CONCURRENCY: DEADLOCK

Shivaram Venkataraman

CS 537, Spring 2020

ADMINISTRIVIA

Midterm is on ~~Wednesday~~ Thursday 3/12 at 5.30pm-7pm, details on Piazza

Venue: If your last name starts with A-R, go to Humanities 3650
else (last name starts with S-Z), go to Psych 113

Bring your ID!

Calculators allowed

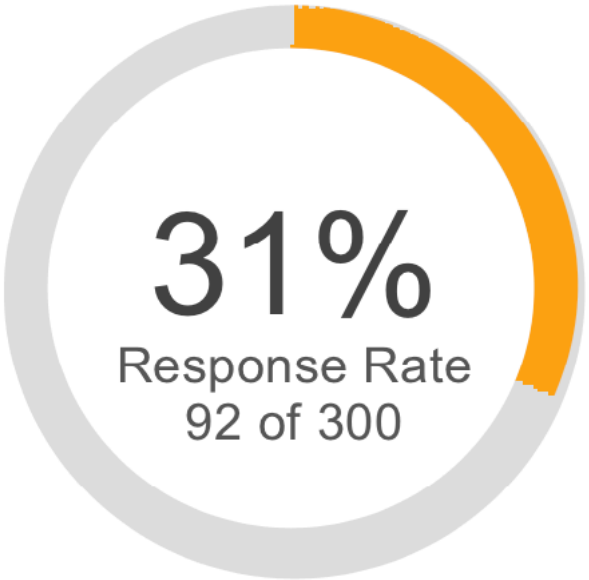
No cheat sheet, closed book

AEFIS SURVEY RESULTS

Thank you for the responses!

Points to improve

1. Upload slides earlier ← Try to do this
2. Go slower
3. More details on project



AGENDA / LEARNING OUTCOMES

Concurrency

- How do we build semaphores?
- 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*

thread join

Producer

Consumer

buffer

SEMAPHORE OPERATIONS

queue of threads, + state

Wait or Test: sem_wait(sem_t*)

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

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

BUILD ZEMAPHORE!

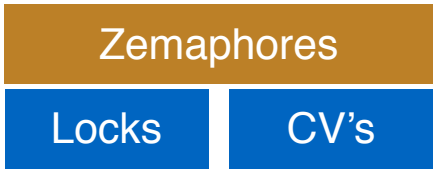
zem_wait(): Waits while value <= 0, Decrement

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

```
Typedef struct {
    int value;
    cond_t cond;
    lock_t lock;
} zem_t;

void zem_init(zem_t *s, int value) {
    s->value = value;
    cond_init(&s->cond);
    lock_init(&s->lock);
}
```

