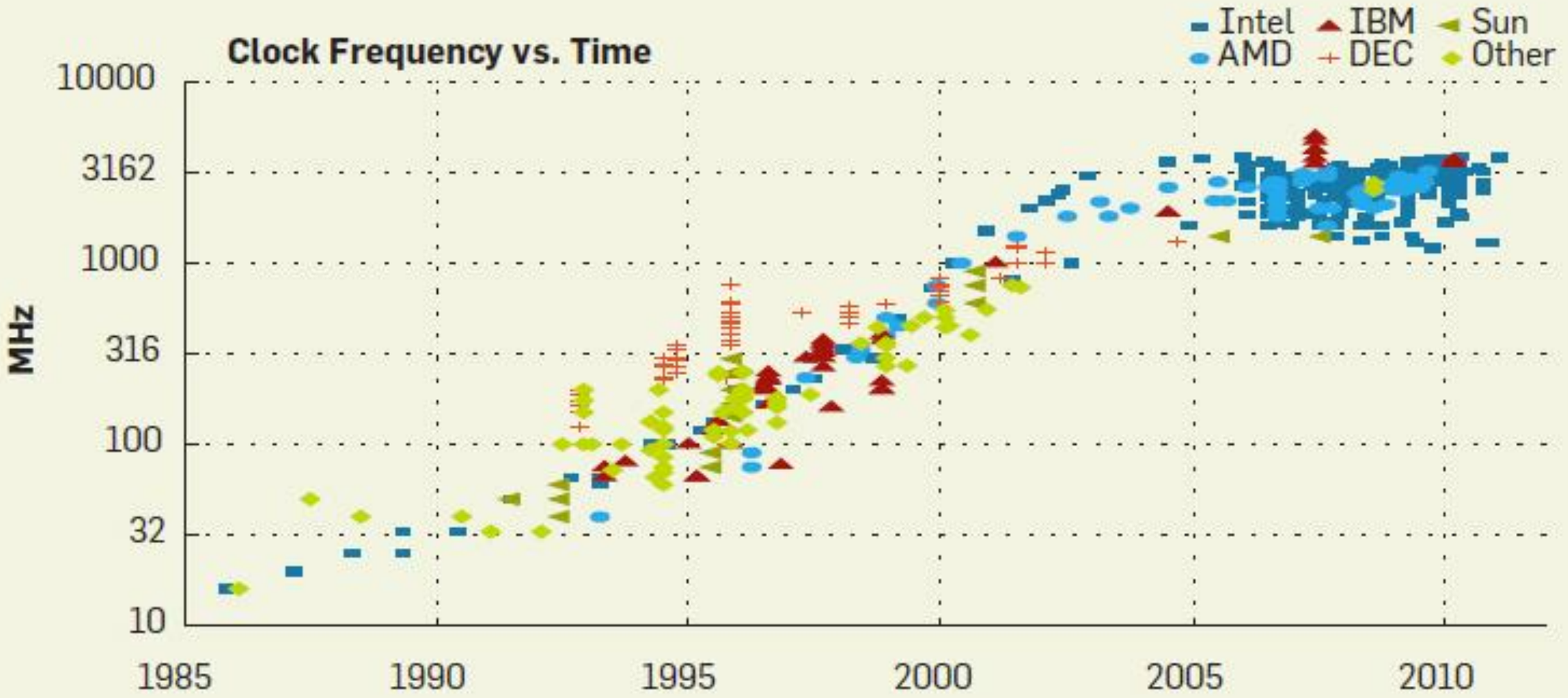
What is a thread and how does it differ from processes?

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

FIRST PART OF COURSE



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

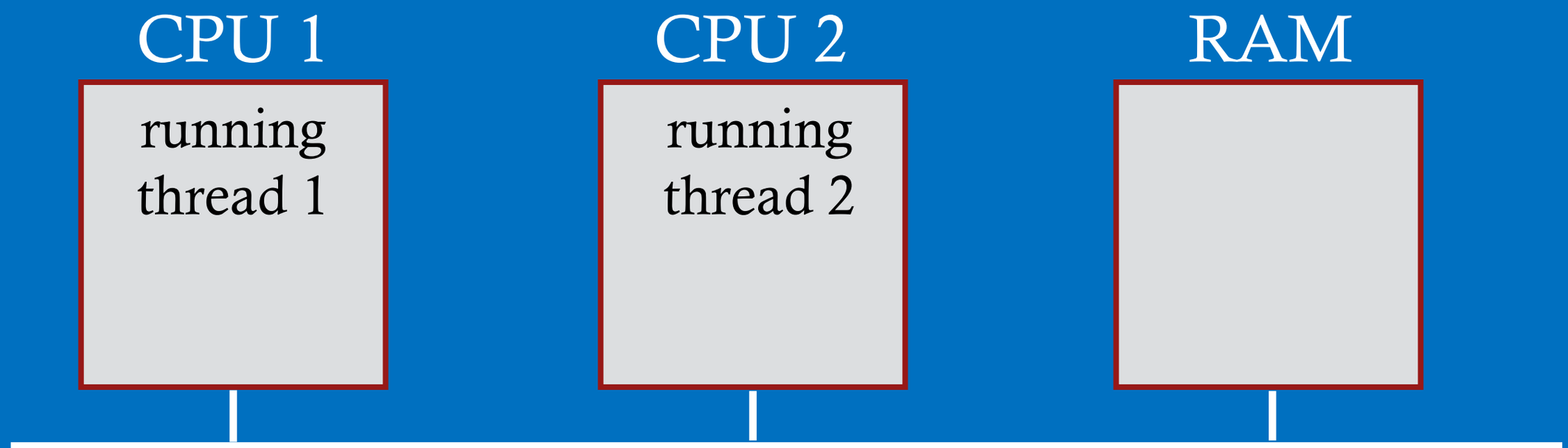
Divide large task across several cooperative threads

