CS444/544
Operating Systems II

Lecture 15

Deadlock (cont.)

Prep. for Quiz 3

5/29/2024

Acknowledgement: Slides drawn heavily from Yeongjin Jiang

Oregon State University

Recap: Concurrency Bugs

- Code does not have a bug when it runs with single thread could have a bug when it runs with multiple threads
  - Multiple cores, etc.

- What are the types of concurrency bugs?
  - Atomicity
  - Ordering
  - Deadlock

Recap: Atomicity: Use Lock

```
1   pthread_mutex_t proc_info_lock = PTHREAD_MUTEX_INITIALIZER;
2
3   Thread 1::
4   pthread_mutex_lock(&proc_info_lock);
5   if (thd->proc_info) {
6     ...
7     fputs(thd->proc_info, ...);
8     ...
9   }
10  pthread_mutex_unlock(&proc_info_lock);
11
12  Thread 2::
13  pthread_mutex_lock(&proc_info_lock);
14  thd->proc_info = NULL;
15  pthread_mutex_unlock(&proc_info_lock);
```

Time of check (line 5)

Time of use (line 7)

Update! (line 14)

In critical section, NO UPDATE

Do not have TOCTTOU!

This will also block other threads that run line 5 while thread 2 updates thd->proc_info..

Recap: How Can We Resolve the Ordering Issue?

