Another snowy Thursday!

# CONCURRENCY: INTRODUCTION

Shivaram Venkataraman

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# ADMINISTRIVIA

- Project 4 is out. Due March 6th → after midterm
- Project 2 grades very soon

- Midterm 1 details: Piazza, Canvas
  - → next week

Practice problems!

- Office hours → end at 3.30pm

# AGENDA / LEARNING OUTCOMES

- Virtual memory: Summary
- Concurrency
  - What is the motivation for concurrent execution?
  - What are some of the challenges?

# RECAP

# SWAPPING

OS goal: Support processes when not enough physical memory

- Single process with very large address space
- Multiple processes with combined address spaces

→ Transparency

User code should be independent of amount of physical memory

- Correctness, if not performance

# CLOCK ALGORITHM

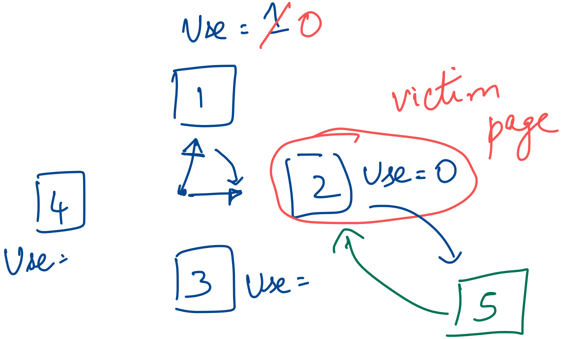
approx. LRU
but is cheaper to implement

Hardware

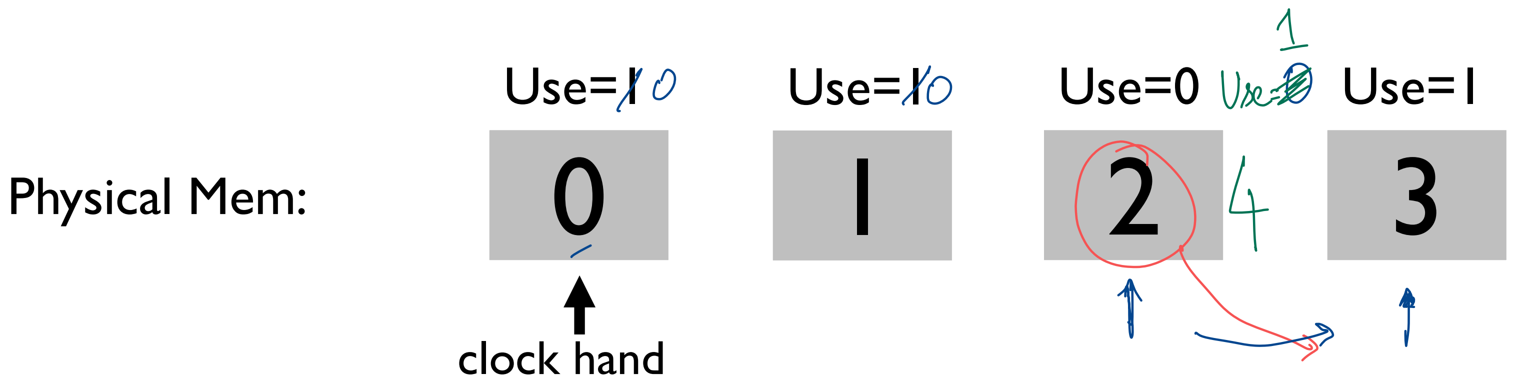
- Keep use (or reference) bit for each page frame
- When page is referenced: set use bit

Operating System

- Page Replacement:
  - Keep pointer to last examined page frame
  - Traverse pages in circular buffer
  - Clear use bits as we search
  - Stop when find page with already cleared use bit, replace this page



# CLOCK: LOOK FOR A PAGE



→ Evict page 2 (not recently used).
Bring in page 4

Clarification:

Use bit for page 4?

- After 4 is brought in
→ Reference page 4

Clarification:

Where does the hand start from next?

