Welcome back!

CONCURRENCY: DEADLOCK

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CS 537, Spring 2023

ADMINISTRIVIA

Regrade requests

Grades

Today

- Project 3, Project 4 – Check Piazza
- Midterm 1 – Check Canvas post

Upcoming

email

- Project 5 – Out today! Check your groups on Canvas!
- Midterm 2 – Conflict form on Piazza

April 4th

5:45 pm - 7:15 pm

Practice exams – this week!

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* → xchg

lock()

only want 1 thread to be active

unlock()

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

solved with *condition variables* and *semaphores*

Parent thread

join() ← child

SEMAPHORES

internal state
→ integer value

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

BINARY SEMAPHORE (LOCK)

```
typedef struct __lock_t {
     sem_t sem;
} lock_t;

void init(lock_t *lock) {
    sem_init(&lock->sem, 1);
}

void acquire(lock_t *lock) {
    sem_wait(&lock->sem);
}

void release(lock_t *lock) {
    sem_post(&lock->sem);
}
```

sem_init(sem_t*, int initial)
sem_wait(sem_t*): Decrement, wait if value < 0
sem_post(sem_t*): Increment value
then wake a single waiter

how do you a binary semaphore

→ Decrement & acquire lock T1
→ Decrement, blocked T2
→ Increment and wake up T2

READER/WRITER LOCKS

Let multiple reader threads grab lock (shared)

Only one writer thread can grab lock (exclusive)

- No reader threads
- No other writer threads

Let us see if we can understand code…

Example:

Bank account

Phone — Read balance

Web browser — Read balance

read at same time → safe

READER/WRITER LOCKS

```
typedef struct _rwlock_t {
    sem_t lock;
    sem_t writelock;
    int readers;
} rwlock_t;

void rwlock_init(rwlock_t *rw) {
    rw->readers = 0;
    sem_init(&rw->lock, 1);
   sem_init(&rw->writelock, 1);
}
```

two semaphores

number of active reader threads

Initialized similar to binary lock

READER/WRITER LOCKS

```
13 void rwlock_acquire_readlock(rwlock_t *rw) {
14     sem_wait(&rw->lock);
15     rw->readers++;
16     if (rw->readers == 1)
17         sem_wait(&rw->writelock);
18     sem_post(&rw->lock);
19 }
21 void rwlock_release_readlock(rwlock_t *rw) {
22     sem_wait(&rw->lock);
23     rw->readers--;
24     if (rw->readers == 0)
25         sem_post(&rw->writelock);
26     sem_post(&rw->lock);
27 }
29 rwlock_acquire_writelock(rwlock_t *rw) { sem_wait(&rw->writelock); }
31 rwlock_release_writelock(rwlock_t *rw) { sem_post(&rw->writelock); }
```

- Not fair!
- ensure no writers are present
- protect readers from racing
- rw → readers ++ grab write lock.
- increment
- first reader
- grab write lock
- release line 14 lock
- Decrement active
- last reader → wake up writer threads
- behave similar to exclusive lock

	nR	wL	L
T1: acquire_readlock()	1	0	1
T2: acquire_readlock()	2	0	1
T3: acquire_writelock()		-1	
T2: release_readlock()	1	-1	
T1: release_readlock()	0	0	
T4: acquire_readlock()			
T5: acquire_readlock()			
T3: release_writelock()			

(T1: release_readlock() → wake up T3)

// what happens next?

QUIZ 18

https://tinyurl.com/cs537-sp23-quiz18

T1: acquire_readlock()
T2: acquire_readlock()
T3: acquire_writelock()

→ Running. We allow multiple reader threads

T4: acquire_writelock()
T5: acquire_writelock()
T6: acquire_readlock()

→ Waiting for write lock

T8: acquire_writelock()
T7: acquire_readlock()
T9: acquire_readlock()

→ Waiting for read lock

BUILD ZEMAPHORE!

Textbook

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

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

```
Typedef struct {
    int value;     ← state
    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);
}
```

