Hello!

MIDTERM 2 REVIEW

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CS 537, Fall 2024

ADMINISTRIVIA

Midsemester grades → Piazza

Upcoming

Midterm 2 → Thu 5:45pm

Project 4 → Tue

Shivaram travel

AGENDA / LEARNING OUTCOMES

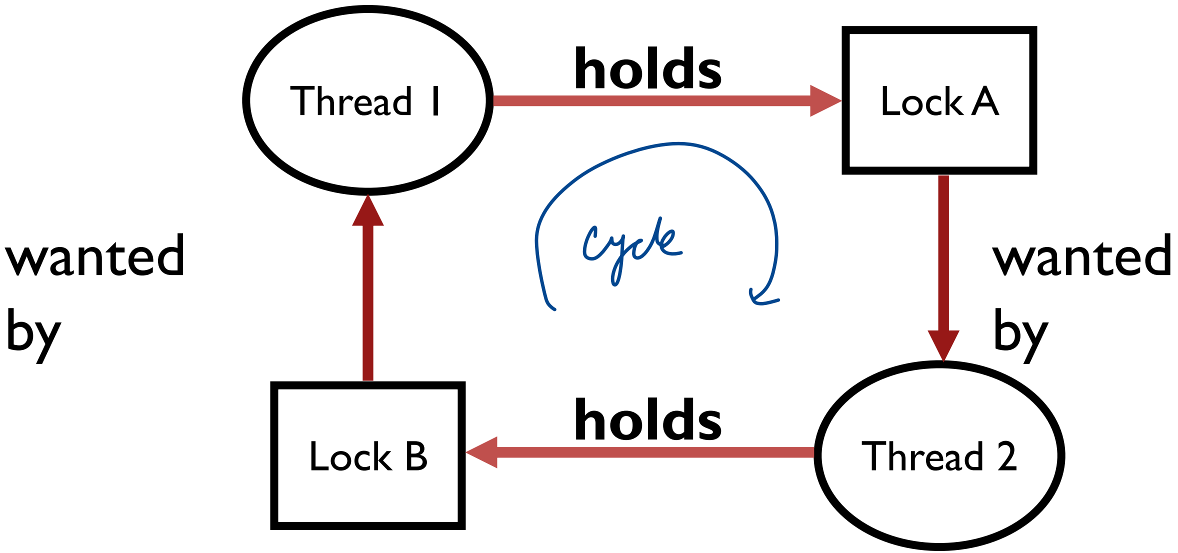
Concurrency

- What are common pitfalls with concurrent execution?

Summary of Concurrency

RECAP

DEADLOCK: CIRCULAR DEPENDENCY



No progress can be made because two or more threads are waiting for the other to take some action and thus neither ever does

DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

1. mutual exclusion → need to use locks
2. hold-and-wait → grab lock & wait until next lock
3. no preemption → holding lock are not pre-empted
4. circular wait

   ↳ cycle in dependency graph

Can eliminate deadlock by eliminating any one condition

1. MUTUAL EXCLUSION

Problem: Threads claim exclusive control of resources that they require

Strategy: Eliminate locks!

Try to replace locks with atomic primitive e.g. xchg → good performance as well!

linked list insert

```
void insert (int val) {
    node_t *n = Malloc(sizeof(*n));
    n->val = val;
    lock(&m);
    n->next = head;
    head = n;
    unlock(&m);
}
```

```
void insert (int val) {
    node_t *n = Malloc(sizeof(*n));
    n->val = val;
    do {
        n->next = head;
    } while (!CompAndSwap(&head,
                 n->next, n));
}
```

2. HOLD-AND-WAIT

Problem: Threads hold resources allocated to them while waiting for additional resources

→ locks

Strategy: Acquire all locks atomically **once.** Can release locks over time, but cannot acquire again until all have been released

How to do this? Use a meta lock:

```
lock(A);
  :        → holding A
lock(B);
  :
lock(C);
```

```
lock(meta);
  lock(A);
  lock(B);
  lock(C);
unlock(meta);
  :
unlock(A)
  :
```

no more locks are acquired

Disadvantages?