sem_wait : Decrement and then wait if necessary



BUILD ZEMAPHORE FROM LOCKS AND CV

T1

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

T2

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

Hold lock

State

Shared state

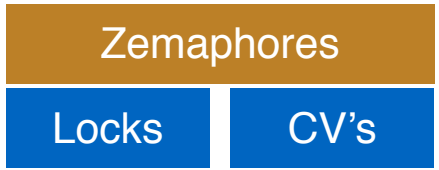
Return from wait

lock is held

while loop

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

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



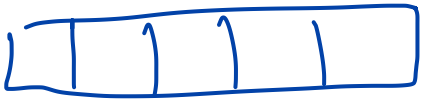
SUMMARY: SEMAPHORES

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



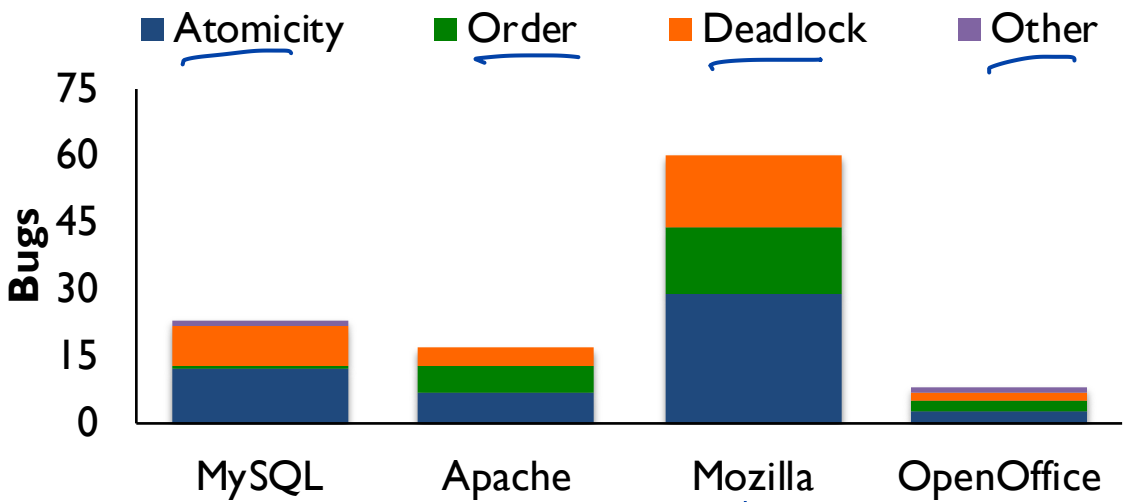
sem_wait(): Decrement and waits if value < 0

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);
```

fwrite

T1 runs
if (thd → proc_info)

T2
thd → proc_info = NULL

Error → fputs(NULL)

FIX ORDERING BUGS WITH CONDITION VARIABLES

Parent

```
Thread 1:
void init() {
    …

    mThread =
    PR_CreateThread(mMain, …);
    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);

    …
}
```

mState is initialized → state

Child

```
Thread 2:

void mMain(…) {
  …

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

  mState = mThread->State;
  …
}
```

Parent init → Child runs after

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);
```

T1 grabs lock A

T1 .... blocked

Thread 2:

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

T2 runs, grabs lock B

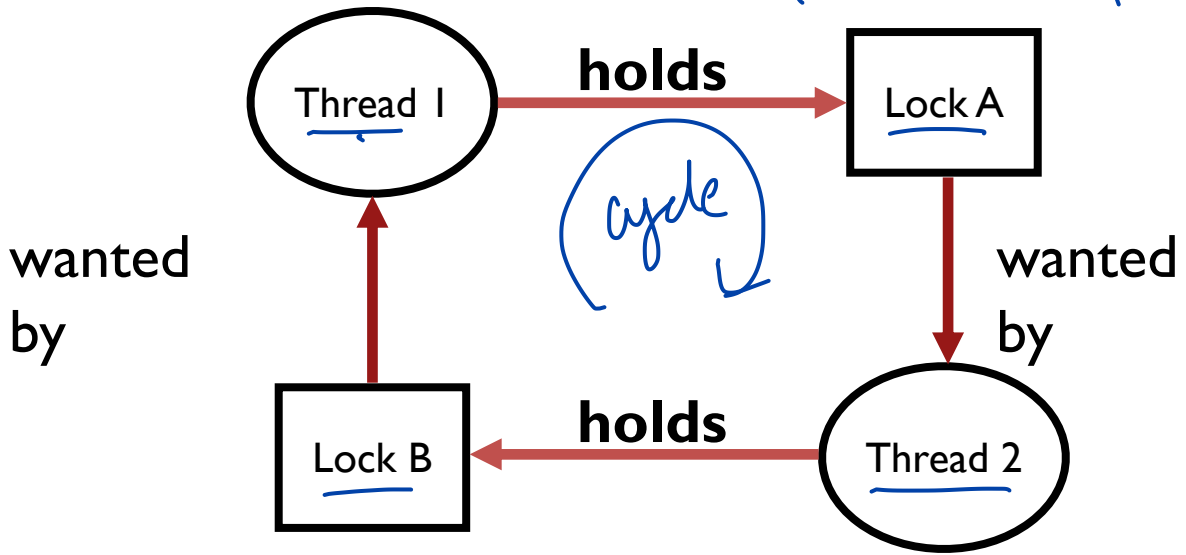
T2 .... blocked

CIRCULAR DEPENDENCY

T1
lock(A)
lock(B).