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);
}
```

acquire lock before cond_wait

while so that we recheck

wake up threads

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

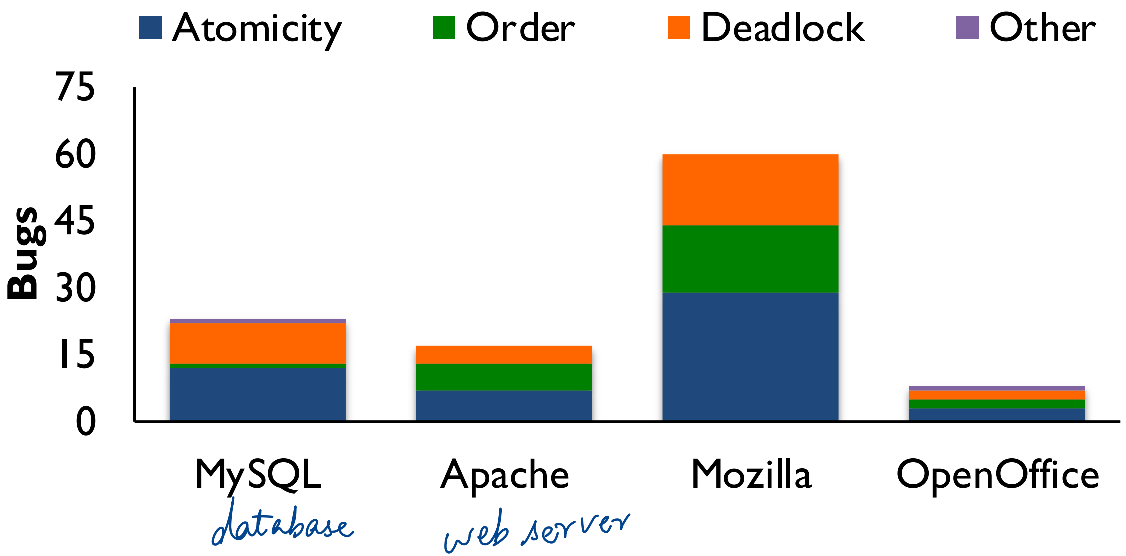
Semaphores contain **state** → good for programmer

- 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

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);
```

using shared variable

Thread 2:

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

setting shared var to NULL

FIX ORDERING BUGS WITH CONDITION VARIABLES

Thread 1:

```
void init() {
    …

    mThread =
    PR_CreateThread(mMain, …);

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

    …
}
```

shared state used to indicate init is complete

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

Order of locks
No other coordination

No way to release
or preempt

Thread 1:

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

Thread 2:

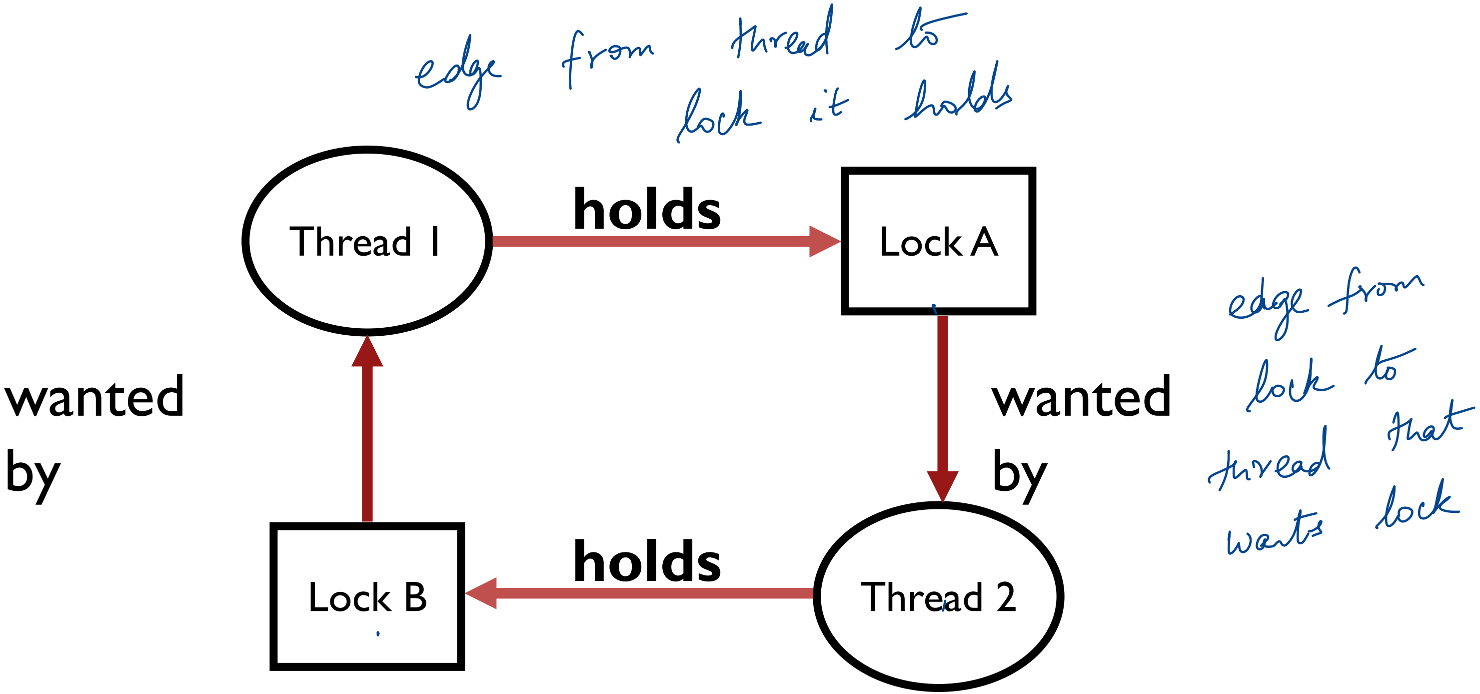
→ lock(&B);
lock(&A);

