HI!

CONCURRENCY: DEADLOCK

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CS 537, Spring 2019

ADMINISTRIVIA

Midterm is on Wednesday 3/13 at 5.15pm, details on Piazza

Venue: If your last name starts with A-L, go to VanVleck B102

else (last name starts with M-Z), go to VanVleck B130

Bring your ID! Calculators allowed, no cheat sheet

Review session, Office hours at 5.30pm at Noland Hall, Room 132

Fill out mid semester course evaluation? https://aefis.wisc.edu/

AGENDA / LEARNING OUTCOMES

Concurrency

- What are common pitfalls with concurrent execution?

RECAP

CONCURRENCY OBJECTIVES

Mutual exclusion (e.g., A and B don't run at same time)

solved with *locks*

Ordering (e.g., B runs after A does something)

solved with *condition variables* and *semaphores*

critical section - only one thread

Producer → wait buffer if full

Consumer → wait buffer is empty

SUMMARY: 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

signal(cond_t *cv)

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

1. State variable
2. Hold the lock
3. Recheck condition

SUMMARY: SEMAPHORES

Semaphores are equivalent to locks + condition variables

- Can be used for both mutual exclusion and ordering

Semaphores contain **state**

- How they are initialized depends on how they will be used
- Init to 0: Join (1 thread must arrive first, then other)
- Init to N: Number of available resources

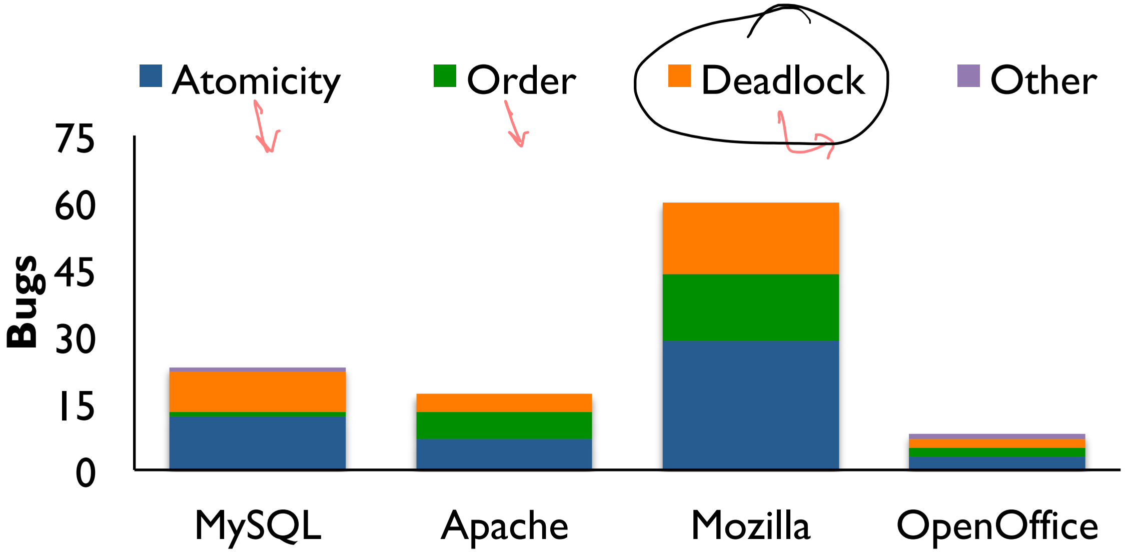
sem_wait(): Decrement and waits IF value < 0

sem_post() or sem_signal(): Increment value, then wake a single waiter (atomic)

Can use semaphores in producer/consumer and for reader/writer locks

CONCURRENCY BUGS

CONCURRENCY STUDY



Lu *etal.* [ASPLOS 2008]:

For four major projects, search for concurrency bugs among >500K bug reports. Analyze small sample to identify common types of concurrency bugs.