T2
lock(B)
lock(A).

edge from Thread to lock if Thread holds lock



FIX DEADLOCKED CODE

Thread 1:

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

Thread 2:

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

Thread 1

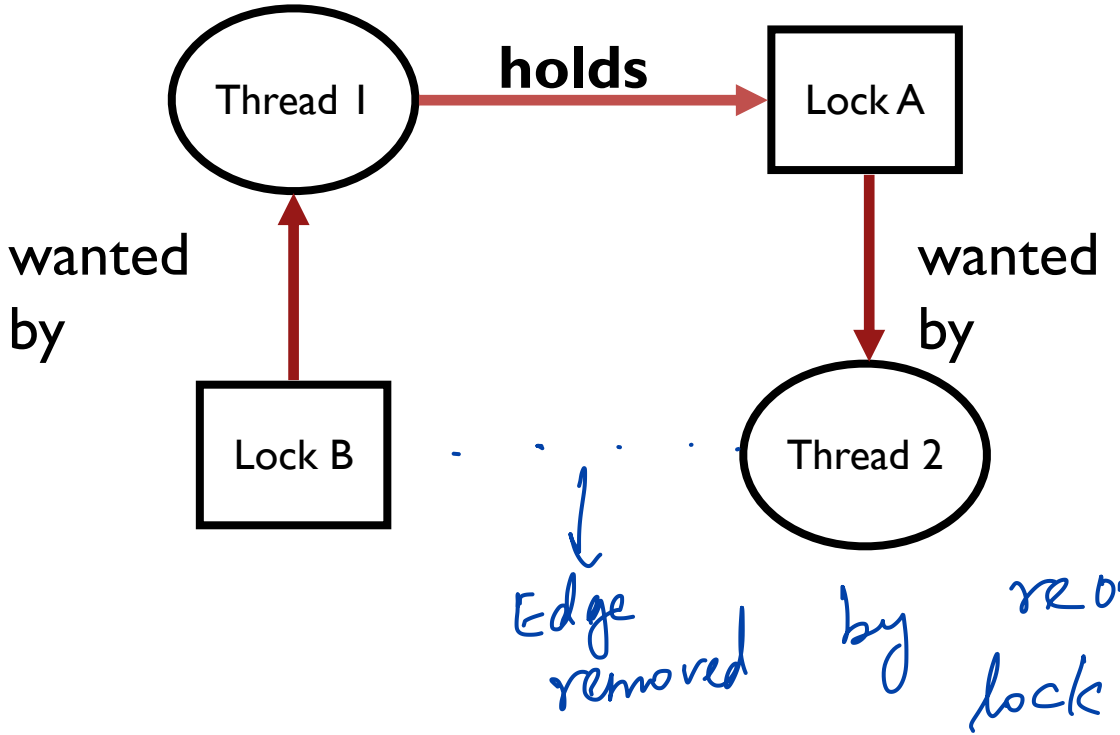
```
lock(&A);
lock(&B);
```

Thread 2

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

← blocked

NON-CIRCULAR DEPENDENCY



```
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);
}
```

inside function call

1. Order of lock acquisition
2. Non-trivial fix order in which locks are acquired

T1

T2

lock(A) → lock(B)

lock(B)

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

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

ENCAPSULATION

Modularity can make it harder to see deadlocks

mutex * m1, m2;

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?

m1 = m2

QUIZ 19

https://tinyurl.com/cs537-sp20-quiz19

Deadlock

```
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);
}
```

Deadlock!