Communicate through shared address space

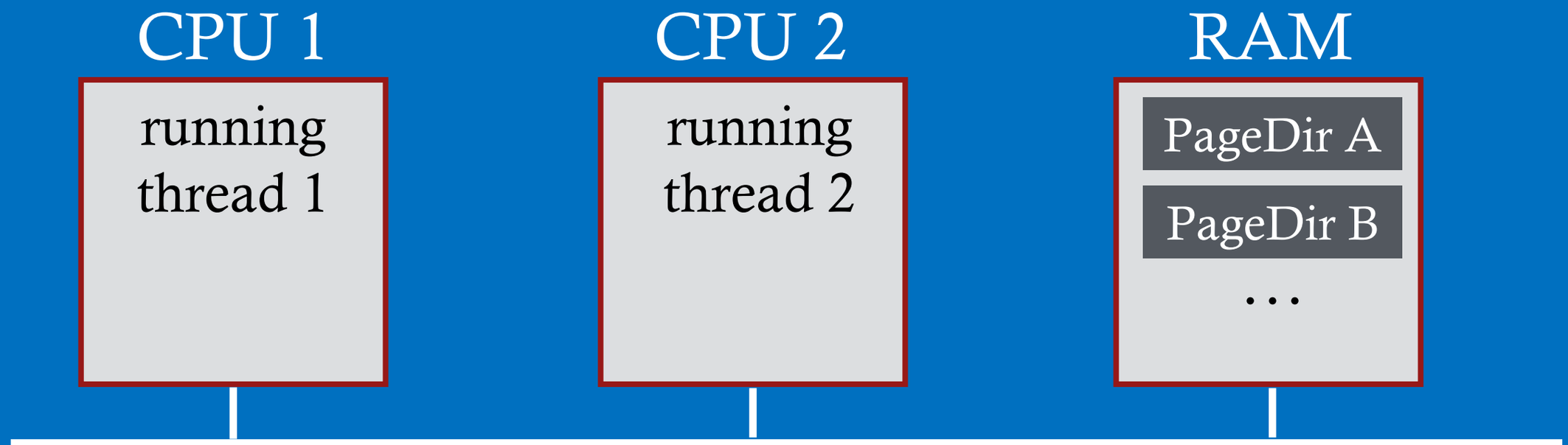
COMMON PROGRAMMING MODELS

Multi-threaded programs tend to be structured as:

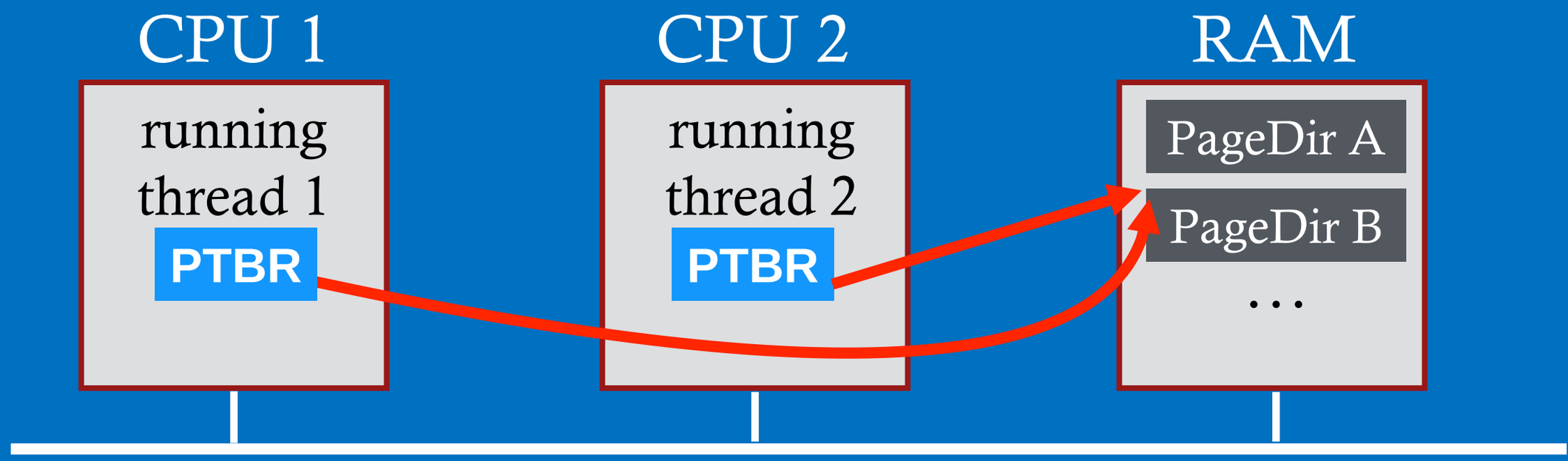
- **Producer/consumer**
  Multiple producer threads create data (or work) that is handled by one of the multiple consumer threads
- **Pipeline**
  Task is divided into series of subtasks, each of which is handled in series by a different thread
- **Defer work with background thread**
  One thread performs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