- Before next eviction
move clock hand one step

https://courses.cs.washington.edu/courses/csep544/99au/minirel/bufmgr.html

# CLOCK EXTENSIONS

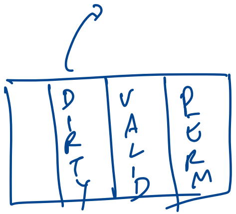
Replace multiple pages at once → don't stop until you find k victim pages

- Intuition: Expensive to run replacement algorithm and to write single block to disk
- Find multiple victims each time and track free list → a list of physical memory pages

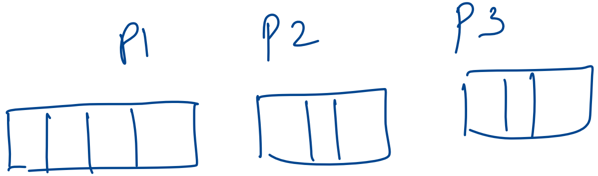
~ 5-10%

Use dirty bit to give preference to dirty pages

- Intuition: More expensive to replace dirty pages
  Dirty pages must be written to disk, clean pages do not
- Replace pages that have use bit and dirty bit cleared



# GLOBAL VS LOCAL REPLACEMENT

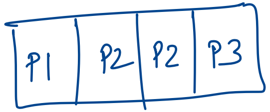


What if a victim page belongs to another process?

- Fixed space algorithms

  Process limit 2 pages Phys mem
  - each process is given a limit of pages it can use
  - when it reaches its limit, it replaces from its own pages
  - local replacement: some process may do well, others suffer
- Variable space algorithms
  - processes' set of pages grows and shrinks dynamically
  - global replacement: one process can ruin it for the rest
  - Clock is global replacement

Phy mem



P1 wants a new page

Global → evict P2 or P3's pages

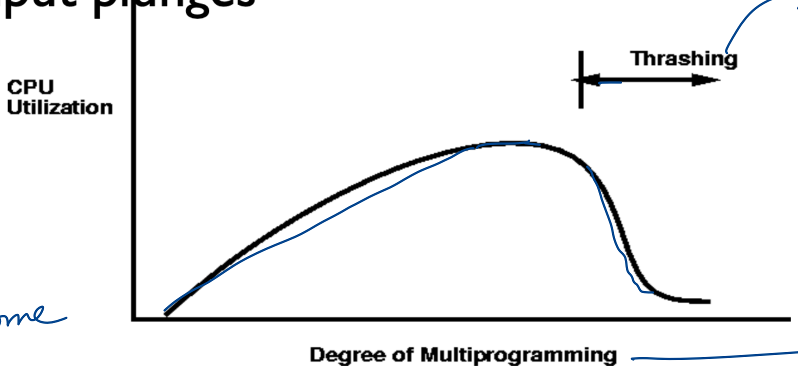
# THRASHING

I/o operation

- As page fault rate goes up, processes get suspended on page out queues for the disk
- System may try to optimize performance by starting new jobs
- Starting new jobs will reduce the number of page frames available to each process, increasing the page fault requests
- System throughput plunges

Solution? Stop running some processes

oom - killer
↳ OS kills some processes



act of constantly page faults

number of active process

# SUMMARY: VIRTUAL MEMORY

Abstraction: Virtual address space with code, heap, stack

Address translation

- Contiguous memory: base, bounds, segmentation
- Using fixed sizes pages with page tables