FIX ATOMICITY BUGS WITH LOCKS

Thread 1:

```
pthread_mutex_lock(&lock);
if (thd->proc_info) {
    …
    fputs(thd->proc_info, …);
    …
}
pthread_mutex_unlock(&lock);
```

Thread 2:

```
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```

Thread 2 if

Thread 2 set it NULL

Thread 1 fputs

FIX ORDERING BUGS WITH CONDITION VARIABLES

Mozilla

Thread 1:

```
void init() {
    …

    mThread =
    PR_CreateThread(mMain, …);

    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);

    …
}
```

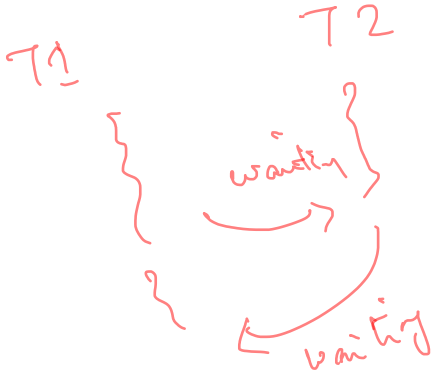
Thread 2:

```
void mMain(…) {
    …

    mutex_lock(&mtLock);
    while (mtInit == 0)
        Cond_wait(&mtCond, &mtLock);
    Mutex_unlock(&mtLock);

    mState = mThread->State;
    …
}
```

DEADLOCK



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

CODE EXAMPLE

Thread 1:

```
lock(&A);
lock(&B);
```

Thread 2:

```
lock(&B);
lock(&A);
```

T1 grabs lock A

↳ T2 grabs lock B

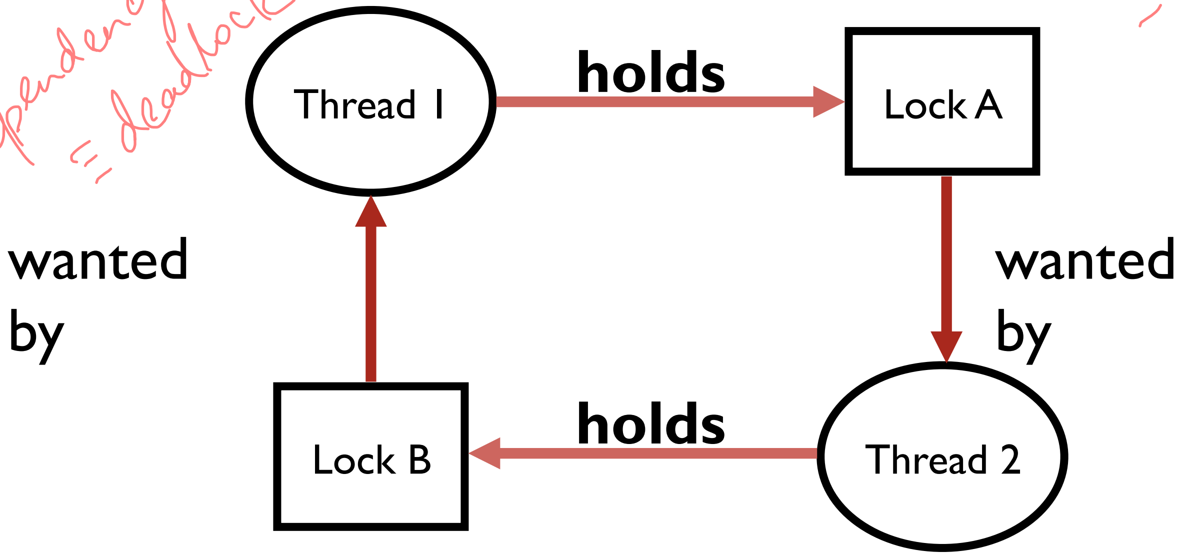
T2 tries lock A = BLOCKED

↳ T1 tries lock B = BLOCKED

CIRCULAR DEPENDENCY

cycle in dependency graph = deadlock

node
- locks
- threads



FIX DEADLOCKED CODE

Thread 1:

```
lock(&A);
lock(&B);
```

Thread 2:

```
lock(&B);
lock(&A);
```

Thread 1

lock (&A);

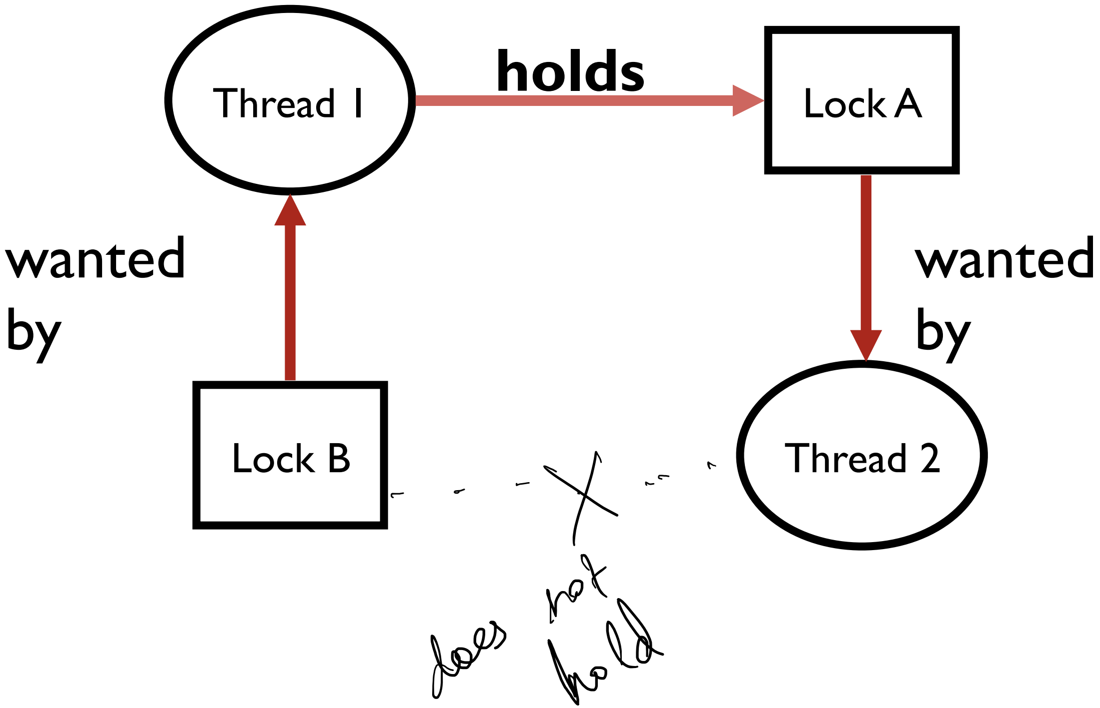
lock (&B);

Thread 2

lock (&A);

lock(&B);

NON-CIRCULAR DEPENDENCY



```c
set_t *set_intersection (set_t *s1, set_t *s2) {
    set_t *rv = malloc(sizeof(*rv));
    mutex_lock(&s1->lock);
    mutex_lock(&s2->lock);
    for(int i=0; i<s1->len; i++) {
        if(set_contains(s2, s1->items[i])
            set_add(rv, s1->items[i]);
    mutex_unlock(&s2->lock);
    mutex_unlock(&s1->lock);
}
```

T1

S1: set A

S2: set B

T2

S1: set B

S2: set A

Could lead to a deadlock

Thread 1: rv = set_intersection(setA, setB);

Thread 2: rv = set_intersection(setB, setA);

ENCAPSULATION

Modularity can make it harder to see deadlocks

Solution?