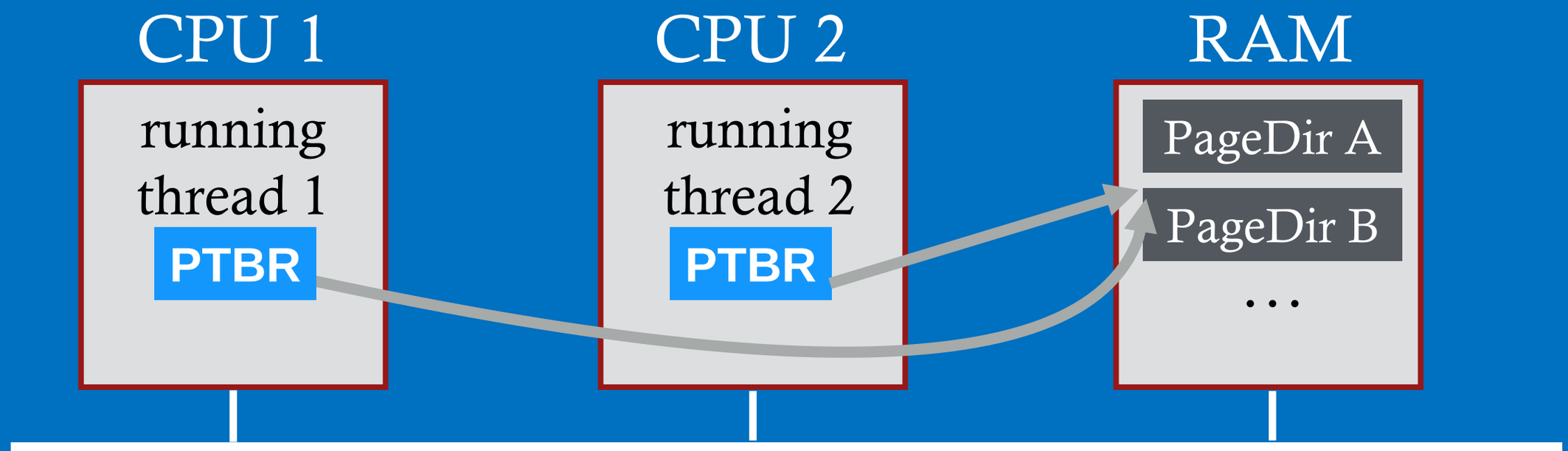


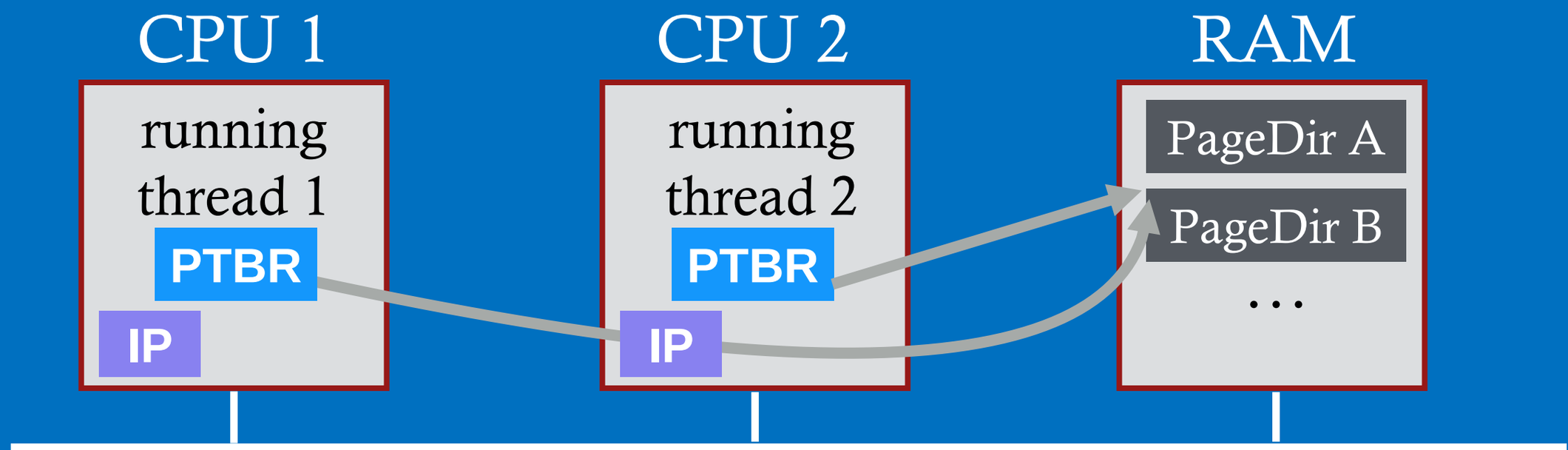
What state do threads share?