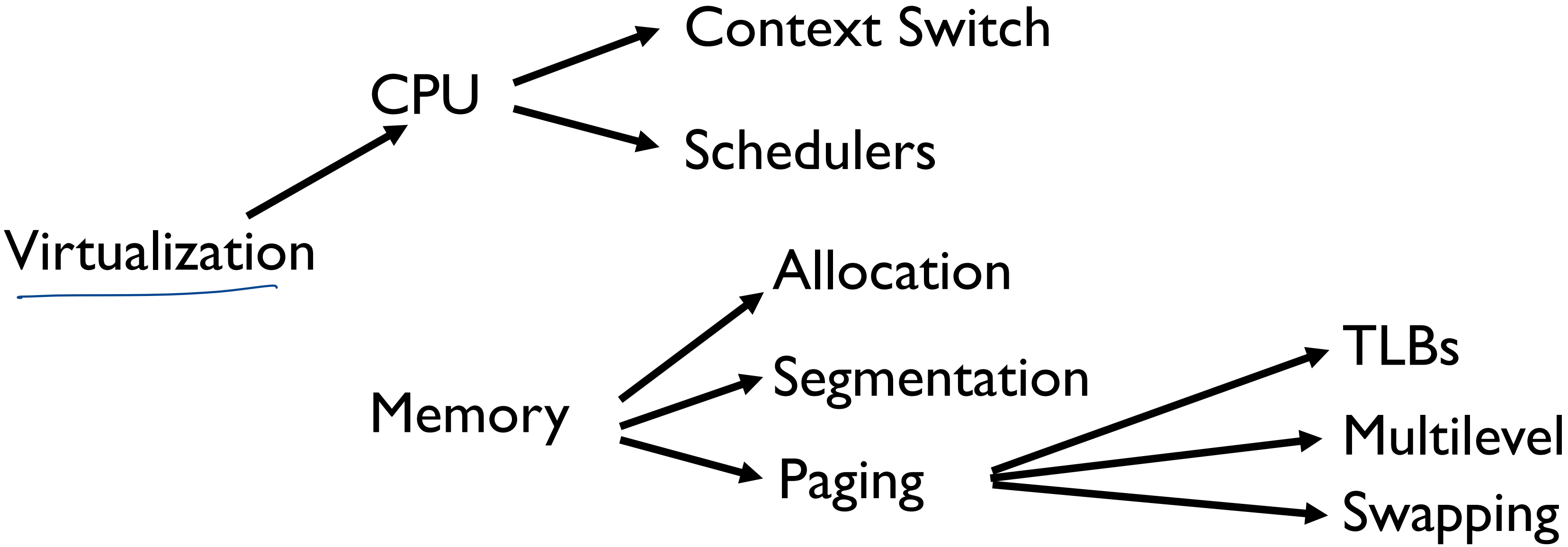
Challenges with paging

- Extra memory references: avoid with TLB
- Page table size: avoid with multi-level paging, inverted page tables etc.

Larger address spaces: Swapping mechanisms, policies (LRU, Clock)

