Hello!

CONCURRENCY: INTRODUCTION

Shivaram Venkataraman

CS 537, Fall 2024

ADMINISTRIVIA

- Project 3 done?!
- Code review: Sign up?
- Midterm 1 details: Piazza

Survey

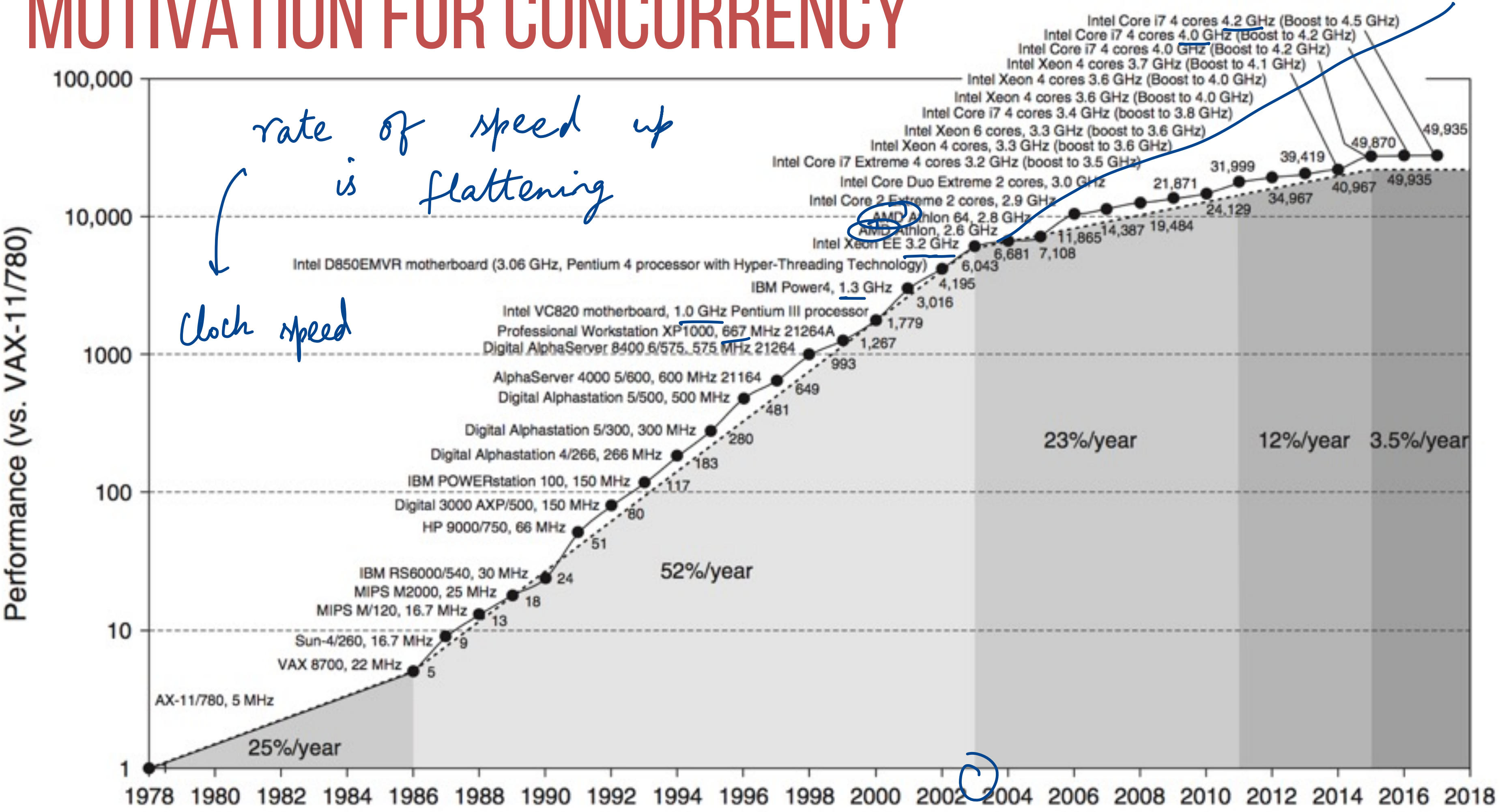
AGENDA / LEARNING OUTCOMES

Concurrency

- What is the motivation for concurrent execution?
- What are some of the challenges?