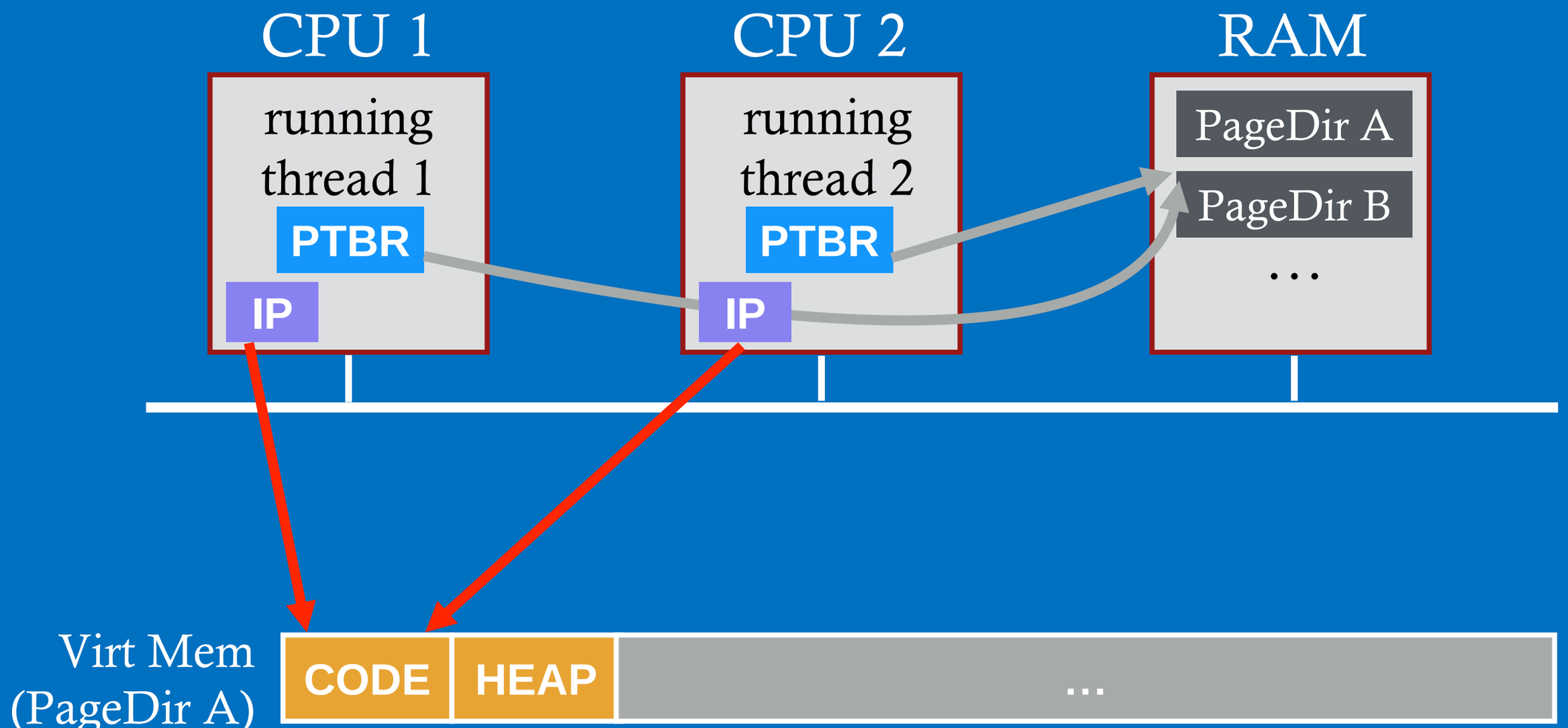
What threads share page directories?