- Use locks and conditional variables to force a specific ordering…

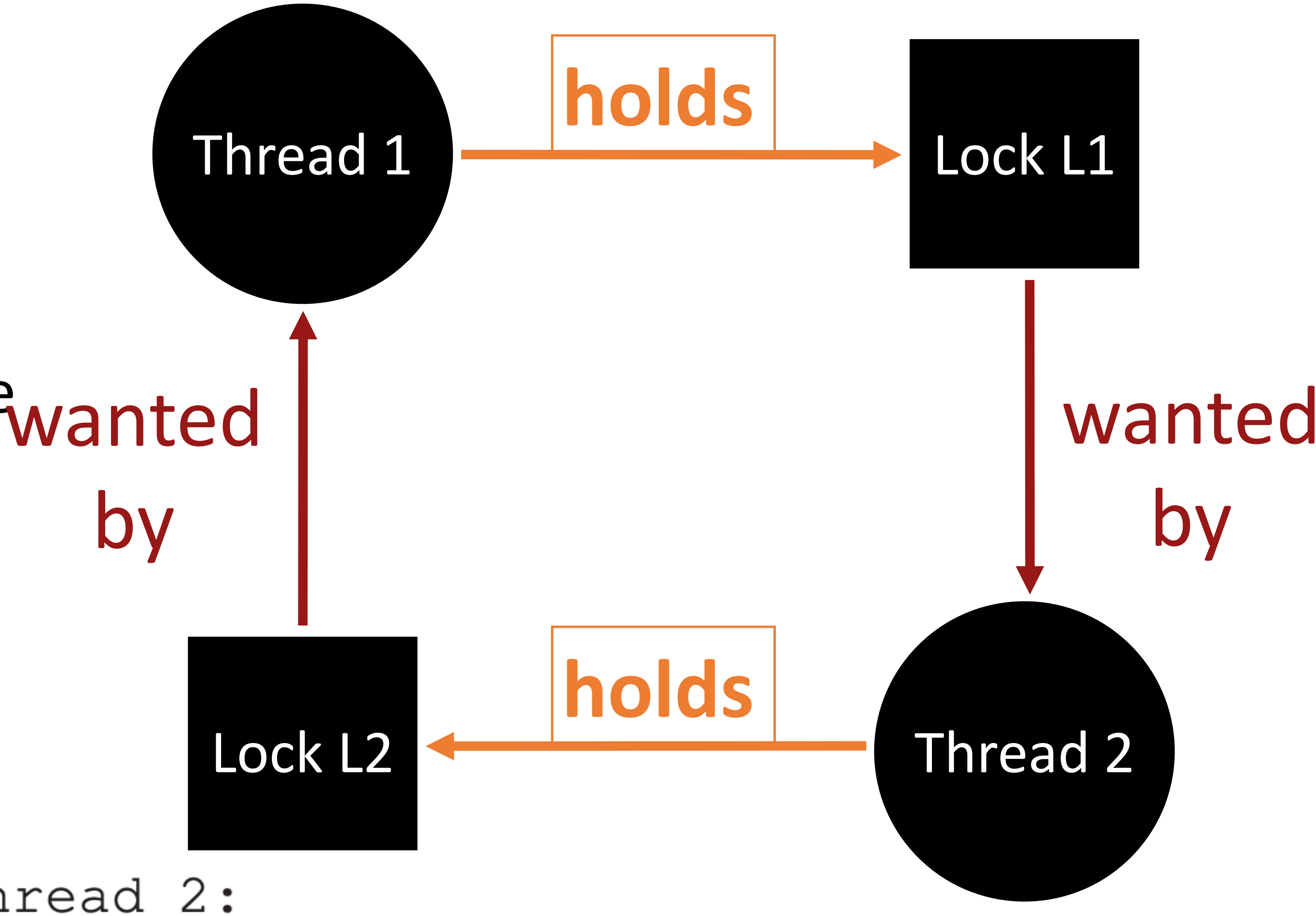
```
Thread 1::
void init() {
    ...
    mThread = PR_CreateThread(mMain, ...);

    // signal that the thread has been created...
    pthread_mutex_lock(&mtLock);
    mtInit = 1;
    pthread_cond_signal(&mtCond);
    pthread_mutex_unlock(&mtLock);
    ...
}

Thread 2::
void mMain(...) {
     ...
     // wait for the thread to be initialized...
     pthread_mutex_lock(&mtLock);
     while (mtInit == 0)
         pthread_cond_wait(&mtCond, &mtLock);
     pthread_mutex_unlock(&mtLock);

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

Sends Signal..

Waits condition..

Recap: Deadlock

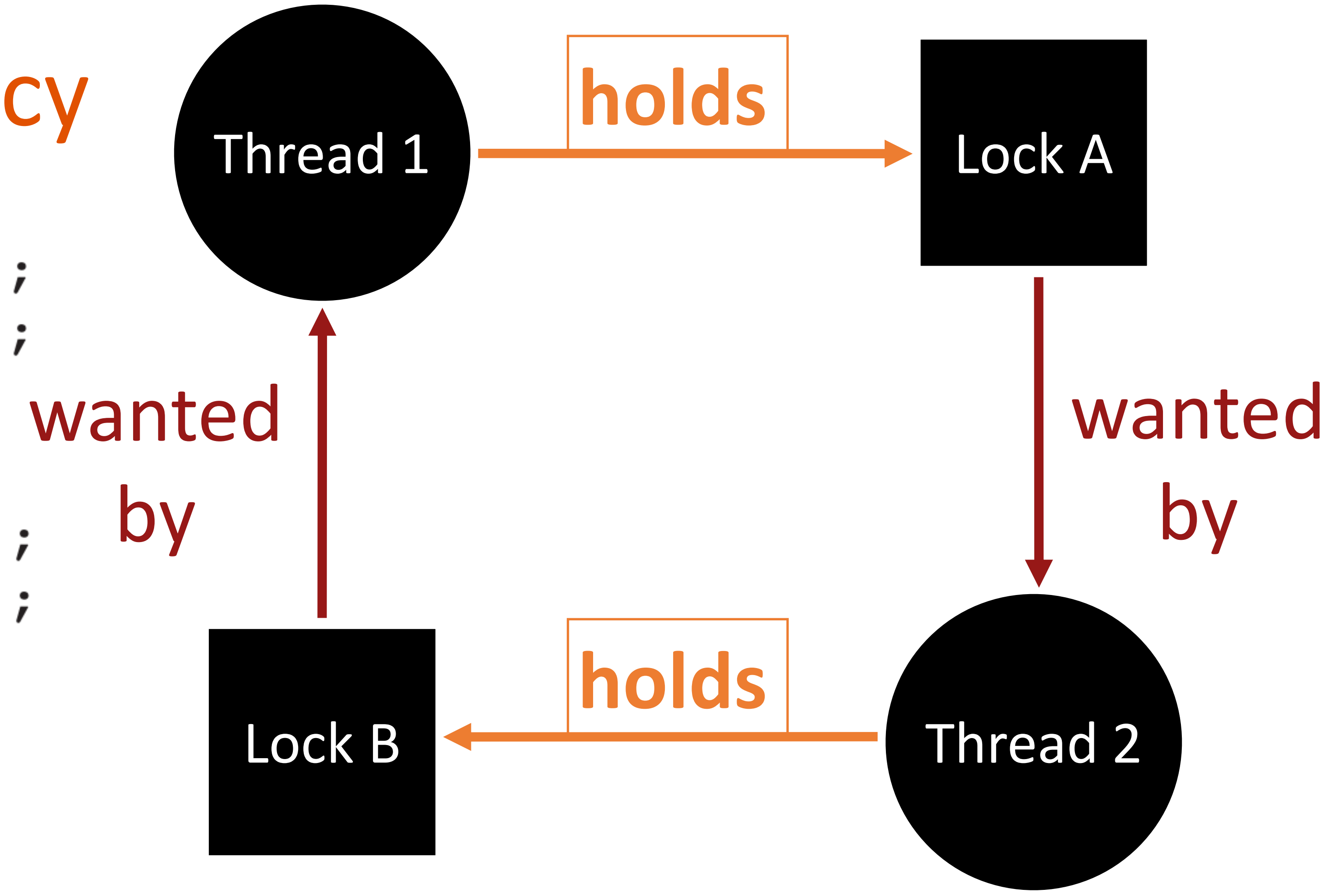
- Two or more threads are waiting for the other to take some actions thus neither makes any progress