→ limits concurrency

↳ extreme case no parallelism

3. NO PREEMPTION

Thread
lock(A)
lock(B) ... holding lock A

Problem: Resources (e.g., locks) cannot be forcibly removed from threads holding them

Strategy: if thread can't get what it wants, release what it holds

threads are running but no useful work
live lock
random or exponential

```
top:
  lock(A);
  if (trylock(B) == -1) {
      unlock(A);
       sleep(??)
      goto top;
  }
  ...
```

if you get lock return 0;
else return -1;

sleep for constant?
(backoff)

Disadvantages?

T1	T2
A, B	B, A
A	
sleep 1;	
A	B
sleep 1;	

4. CIRCULAR WAIT

Circular chain of threads such that each thread holds a resource (e.g., lock) being requested by next thread in the chain.

Strategy:

- decide which locks should be acquired before others
- if A before B, never acquire A if B is already held!
- document this, and write code accordingly → software engineering/ code base design

Works well if system has distinct layers

QUIZ 14

```c
void foo(pthread_mutex_t *t1, pthread_mutex_t *t2, , pthread_mutex_t *t3) {
 pthread_mutex_lock(t1);
 pthread_mutex_lock(t2);
 pthread_mutex_lock(t3);

 do_stuffs();
 pthread_mutex_unlock(t1);
 pthread_mutex_unlock(t2);
 pthread_mutex_unlock(t3);
}
```

T1 foo(a,b,c)
T2 foo(b,c,a)
T3 foo(c,a,b)

T1 : A
T2 : B
T3 : C

Deadlock !

T1 foo(a,b,c)
T2 foo(a,b,c)
T3 foo(a,b,c)

No !

T1 foo(a,b,c)
T2 foo(b,c,e)
T3 foo(f,e,a)

T1 : A | B
T2 : B | E
T2 : C
T3 : F | A
T3 : E

Deadlock !

CONCURRENCY REVIEW

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

share data

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 SCHEDULES

Thread 1

mov 0x123, %eax

add %0x1, %eax

mov %eax, 0x123

Thread 2

mov 0x123, %eax

add %0x2, %eax

mov %eax, 0x123

LOCKS

Goal: Provide mutual exclusion (mutex)

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 → yield or block
- Pthread_mutex_lock(&mylock);

Release

- Release exclusive access to lock; let another process enter critical section
- Pthread_mutex_unlock(&mylock);

LOCKS USING ATOMIC INSTRUCTIONS

```
// 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;
}
```

this is all happening in 1 instruction

```
int CompareAndSwap(int *addr, int ex, int n) {
  int actual = *addr;
  if (actual == ex)
    *addr = n;
  return actual;
}
```

```
void acquire(lock_t *lock) {
    while(CompareAndSwap(&lock->flag, 0, 1) == 1 ) ;
    // spin-wait (do nothing)
}
```