# REVIEW: EASY PIECE 1

Midterm 1



Virtualization

CPU

Context Switch

Schedulers

Memory

Allocation

Segmentation

Paging

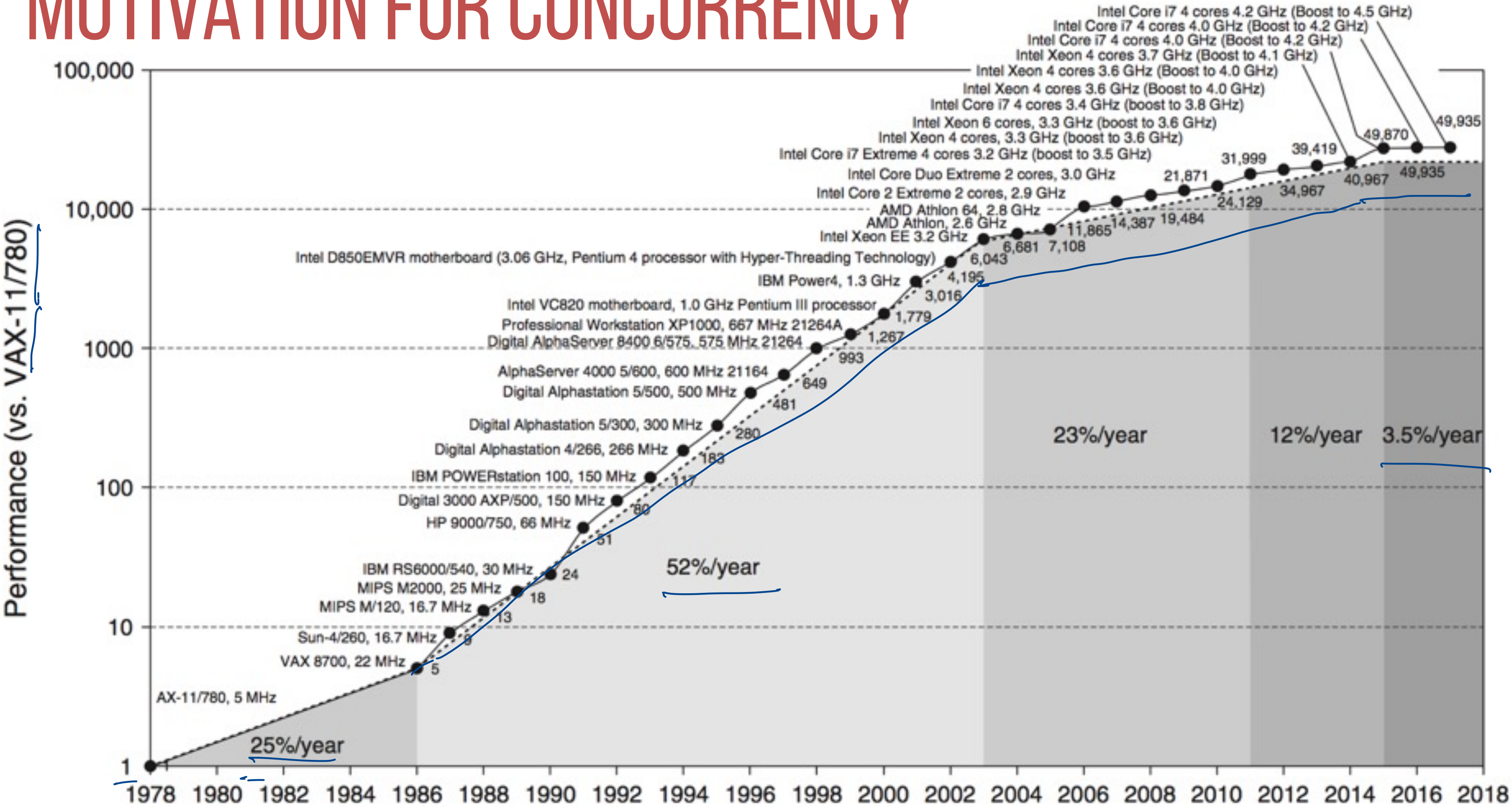
TLBs

Multilevel

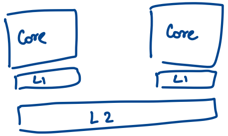
Swapping

# CONCURRENCY

# MOTIVATION FOR CONCURRENCY



# MOTIVATION



CPU Trend: Same speed, but multiple cores → 8 ~ 32 / 64 cores

100s / 1000s cores future?

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 → P3:

/bin/cat | /bin/grep

P1 P2

stdout → stdin

Pros?

- Don't need new abstractions; good for security

Cons?

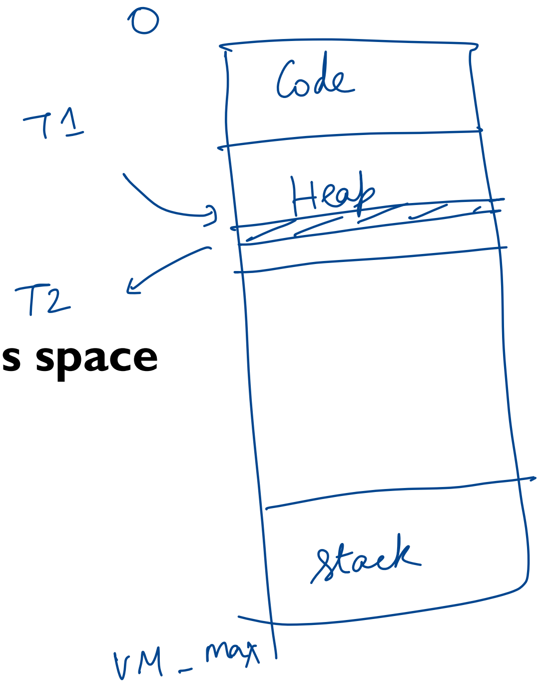
- Cumbersome programming
- High communication overheads
- Expensive context switching (why expensive?) → Caches TLBs Context switch