T1 waiting lock B held by T2
T2 waiting lock C held by T3
T3 waiting for T1

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

A B C
B C A
C A B

No deadlock

T1 locks A waits B
T2 locks B, C waits E
T3 locks F, E waits A

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:

Hardware support for atomic instructions

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

→ CMPXCHG

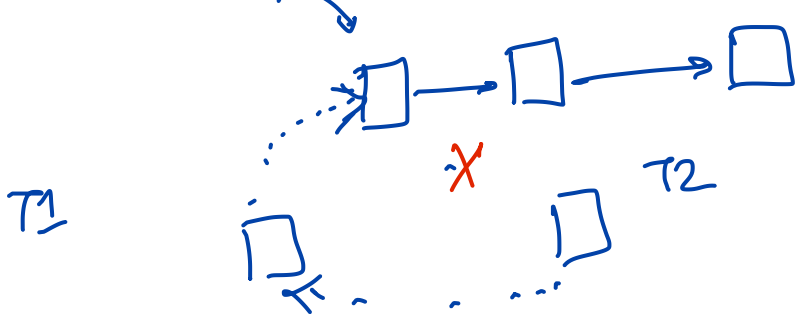
WAIT-FREE ALGORITHM: LINKED LIST INSERT

linked list

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

To safely have multiple inserts at same time

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



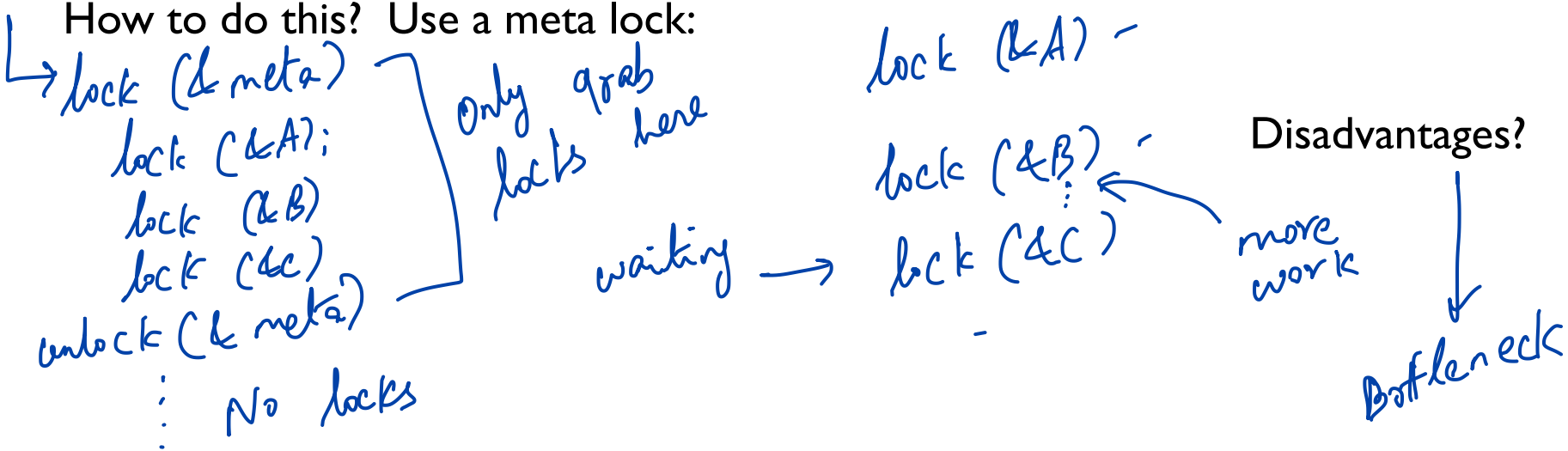
2. HOLD-AND-WAIT

Database

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:



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 → Cooperative

Unfair?

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

now T2 could grab lock A

sleep (rand())

preventing deadlock

Disadvantages?

You can come up scenarios which are called

livelock

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

HARD

Works well if system has distinct layers

CONCURRENCY SUMMARY SO FAR

Motivation: Parallel programming patterns, multi-core machines

Abstractions, Mechanisms

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

Concurrency Bugs

LOOKING AHEAD

Midterm on Thursday!

Thursday class:

- Summary,
- More quizzes?
- In-class OH?