some other thread has lock

FAIRNESS USING TICKET LOCKS

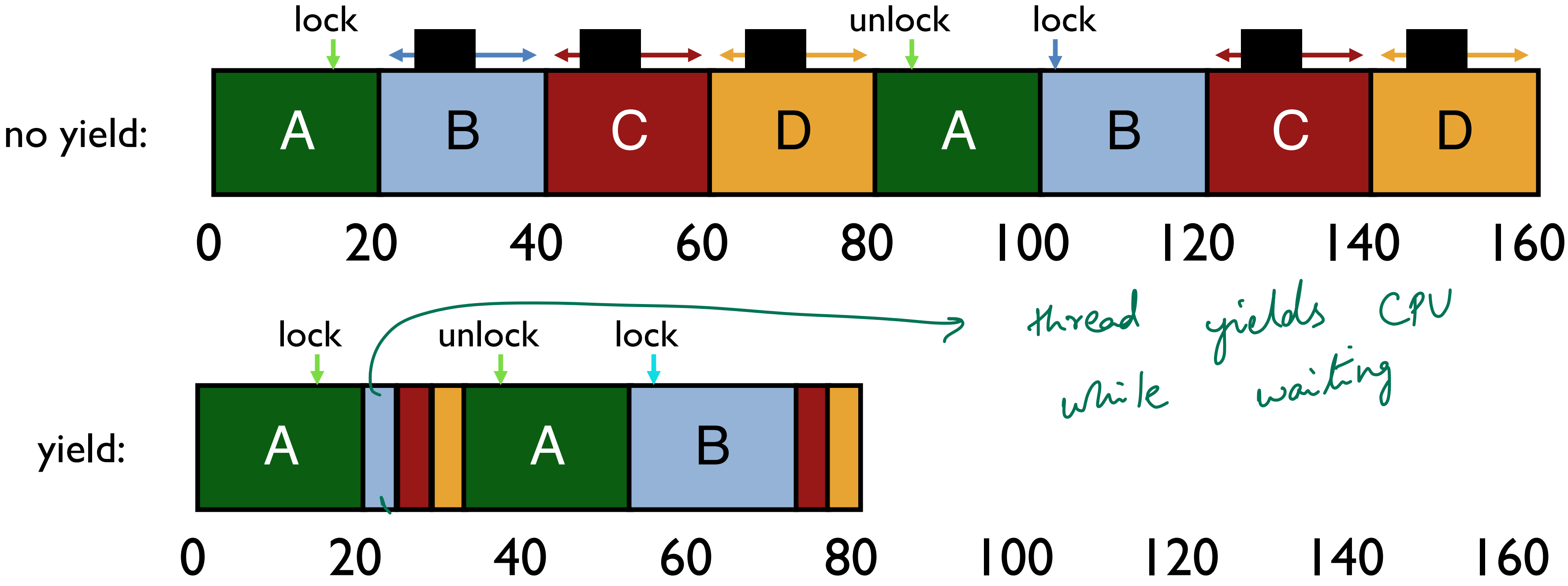
```
typedef struct __lock_t {
    int ticket;   ← grab
    int turn;
}                 ↖ get the lock when ticket = turn

void lock_init(lock_t *lock) {
    lock->ticket = 0;
    lock->turn = 0;
}
```

```
void acquire(lock_t *lock) {
    int myturn = FAA(&lock->ticket);
    // spin
    while (lock->turn != myturn);
}

void release(lock_t *lock) {
    FAA(&lock->turn);
}
```

YIELD INSTEAD OF SPIN



BLOCK WHEN WAITING: FINAL CORRECT LOCK

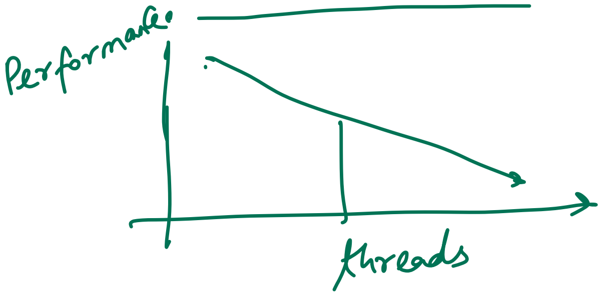
```
typedef struct {
   bool lock = false;
   bool guard = false;
   queue_t q;
} LockT;
```

```
void acquire(LockT *l) {
   while (TAS(&l->guard, true));
   if (l->lock) {
        qadd(l->q, tid);
        setpark(); // notify of plan
        l->guard = false;
        park(); // unless unpark()
   } else {
        l->lock = true;
        l->guard = false;
   }
}
void release(LockT *l) {
   while (TAS(&l->guard, true));
   if (qempty(l->q)) l->lock=false;
   else unpark(qremove(l->q));
   l->guard = false;
}
```

notify the OS

thread is marked as blocked by OS scheduler

CONCURRENT DATA STRUCTURES



Simple approach: Add a lock to each method?!

Check for scalability – weak scaling, strong scaling

Avoid cross-thread, cross-core traffic

- Per-core counter → approximate
- Buckets in hashtable
- Keep critical sections small! → memory alloc outside critical

PRACTICE QUESTIONS

```c
volatile int balance = 0;

void *mythread(void *arg) {
     int result = 0;
     result = result + 200;
     balance = balance + 200;
     printf("Result is %d\n", result);
     printf("Balance is %d\n", balance);
     return NULL;
}
```

Thread p1 prints "Result is %d\n", what value?

A. Due to race conditions, "result" may have different values on different runs.
B. 0
C. 200
D. 400
E. A constant value, but none of the above

```c
int main() {
   pthread_t p1, p2;
   pthread_create(&p1, NULL, mythread, "A");
   pthread_create(&p2, NULL, mythread, "B");
   pthread_join(p1, NULL);
   pthread_join(p2, NULL);
   printf("Final Balance is %d\n", balance);
}
```

Thread p1 prints "Balance is %d\n", what value?