# 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

↳ simplifies communication across threads

# COMMON PROGRAMMING MODELS

Data analytics

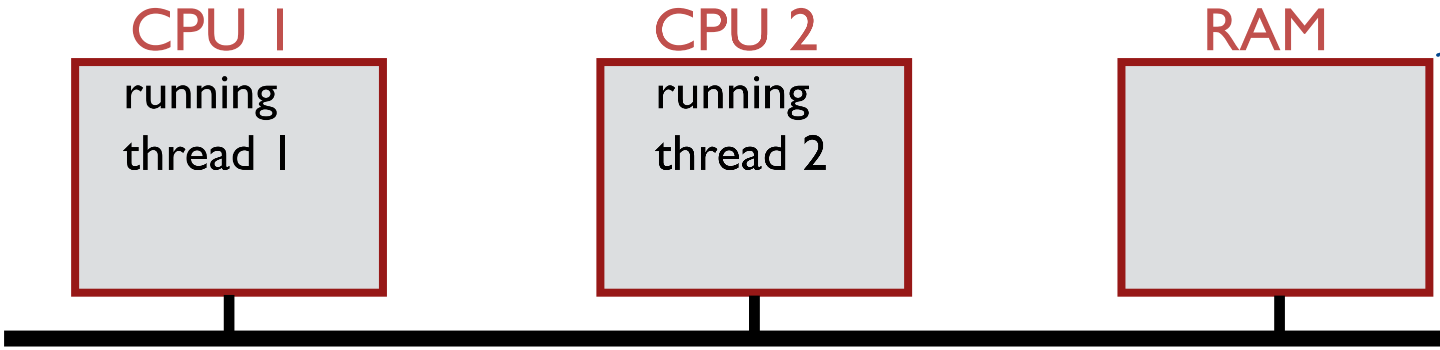
read data disk ← T1

Sort ← T2

network output ← T3

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)



CPU 1

running thread 1

CPU 2

running thread 2

RAM

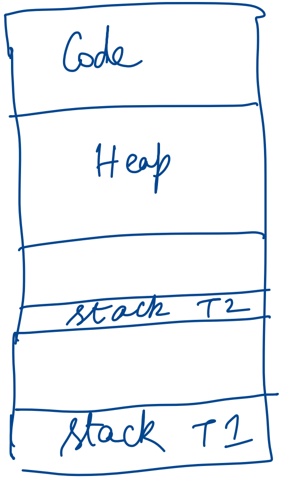
```
f1() {
  int x;
}

f2() {
  int x;
}
```

# What state do threads share?

Thread ID
→ unique per thread

Stack
→ local variable
func. args, local variable

Instruction Pointer, other registers
-> unique



Process ID
→ shared

Code segment
→ shared

Heap → shared

# 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)

# OS SUPPORT: APPROACH 1

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

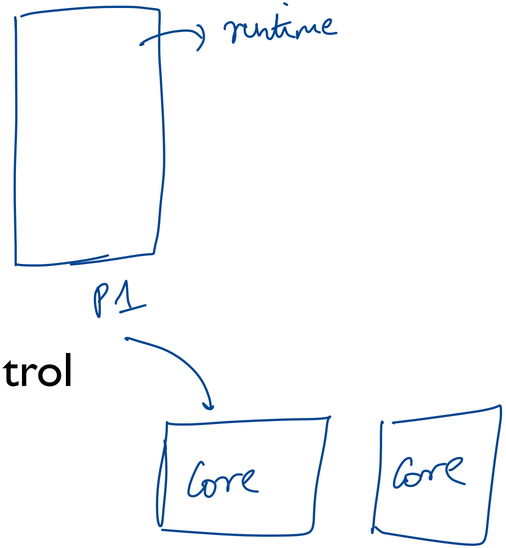
- Implemented by user-level runtime libraries
  Create, schedule, synchronize threads at user-level
- OS is not aware of user-level threads
  OS thinks each process contains only a single thread of control

Advantages

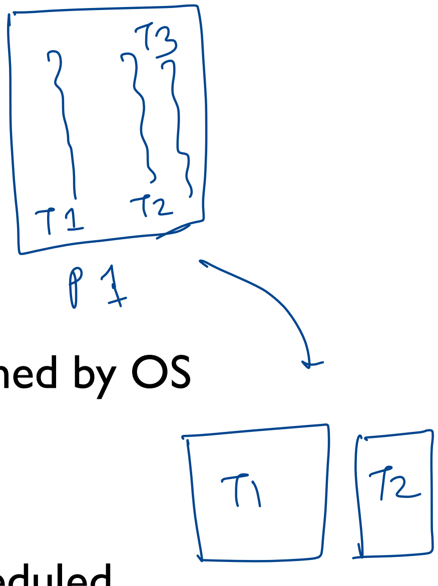
- Does not require OS support; Portable
- Lower overhead thread operations since no system call