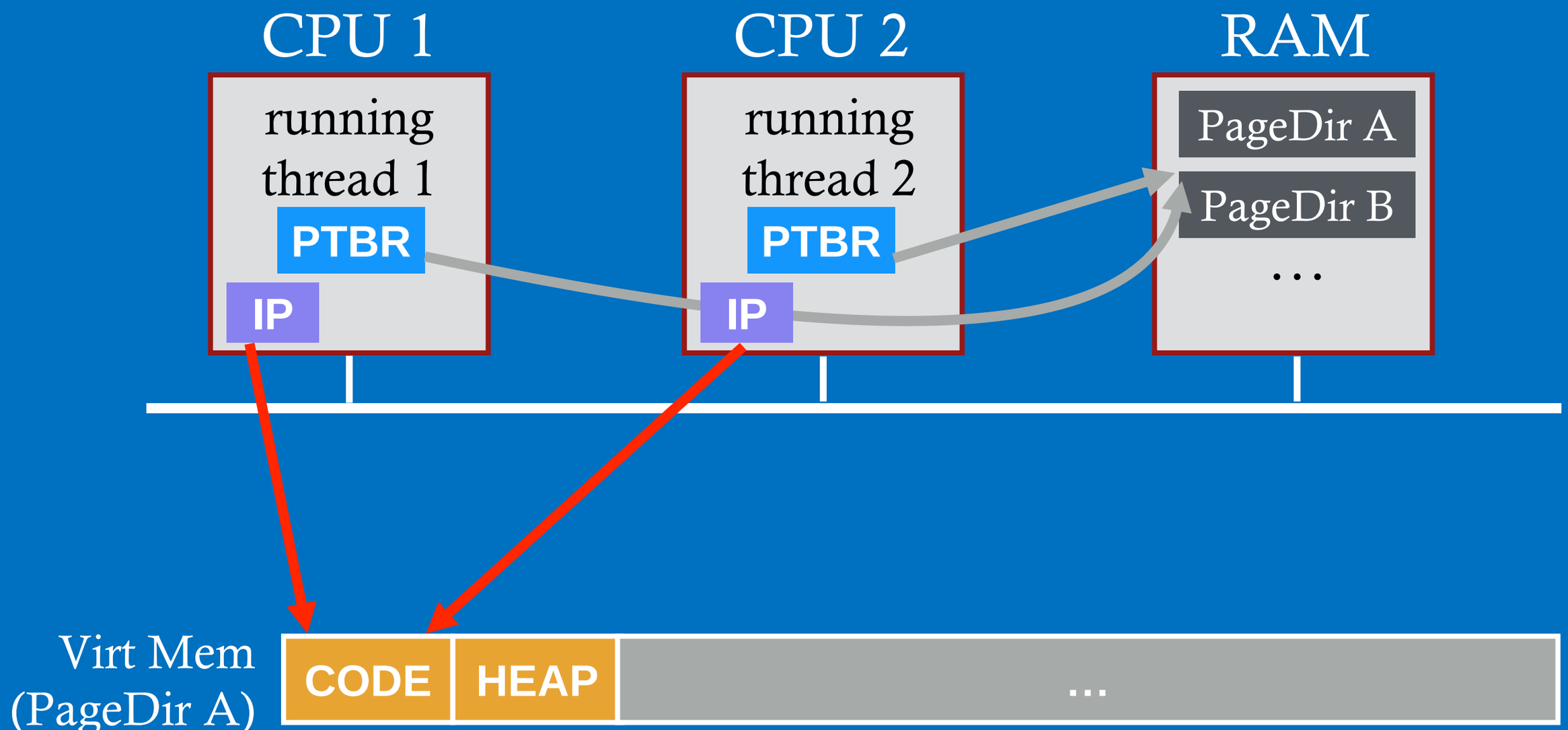

CPU 1
running
thread 1
PTBR
CPU 2
running
thread 2
PTBR
RAM
PageDir A
PageDir B
...


CPU 1
running
thread 1
PTBR
CPU 2
running
thread 2
PTBR
RAM
PageDir A
PageDir B
...