A. Due to race conditions, "result" may have different values on different runs.
B. 0
C. 200
D. 400
E. A constant value, but none of the above

```
Thread 0                     Thread 1
1000 mov 2000, %ax
1001 add $1, %ax
------ Interrupt ------ Interrupt ------
                        1000 mov 2000, %ax
                        1001 add $1, %ax
------ Interrupt ------ Interrupt ------
1002 mov %ax, 2000 37.
------ Interrupt ------ Interrupt ------
                        1002 mov %ax, 2000 38.
------ Interrupt ------ Interrupt ------
1003 sub $1, %bx
1004 test $0, %bx
------ Interrupt ------ Interrupt ------
                        1003 sub $1, %bx
------ Interrupt ------ Interrupt ------
1005 jgt .top
```

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Incrementing a variable many times in a loop. Assume that the %bx register begins with the value 3, (each thread performs the loop 3 times).

Assume the code is loaded at address 1000 and that the memory address 2000 originally contains the value 0.

Determine the contents of the memory address 2000 AFTER that assembly instruction

37 : 1 (option A)

38 : 1 (option A)

A. 1
B. 2
C. 3
D. 4
E. None of the above

```
typedef struct __lock_t {
    int flag;
} lock_t;
void init(lock_t *lock) {
    lock->flag = abc;
}

void acquire(lock_t *lock) {
    while(xchg(&lock->flag, xyz) == xyz)
    ; //spin-wait
}
void release(lock_t *lock) {
    lock->flag = 1;
}
```

0 0 ✓

What should be the value of abc?

A. 0
B. 1 → because release sets it to 1
C. 2
D. 0 or 2
E. 0 or 1

What should be the value of xyz?

A. 0
B. 1
C. 2
→ D. 0 or 2 Any number not 1
→ E. 0 or 1

CONDITION VARIABLES

wait(cond_t *cv, mutex_t *lock)

- assumes the lock is held when wait() is called
- puts caller to sleep + releases the lock (atomically)
- when awoken, reacquires lock before returning

API definition

signal(cond_t *cv)

- wake a single waiting thread (if >= 1 thread is waiting)
- if there is no waiting thread, just return, doing nothing

any threads waiting

JOIN IMPLEMENTATION: CORRECT

Parent:

```
void thread_join() {
        Mutex_lock(&m);          // w
        if (done == 0)           // x
            Cond_wait(&c, &m); // y
        Mutex_unlock(&m);         // z
}
```

state

Child:

```
void thread_exit() {
        Mutex_lock(&m);        // a
        done = 1;              // b
        Cond_signal(&c);       // c
        Mutex_unlock(&m);      // d
}
```

hold lock

Parent:	w	x	y					z
Child:				a	b	c	d	

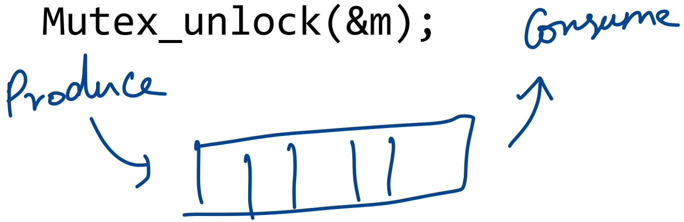
Use mutex to ensure no race between interacting with state and wait/signal

PRODUCER/CONSUMER: TWO CVS AND WHILE

```
void *producer(void *arg) {
    for (int i = 0; i < loops; i++) {
        Mutex_lock(&m); // p1
        while (numfull == max) // p2
            Cond_wait(&empty, &m); // p3
        do_fill(i);  // p4
        Cond_signal(&fill); // p5
        Mutex_unlock(&m); //p6
    }
}
```

recheck state after the thread wakes up

```
void *consumer(void *arg) {
    while (1) {
        Mutex_lock(&m);
        while (numfull == 0)
            Cond_wait(&fill, &m);
        int tmp = do_get();
        Cond_signal(&empty);
        Mutex_unlock(&m);
    }
}
```



1. Keep state in addition to CV's
2. Always do wait/signal with lock held
3. Whenever thread wakes from waiting, recheck state

SEMAPHORE OPERATIONS

State inside the semaphore
↳ initialized by user

Wait or Test: sem_wait(sem_t*)