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

# THREAD SCHEDULE

1st class

Code segment
shared

```
volatile int balance = 0;
int loops;

void *worker(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
      balance++;
    }
    pthread_exit(NULL);
}
```

```
int main(int argc, char *argv[]) {
    loops = atoi(argv[1]);
    pthread_t p1, p2;
    printf("Initial value : %d\n", balance);
    Pthread_create(&p1, NULL, worker, NULL);
    Pthread_create(&p2, NULL, worker, NULL);
    Pthread_join(p1, NULL);
    Pthread_join(p2, NULL);
    printf("Final value   : %d\n", balance);
    return 0;
}
```

```
» ./threads 100000
Initial value : 0
Final value   : 162901
```

Expect : 200,000

or some other number

# THREAD SCHEDULE #1

```
balance = balance + 1;
balance at 0x9000
```

**State:**

0x9000: ~~100~~ ~~101~~ 102

%eax:

%rip = 0x195

```
0x195   mov 0x9000, %eax
0x19a   add $0x1, %eax
0x19d   mov %eax, 0x9000
```

thread control blocks:

**Thread 1**

%eax: ~~100~~ 101

%rip:

**Thread 2**

%eax: ~~101~~ 102

%rip:

T1

1. Read 0x9000
2. Add
3. Write 0x9000

T2

Read 0x9000

Add

Write 0x9000

# THREAD SCHEDULE #2

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

**State:**

0x9000: ~~100~~ ~~101~~ 101

%eax:

%rip = 0x195

```
0x195  mov 0x9000, %eax
0x19a  add $0x1, %eax
0x19d  mov %eax, 0x9000
```

Context switch non

deterministic → bad outcomes

thread control blocks:

Thread 1

%eax: ~~100~~ 101

%rip:

Thread 2

%eax: ~~100~~ 101

%rip:

T1

Read 0x9000

Add

Write

T2

Read 0x9000

Add

Write

# TIMELINE VIEW

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

# QUIZ 14

https://tinyurl.com/cs537-sp23-quiz14

Process A with threads TA1 and TA2 and process B with a thread TB1.

1. With respect to TA1 and TA2 which of the following are true?

- Their own TID
- Their own PC

P1 P2

2. Which of the following are true with respect to TA1 and TB1?

- Code Heap, Stack, not shared
- Separate page tables

| Thread 1 | Thread 2 |
|---|---|
| mov 0x123, %eax | |
| add %0x1, %eax → 1 added | |
| | mov 0x123, %eax |
| mov %eax, 0x123 | |
| | add %0x2, %eax |
| | mov %eax, 0x123 |

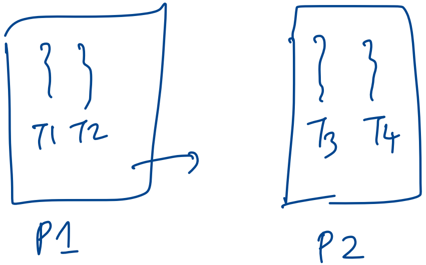
2 added

---

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

1 added

---



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

3 added

# NON-DETERMINISM

Concurrency leads to non-deterministic results

- Different results even with same inputs
- race conditions

Whether bug manifests depends on CPU schedule!

How to program: imagine scheduler is malicious?!

# WHAT DO WE WANT?

Want 3 instructions to execute as an uninterruptable group

That is, we want them to be atomic

atomic execution

→ as if all executed at same time

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

read

add

write

T1

Critical section

T2

↓

blocked

More general: Need mutual exclusion for critical sections

if thread A is in critical section C, thread B isn't

(okay if other threads do unrelated work)