```
Thread 1:                 Thread 2:
pthread_mutex_lock(L1);   pthread_mutex_lock(L2);
pthread_mutex_lock(L2);   pthread_mutex_lock(L1);
```

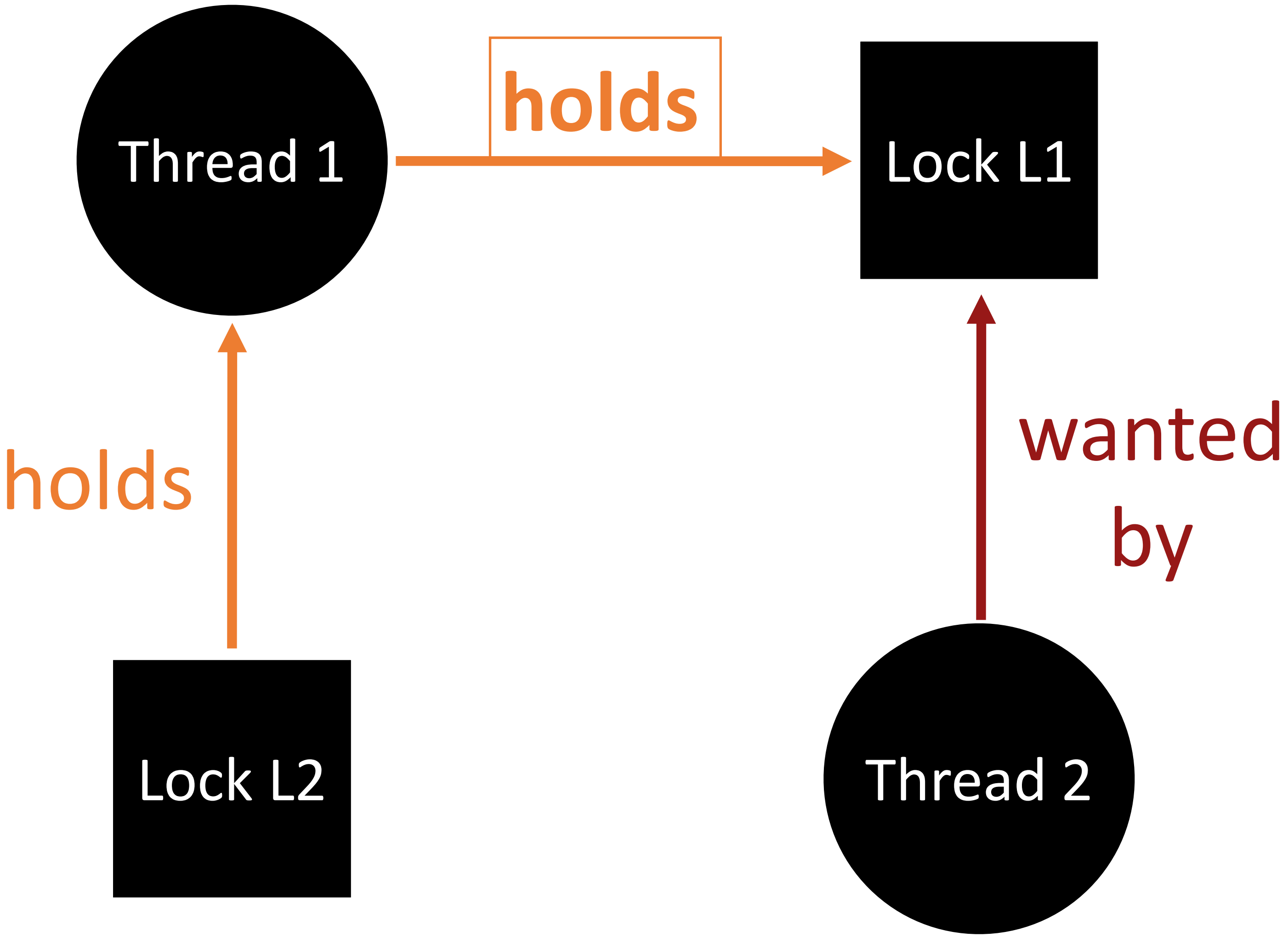
Recap: Circular Dependency

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```



Recap: Non-Circular Dependency

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);


Thread 2:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```



Thread-safe Data structure