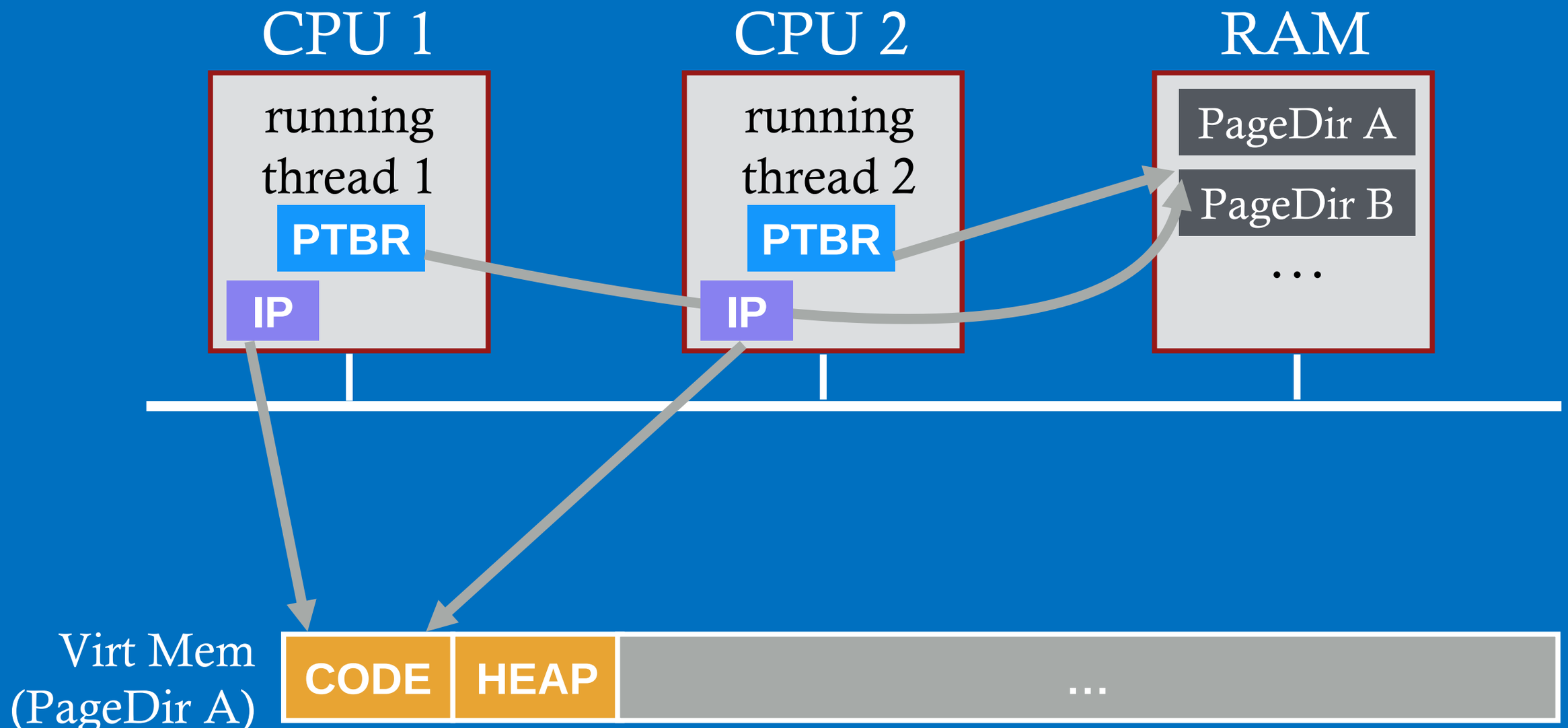
Do threads share Instruction Pointer?