```
if (m1 > m2) {
    // grab locks in high-to-low address order
    pthread_mutex_lock(m1);
    pthread_mutex_lock(m2);
} else {
    pthread_mutex_lock(m2);
    pthread_mutex_lock(m1);
}
```

Any other problems?

DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

1. mutual exclusion
2. hold-and-wait
3. no preemption
4. circular wait

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:

```
int CompareAndSwap(int *address, int expected, int new) {
   if (*address == expected) {
      *address = new;
      return 1; // success
   }
   return 0; // failure
}
```

swap happens

→ no swap


https://tinyurl.com/cs537-sp19-bunny9
BUNNY

https://tinyurl.com/cs537-sp19-bunny9

BUNNY

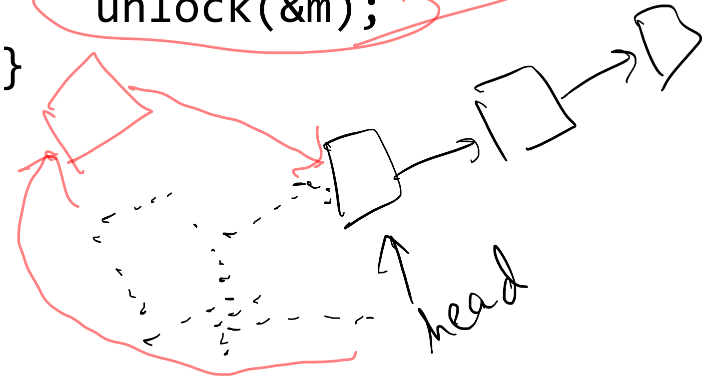
```
void add (int *val, int amt) {
    Mutex_lock(&m);
    *val += amt;
    Mutex_unlock(&m);
}
```

```
int CompareAndSwap(int *address,
        int expected, int new) {
    if (*address == expected) {
        *address = new;
        return 1; // success
    }
    return 0; // failure
}
```

```
void add (int *val, int amt) {
    do {
        int old = *value;
    } while(!CompAndSwap(___, ___, ___));
}
```

WAIT-FREE ALGORITHM: LINKED LIST INSERT

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




```c
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

```
grab_locks(l1, l2, l3) {
  lock(&meta);
  l1.lock();
  l2.lock()
}
```

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

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(&meta);
lock(&L1);
lock(&L2);
...
unlock(&meta);
```

→ One Big Lock → (L1, L2, L3 ...)

↳ lose advantages of fine grained locks!

Disadvantages?

3. NO PREEMPTION

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

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

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

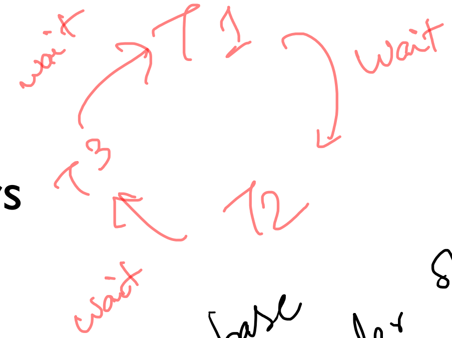
Disadvantages?

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



Complex code base convention in order of grabbing locks.

Works well if system has distinct layers

CONCURRENCY SUMMARY SO FAR

turn variable ticket variable

Motivation: Parallel programming patterns, multi-core machines

Mutual exclusion | Fairness | Performance

Abstractions, Mechanisms

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

Ordering

Concurrency Bugs → Deadlocks → Some techniques to get rid of deadlocks

MIDTERM REVIEW

VA = 15 bits

Page size = 32 bytes

PTE = 7 bits + 1 valid

Page Dir	Inner Page Table	Offset (5 bits)

VA

1. Solutions from 2012

Each Inner Page Table fits in 1 Page

$\log_2(\text{Page Size})$

32 bytes / page, PTE 1 bytes

⇒ 32 entries inner PTE

↳ 5 bit

5	5	5

2. Assumption offset