```
set_t *set_intersection (set_t *s1, set_t *s2) {
        set_t *rv = new set_t();
        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);
        return rv;
}
```

Thread-safe Data structure

Thread 1:

rv = set_intersection(setA, setB);

Thread 2:

rv = set_intersection(setA, setB);

```
set_t *set_intersection (set_t *s1, set_t *s2) {
        …
        Mutex_lock(&s1->lock);
        Mutex_lock(&s2->lock);
        …
}
```

Thread-safe Datastructure

Thread 1:

```
rv = set_intersection(setA, setB);

    Mutex_lock(&setA->lock);
    Mutex_lock(&setB->lock);

    …
    Mutex_unlock(&setB->lock);
    Mutex_unlock(&setA->lock);
```

Thread 2:

```
rv = set_intersection(setA, setB);

Mutex_lock(&setA->lock);
Mutex_lock(&setB->lock);

…
Mutex_unlock(&setB->lock);
Mutex_unlock(&setA->lock);
```

Is This a Thread-safe Datastructure?

```
set_t *set_intersection (set_t *s1, set_t *s2) {
	set_t *rv = new set_t();
	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);
	return rv;
}
```

Find a Problem..

Thread 1:

rv = set_intersection(**setA**, **setB**);

Thread 2:

rv = set_intersection(**setB**, **setA**);

```
set_t *set_intersection (set_t *s1, set_t *s2) {
        …
        Mutex_lock(&s1->lock);
        Mutex_lock(&s2->lock);
        …
}
```

Find a Problem..

Thread 1:

rv = set_intersection(**setA**, **setB**);

Mutex_lock(&**setA**->lock);

Mutex_lock(&**setB**->lock);

Thread 2:

rv = set_intersection(**setB**, **setA**);

Mutex_lock(&**setB**->lock);

Mutex_lock(&**setA**->lock);

Deadlock!

Deadlock Theory

- Deadlocks can only happen if threads are having
  - Mutual exclusion
  - Hold-and-wait
  - No preemption
  - Circular wait

- We can eliminate deadlock by removing such conditions…

Mutual Exclusion

- Definition
  - Threads claims an exclusive control of a resource
  - E.g., Threads grabs a lock

How to Remove Mutual Exclusion

- Do not use lock
  - What???
- Replace locks with atomic primitives
  - compare_and_swap(uint64_t *addr, uint64_t prev, uint64_t value);
  - if *addr == prev, then update *addr = value;
  - lock cmpxchg in x86..

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

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

old

Hold-and-Wait

- Definition
  - Threads hold resources allocated to them (e.g., locks they have already acquired) while waiting for additional resources (e.g., locks they wish to acquire).