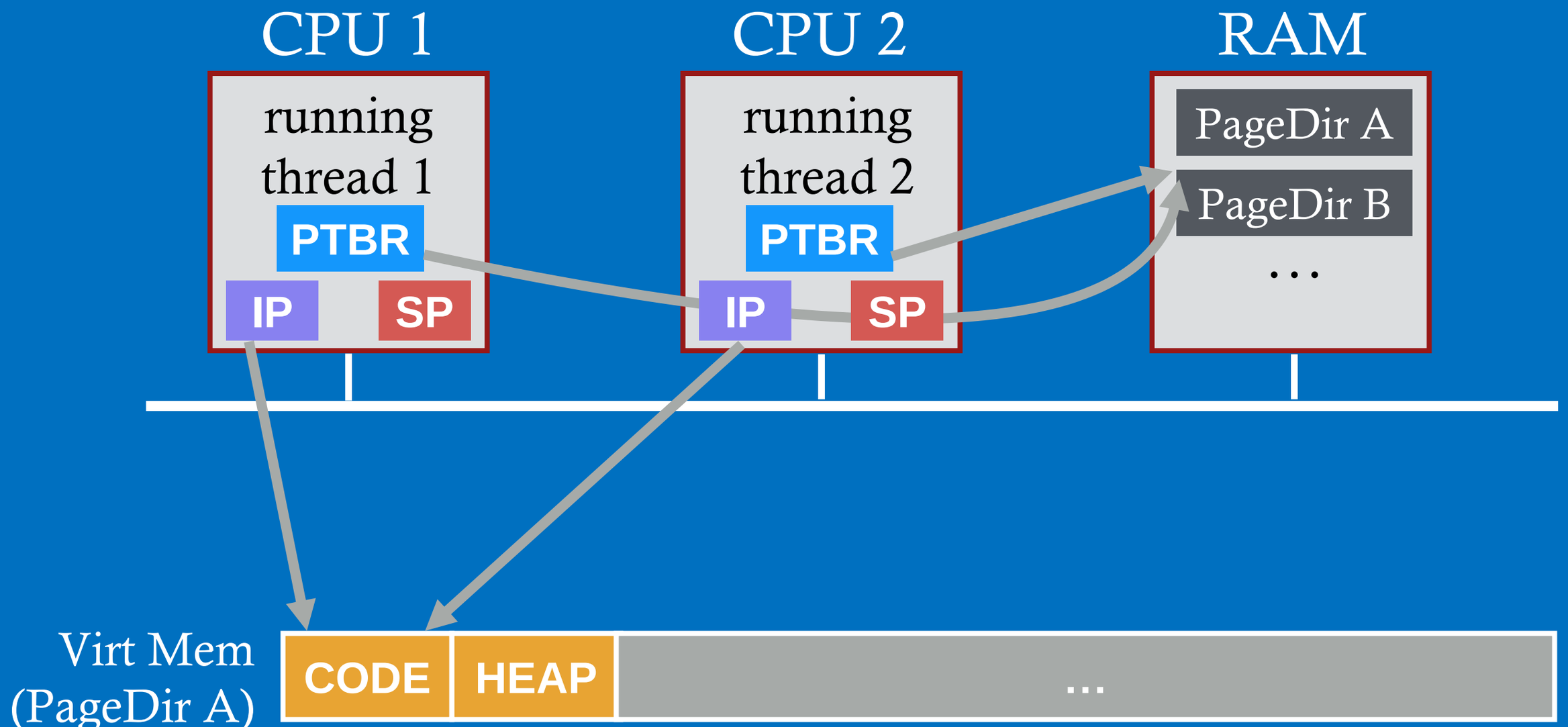

CPU 1
CPU 2
RAM
running
thread 1
PTBR
IP
running
thread 2
PTBR
IP
PageDir A
PageDir B
...
Virt Mem
(PageDir A)
CODE
HEAP
...



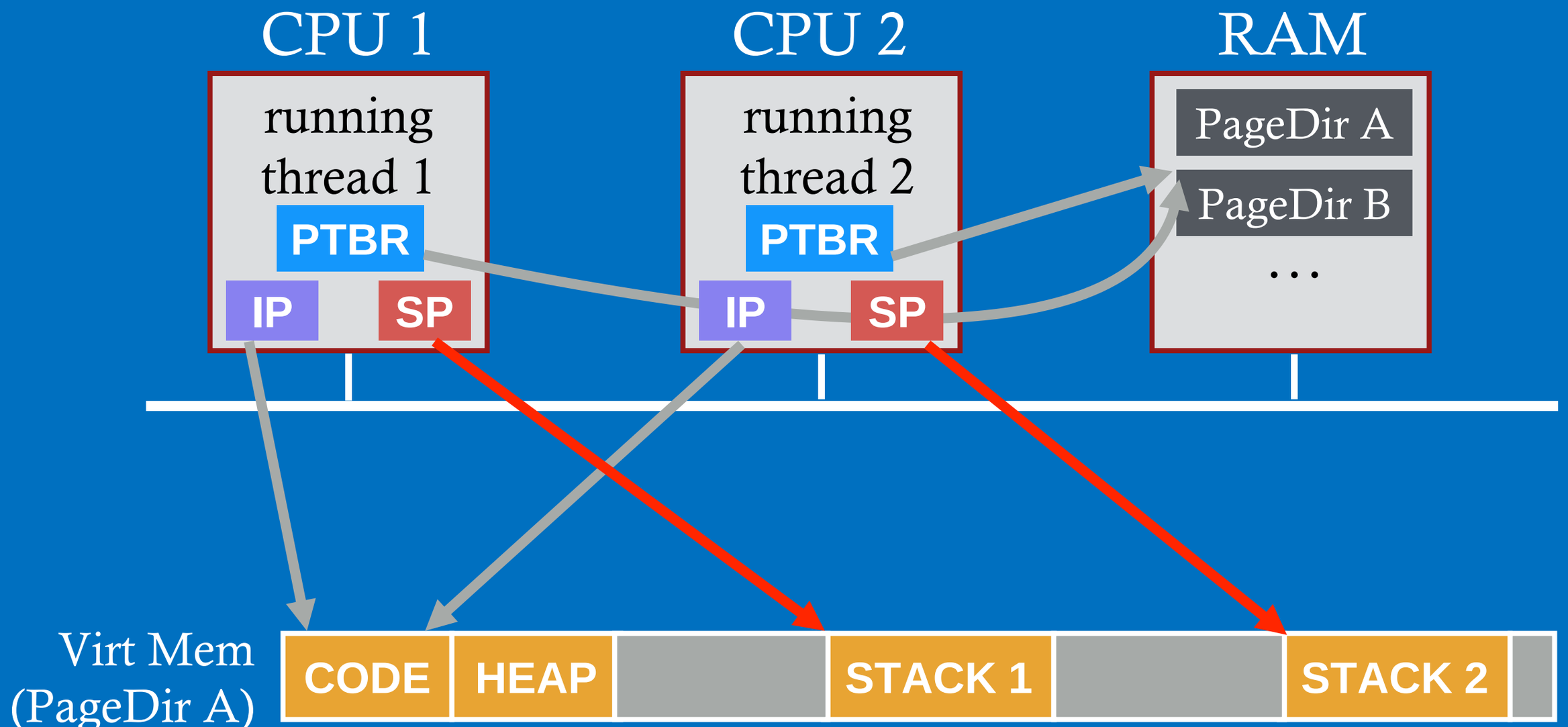
Share code, but each thread may be executing different code at the same time