Decrements sem value by 1, Waits if value of sem is negative (< 0)

slightly diff from linux

Signal or Post: sem_post(sem_t*)

Increment sem value by 1, then wake a single waiter if exists

Value of the semaphore, when negative = the number of waiting threads

PRODUCER/CONSUMER: MULTIPLE THREADS

```
Producer #3
    sem_wait(&emptyBuffer);
    sem_wait(&mutex);
    myi = findempty(&buffer);
    sem_post(&mutex);
    Fill(&buffer[myi]);
    sem_post(&fullBuffer);
```

```
Consumer #3
    sem_wait(&fullBuffer);
    sem_wait(&mutex);
    myj = findfull(&buffer);
    sem_post(&mutex);
    Use(&buffer[myj]);
    sem_post(&emptyBuffer);
```

Works and increases concurrency; only finding a buffer is protected by mutex;
Filling or Using different buffers can proceed concurrently

READER/WRITER LOCKS

```
void rwlock_acquire_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers++;
    if (rw->readers == 1)
        sem_wait(&rw->writelock);
    sem_post(&rw->lock);
}
void rwlock_release_readlock(rwlock_t *rw) {
    sem_wait(&rw->lock);
    rw->readers--;
    if (rw->readers == 0)
        sem_post(&rw->writelock);
    sem_post(&rw->lock);
}
rwlock_acquire_writelock(rwlock_t *rw) { sem_wait(&rw->writelock); }
rwlock_release_writelock(rwlock_t *rw) { sem_post(&rw->writelock); }
```

Multiple readers can acquire

1 writer

↳ no readers

BUILD ZEMAPHORE FROM LOCKS AND CV

```
zem_wait(zem_t *s) {
    lock_acquire(&s->lock);
    while (s->value <= 0)
        cond_wait(&s->cond);
    s->value--;
    lock_release(&s->lock);
}
```

```
zem_post(zem_t *s) {
    lock_acquire(&s->lock);
    s->value++;
    cond_signal(&s->cond);
    lock_release(&s->lock);
}
```

zem_wait(): Waits while value <= 0, Decrement

zem_post(): Increment value, then wake a single waiter

PRACTICE QUESTIONS

```
Acquire_readlock() {
     Sem_wait(&mutex); // AR1
     If (ActiveWriters + // AR2
          WaitingWriters==0) { // AR3
          sem_post(OKToRead); // AR4
          ActiveReaders++; // AR5
     } else WaitingReaders++; // AR6
     Sem_post(&mutex); // AR7
     Sem_wait(OKToRead); // AR8
}
```

init 1

first reader with active writer to block ⇒ init to 0

```
Release_readlock() {
     Sem_wait(&mutex); // RR1
     ActiveReaders--; // RR2
     If (ActiveReaders==0 && // RR3
        WaitingWriters > 0) { // RR4
          ActiveWriters++; // RR5
          WaitingWriters--; // RR6
          Sem_post(OKToWrite); // RR7
     }
     Sem_post(&mutex); // RR8
```

```
Acquire_writelock() {
   Sem_wait(&mutex); // AW1
   If (ActiveWriters + ActiveReaders +
       WaitingWriters==0) { // AW2
       ActiveWriters++; // AW3
       sem_post(OKToWrite); // AW4
   } else WaitingWriters++; // AW5
   Sem_post(&mutex); // AW6
   Sem_wait(OKToWrite); // AW7
}
```

```
Release_writelock() {
     Sem_wait(&mutex); // RW1
     ActiveWriters--; // RW2
     If (WaitingWriters > 0) { // RW3
          ActiveWriters++; // RW4
          WaitingWriters--; // RW5
          Sem_post(OKToWrite); // RW6
     } else while(WaitingReaders>0) { // RW7
        ActiveReaders++; // RW8
        WaitingReaders--; // RW9
        sem_post(OKToRead); // RW10
      }
     Sem_post(&mutex); // RW11
}
```

More such questions?

Little Book of Semaphores - Free online book!

https://greenteapress.com/semaphores/LittleBookOfSemaphores.pdf

CONCURRENCY SUMMARY

Motivation: Parallel programming patterns, multi-core machines

Abstractions, Mechanisms

- Spin Locks, Ticket locks
- Queue locks
- Condition variables
- Semaphores

Concurrency Bugs

LOOKING AHEAD

Midterm 2!

New module on Persistence