# SYNCHRONIZATION

Build higher-level synchronization primitives in OS

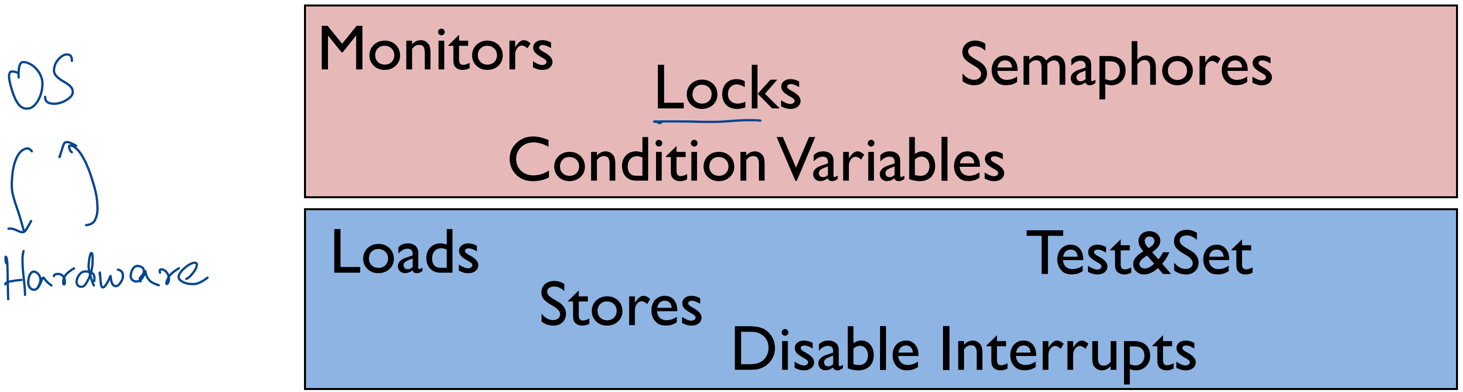
Operations that ensure correct ordering of instructions across threads

Use help from hardware

Applications

Motivation: Build them once and get them right

lock()



OS

Hardware

Monitors

Locks

Semaphores

Condition Variables

Loads

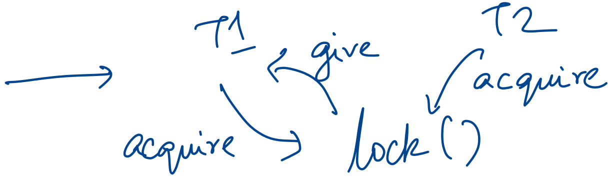
Test&Set

Stores

Disable Interrupts

# LOCKS

# LOCKS



block until
T1 releases
the lock

Goal: Provide mutual exclusion (mutex)
↳ code

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);

```
f1 () {
   lock (&l1)
 → balance ++
   unlock (&l1);
}
```

```
f2 () {
 → lock
   balance ++
   unlock
}
```

# LOCK IMPLEMENTATION GOALS

Correctness

- *Mutual exclusion*
  Only one thread in critical section at a time
- *Progress* (deadlock-free)
  If several simultaneous requests, must allow one to proceed
- *Bounded* (starvation-free)
  Must eventually allow each waiting thread to enter

Fairness: Each thread waits for same amount of time

Performance: CPU is not used unnecessarily

# IMPLEMENTING SYNCHRONIZATION

**Atomic operation**: No other instructions can be interleaved

Approaches

- Disable interrupts
- Locks using loads/stores
- Using special hardware instructions

# IMPLEMENTING LOCKS: W/ INTERRUPTS

Turn off interrupts for critical sections

- Prevent dispatcher from running another thread
- Code between interrupts executes atomically

```
void acquire(lockT *l) {
   disableInterrupts();
}
```

```
void release(lockT *l) {
   enableInterrupts();
}
```

Disadvantages?

Only works on uniprocessors

Process can keep control of CPU for arbitrary length

Cannot perform other necessary work

# IMPLEMENTING LOCKS: W/ LOAD+STORE

Code uses a single **shared** lock variable

```
// shared variable
boolean lock = false;
void acquire(Boolean *lock) {
    while (*lock) /* wait */ ;
    *lock = true;
}
```

```
void release(Boolean *lock) {
    *lock = false;
}
```

Does this work? What situation can cause this to not work?

# RACE CONDITION WITH LOAD AND STORE

```
*lock == 0 initially

Thread 1                 Thread 2
while(*lock == 1)
                              while(*lock == 1)
                              *lock = 1
*lock = 1
```

Both threads grab lock!

Problem: Testing lock and setting lock are not atomic

# NEXT STEPS

Project 4: Out now

Midterm 1: Next week

Next class: More about locks!