Possible Interleaving

T1 : lock (&A) → acquires
T2 : lock (&B) → acquires
T1 : lock (&B) → blocked
T2 : lock (&A) → blocked

Deadlock

CIRCULAR DEPENDENCY



FIX DEADLOCKED CODE

Thread 1:

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

Thread 2:

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

Thread 1

lock(&A); ✓

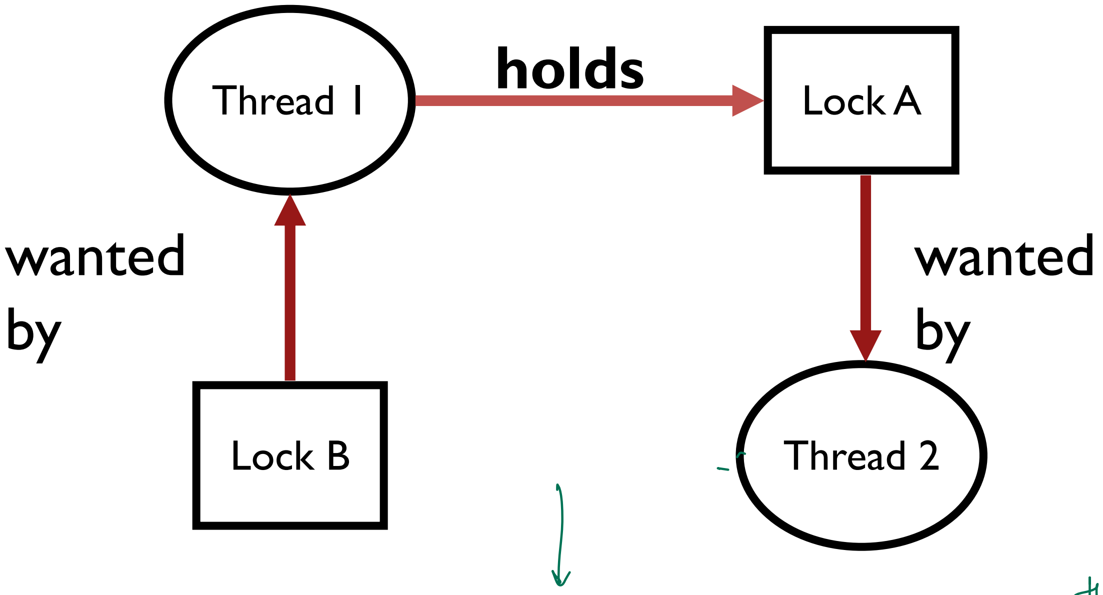
lock(&B) ✓

Thread 2

→ lock(&A); ✗ blocked

lock(&B);

NON-CIRCULAR DEPENDENCY



removed cycle from this graph

```
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);
}
```

always lock s1 first before s2

Modularity can make it harder to see deadlocks

set_intersection is a function used in multiple threads

```
Thread 1: rv = set_intersection(setA, setB);
Thread 2: rv = set_intersection(setB, setA);
```

QUIZ 19

https://tinyurl.com/cs537-sp23-quiz19

```
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 , B
T2 : B , C
T3 : C , A

Deadlock !

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

No !

Same order

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

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

T1 : B , T2 : E , T3 : A

DEADLOCK THEORY

Deadlocks can only happen with these four conditions:

1. mutual exclusion
2. hold-and-wait → thread grab some locks & wait for others
3. no preemption → no way to ask a thread to release lock
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 e.g. xchg

insert into linked list

```
void insert (int val) {
    node_t *n = Malloc(sizeof(*n));
    n->val = val;
  → lock(&m);
    n->next = head;     |  multiple
    head = n;           |  inserts
  → 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 lock A
⋮
lock (B) → wait
⋮
unlock (B)
lock (C) → wait

→ lock (meta)
lock(A);
lock(B);
lock (C);
unlock(meta)
⋮

get all of locks or none of them

Disadvantages?

limits
Concurrency

3. NO PREEMPTION

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

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

Disadvantages?

release resources

back off → random

exponential

1
2
4
⋮

lock(B)
(try lock(A) == 1)

Unfairness
↳ one thread back off

live lock

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

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

Project 5 out!

Midterm 2 on concurrency

Next: New Module on Persistence