CONCURRENCY

MOTIVATION FOR CONCURRENCY



MOTIVATION

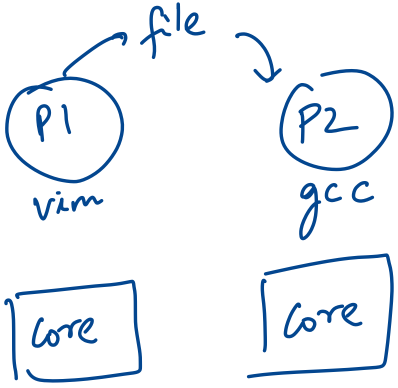
CPU Trend: Same speed, but multiple cores

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?

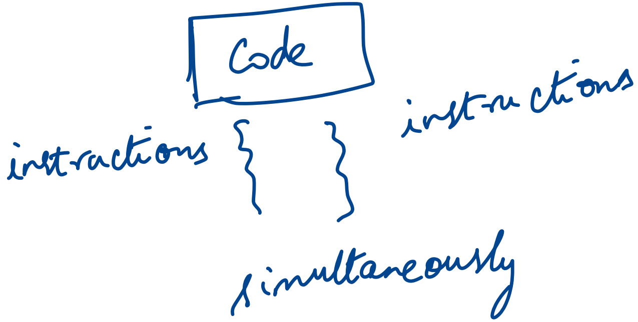
– Cumbersome programming

– High communication overheads

– Expensive context switching (why expensive?)

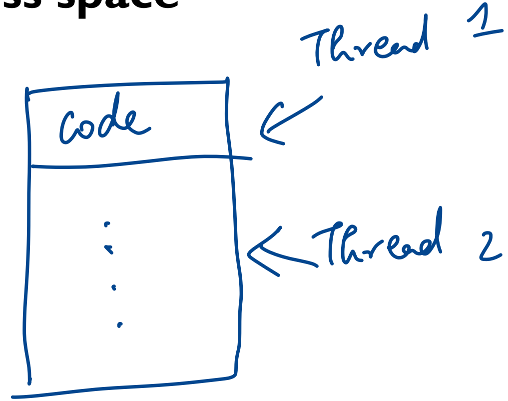
CONCURRENCY: OPTION 2

New abstraction: thread



Threads are like processes, except:

multiple threads of same process share an address space

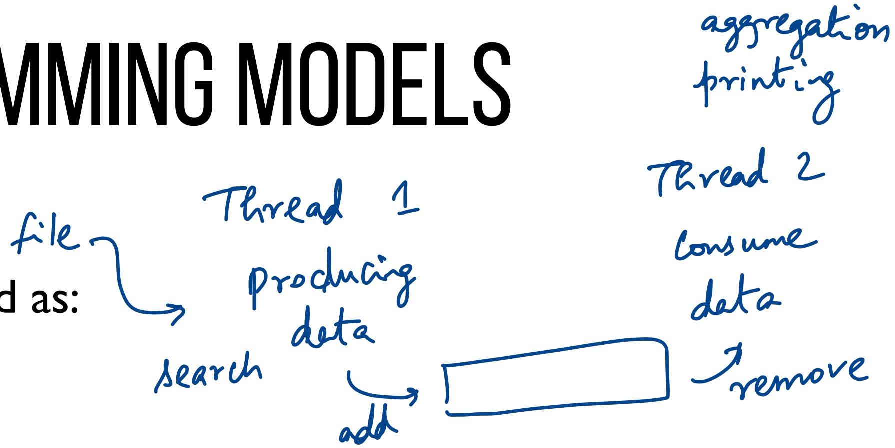


Divide large task across several cooperative threads

Communicate through shared address space

COMMON PROGRAMMING MODELS

Multi-threaded programs tend to be structured as:

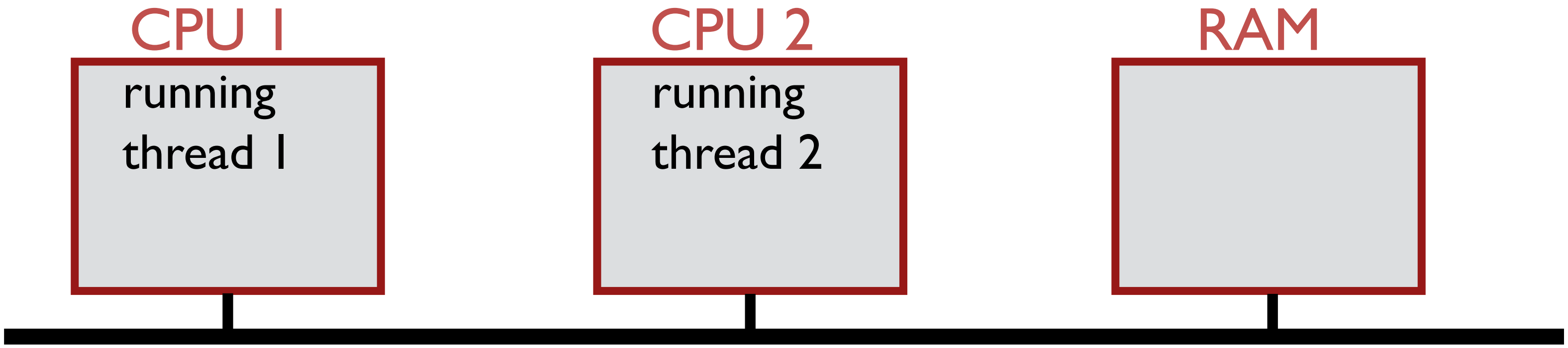


- **Producer/consumer**
  Multiple producer threads create data (or work) that is handled by one of the multiple consumer threads

- **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)

text editor → background / interactive

auto save / spell checking



Process T1 T2

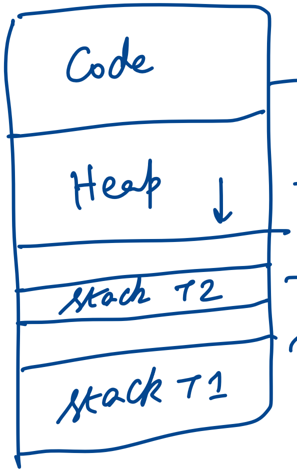
What state do threads share?

register file / instruction pointer ↳ not shared

Process ID → shared

Thread ID → not shared

Addr Space



Code → shared

Heap → shared

stack T2, stack T1 → not shared

```
void f1(){
→ int a;
}

void f2(){
→ int b;
}
```

THREAD VS. PROCESS

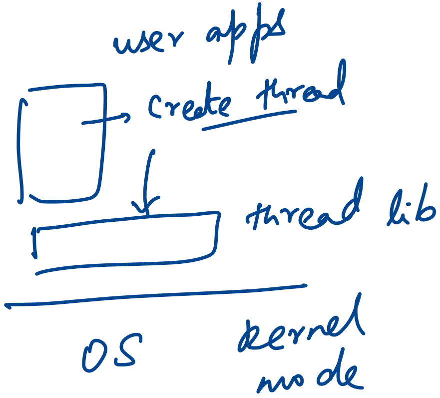
Multiple threads within a single process share:

- Process ID (PID)
- Address space: Code (instructions), Most data (heap)
- Open file descriptors → stdout , stderr
- 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

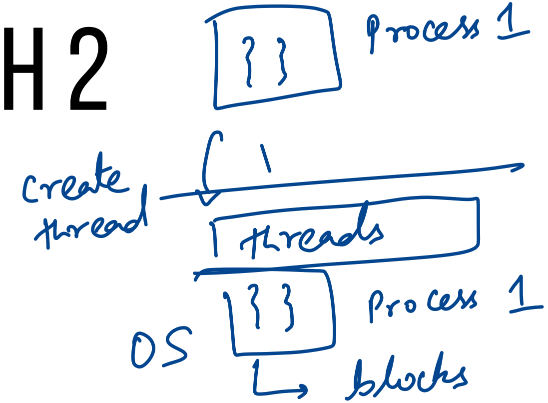
- Does not require OS support; Portable
- Lower overhead thread operations since no system call

Disadvantages?

- Cannot leverage multiprocessors → scheduler only runs 1 thread
- Entire process blocks when one thread blocks

I/O operation → BLOCKED entire process

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

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

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

```c
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

code segment

p1 starts

p2 starts

increment shared variable

lets parent know that thread is done

creates thread

waits for p1 to exit

diff each time

Expect 200,000

THREAD SCHEDULE #1

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

State:
```
0x9000: 100
%eax:
%rip = 0x195
```

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

thread control blocks:

Thread 1	Thread 2
%eax:	%eax:
%rip:	%rip:

read balance register

add 1 register

write register balance

read

add

write

balance++;

diff interleaving can lead to diff results

THREAD SCHEDULE #2

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

State:

```
0x9000: 100
%eax:
%rip = 0x195
```

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

thread control blocks:

Thread 1	Thread 2
%eax:	%eax:
%rip:	%rip:

TIMELINE VIEW

memory

balance x 13

Thread 1

mov 0x123, %eax — 10

add %0x1, %eax

mov %eax, 0x123 — 11

Thread 2

11 mov 0x123, %eax

add %0x2, %eax

13 mov %eax, 0x123

added 3 to shared variable

QUIZ 9

https://tinyurl.com/cs537-fa24-q9

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 ✓

→ Shared code segments

→ own PC ✓

→ Not same register

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

→ False

→ False

→ True

→ True

Thread 1	Thread 2
mov 0x123, %eax	
add %0x1, %eax	
	mov 0x123, %eax (read)
mov %eax, 0x123 (write after)	
	add %0x2, %eax
	mov %eax, 0x123

2

Thread 1	Thread 2
	mov 0x123, %eax (read)
mov 0x123, %eax (read)	
	add %0x2, %eax →
add %0x1, %eax	
	mov %eax, 0x123
mov %eax, 0x123 → write "wins"	

1

Thread 1	Thread 2
	mov 0x123, %eax
	add %0x2, %eax (write)
	mov %eax, 0x123
mov 0x123, %eax → Read after write	
add %0x1, %eax	
mov %eax, 0x123	

3

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?!

↳ any thread scheduler

WHAT DO WE WANT?

Want 3 instructions to execute as an uninterruptable group

That is, we want them to be atomic

mutual exclusion

T2 wait

Thread 1

critical region

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

→ atomic / all of them or none of them

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

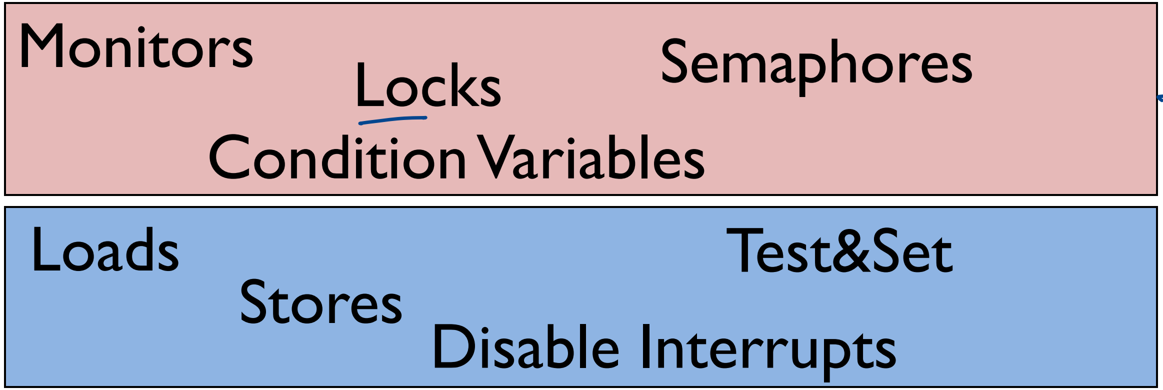
Operations that ensure correct ordering of instructions across threads

Use help from hardware

user program

Motivation: Build them once and get them right

OS

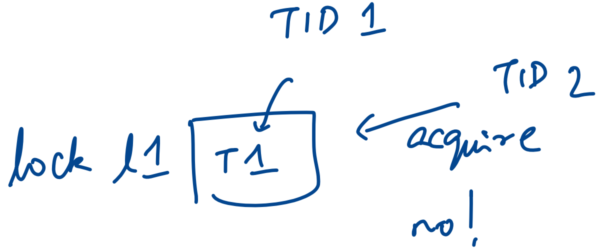


Hardware

How do we implement

LOCKS

LOCKS



Goal: Provide mutual exclusion (mutex)

Allocate and Initialize

– Pthread_mutex_t mylock = PTHREAD_MUTEX_INITIALIZER;

→ heap → all threads access same lock

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);

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

XCHG: ATOMIC EXCHANGE OR TEST-AND-SET

How do we solve this ? Get help from the hardware!

```
// xchg(int *addr, int newval)
// return what was pointed to by addr
// at the same time, store newval into addr
int xchg(int *addr, int newval) {
  int old = *addr;
  *addr = newval;
  return old;
}
```

```
movl 4(%esp), %edx
movl 8(%esp), %eax
xchgl (%edx), %eax
ret
```

LOCK IMPLEMENTATION WITH XCHG

```
typedef struct __lock_t {
    int flag;
} lock_t;

void init(lock_t *lock) {
    lock->flag = ??;
}

void acquire(lock_t *lock) {
    ????;
    // spin-wait (do nothing)
}

void release(lock_t *lock) {
    lock->flag = ??;
}
```

```
int xchg(int *addr, int newval)
```

OTHER ATOMIC HW INSTRUCTIONS

```
int CompareAndSwap(int *addr, int expected, int new) {
  int actual = *addr;
  if (actual == expected)
    *addr = new;
  return actual;
}
```

```
void acquire(lock_t *lock) {
    while(CompareAndSwap(&lock->flag,  ,  ) ==  ) ;
    // spin-wait (do nothing)
}
```

NEXT STEPS

Midterm 1: Next week

Next class: More about locks!