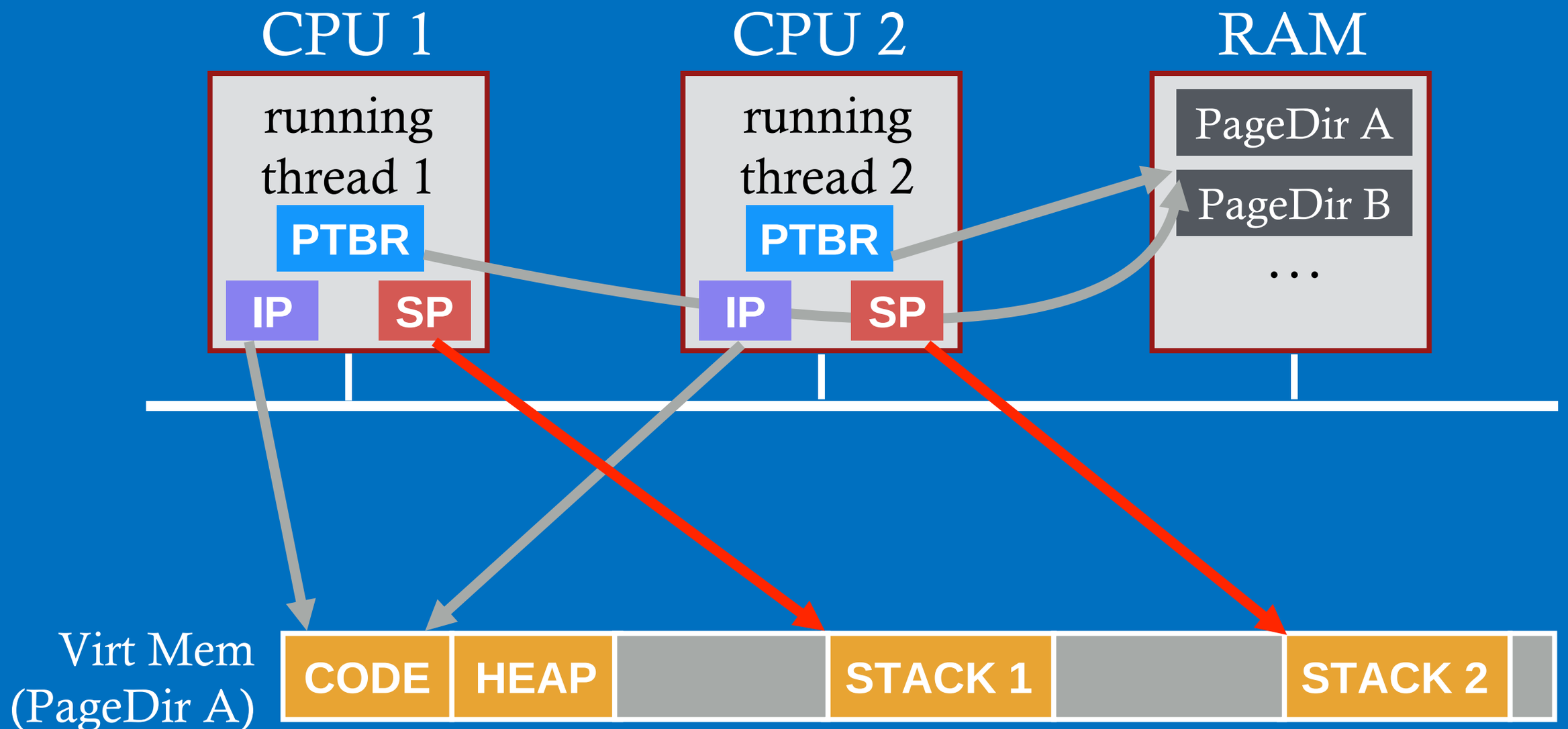
→ Different Instruction Pointers


CPU 1
running
thread 1
PTBR
IP
CPU 2
running
thread 2
PTBR
IP
RAM
PageDir A
PageDir B
...
Virt Mem
(PageDir A)
CODE
HEAP
...



Do threads share stack pointer?


CPU 1
CPU 2
RAM
running thread 1
PTBR
IP
SP
running thread 2
PTBR
IP
SP
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

T1

- 0x195 mov 0x9cd4, %eax
- 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

T1

- 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

T1

- 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

T1

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

T2

- 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

T2

- 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

T2

- 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

T2

- 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

T2 

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

- 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

T1

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

T2

- 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: 101 %rip: 0x19d	%eax: ? %rip: 0x195

T2

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

T2

- 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

T2

- 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

T1

- 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

T1

- 0x195 mov 0x9cd4, %eax
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- 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

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

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

TIMELINE VIEW

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

How much is added?

2: incorrect!

TIMELINE VIEW

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

How much is added?

1: incorrect!

TIMELINE VIEW

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

How much is added?

3: correct!

TIMELINE VIEW

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

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