```
Mutex_lock(&setA->lock);
Mutex_lock(&setB->lock);
```

How to Remove Hold-and-Wait

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

- How to do this? Use a meta lock, like this:

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

// Critical section code
unlock(…);
```

Remove Hold-and-Wait

```
set_t *set_intersection (set_t *s1, set_t *s2) {
        Mutex_lock(&meta_lock)
        Mutex_lock(&s1->lock);
        Mutex_lock(&s2->lock);
        …
        Mutex_unlock(&s2->lock);
        Mutex_unlock(&s1->lock);
        Mutex_unlock(&meta_lock);
}
```

Remove Hold-and-Wait

Thread 1:

rv = set_intersection(setA, setB);

```
Mutex_lock(&meta_lock);
Mutex_lock(&setA->lock);
Mutex_lock(&setB->lock);
…
Mutex_unlock(&setB->lock);
Mutex_unlock(&setA->lock);
Mutex_unlock(&meta_lock);
```

Thread 2:

rv = set_intersection(setB, setA);

```
Mutex_lock(&meta_lock);
Mutex_lock(&setB->lock);
Mutex_lock(&setA->lock);
```

Will wait until Thread 1 finishes (release meta_lock)!

No Preemption

- Definition
  - Resources (e.g., locks) cannot be forcibly removed from threads that are holding them.

```
lock(A);
lock(B);
...
```

In case if B is acquired by other thread

All other threads must wait for acquiring A

How to Remove No Preemption

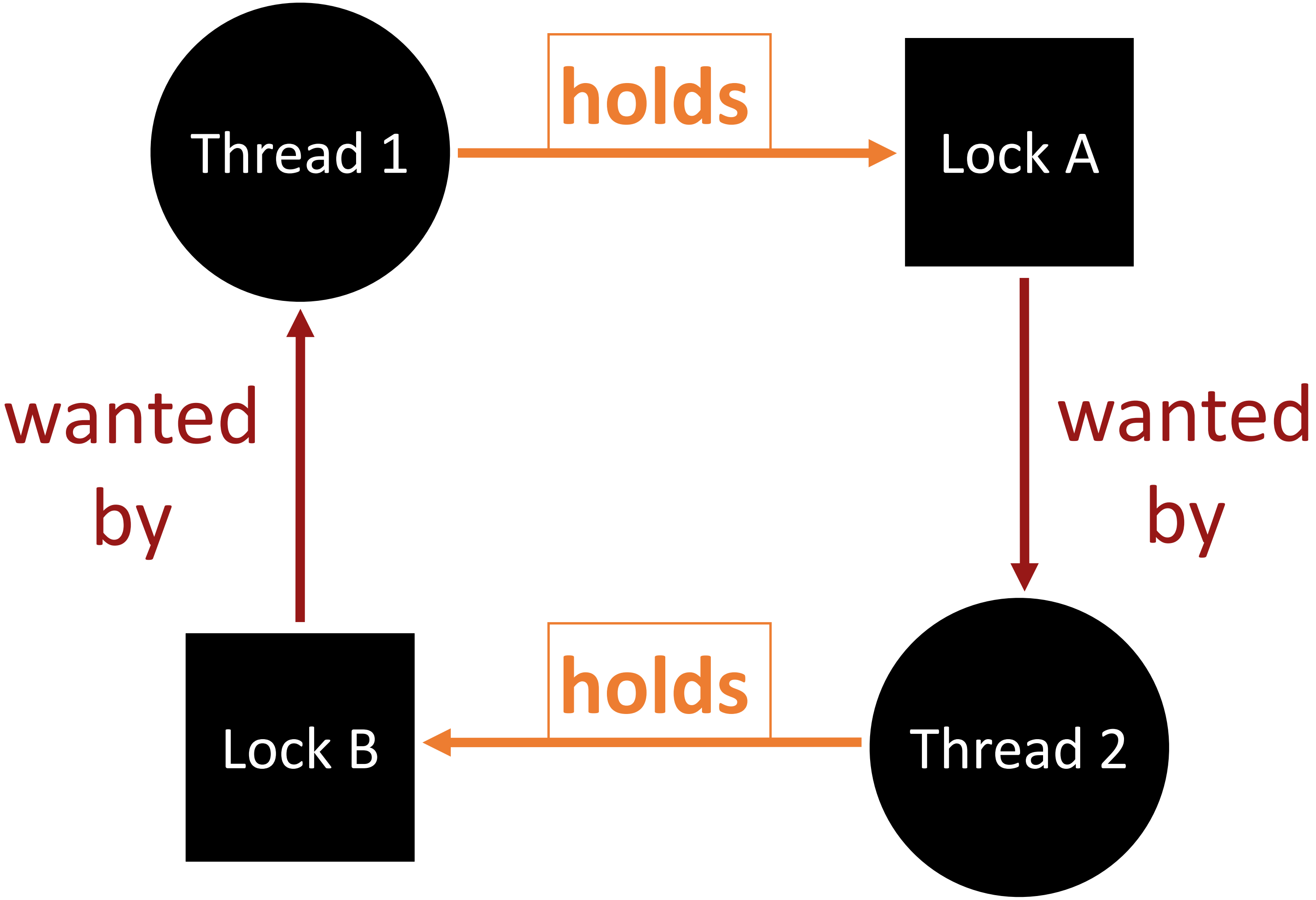
Release the lock if obtaining a resource fails…

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

Can't acquire B, then Release A!

Circular Wait

- Definition
  - There exists a circular chain of threads such that each thread holds a resource (e.g., lock) being requested by next thread in the chain.



How to Remove Circular Wait

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```

How to Remove Circular Wait

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);

Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```

Lock variable is mostly a pointer, then provide a correct order of having a lock

e.g.,

```
if(l1 > l2)  {
        Mutex_lock(l1);
        Mutex_lock(l2);
}
else {
        Mutex_lock(l2);
        Mutex_lock(l1);
}
```

Deadlock Theory

- Deadlocks can only happen if threads are having
  - Mutual exclusion
  - Hold-and-wait
  - No preemption
  - Circular wait

- We can eliminate deadlock by removing such conditions…

Quiz 3

- Next ~~Tues~~day Mon (6/3 from 8:00 am to 11:59 pm)
  - Open materials (slides, videos, code, and textbook)

- You will have 2 attempts for the quiz

Quiz 3 Coverage

- Lab 3 (User/Kernel, System Call and Interrupt Handling)
- Lab 4 (Preemptive Multitasking & Copy-on-write Fork)
- Lecture 12: Multithreading and Synchronization
- Lecture 13-14: Lock and Thread Synchronization
- Lecture 14-15: Concurrency Bugs and Deadlock

Sample Questions

- In x86, which of the following instruction runs atomically?
  - cmpxchg
  - popa
  - lea
  - xchg
  - mov

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Sample Questions

- In x86, which of the following instruction runs atomical test and test-and-set?
  - cmpxchg
  - int $0x30
  - lock cmpxchg
  - lock
  - xchg

Sample Questions

- In x86, which of the following instruction runs atomical test and test-and-set?
  - cmpxchg
  - int $0x30
  - lock cmpxchg
  - lock
  - xchg

cmpxchg in x86 is not a hardware atomic instruction. However, when used with the lock prefix, the instruction will be an atomic test and test-and-set instruction.

Sample Questions

- In x86, which register is being used for storing “compare” value when running the cmpxchg instruction?
  - CR3
  - EAX
  - EBX
  - ESP
  - EIP

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Sample Questions

- T/F: Page table is not relevant to data racing / thread synchronization.

Sample Questions

- T/F: Page table is not relevant to data racing / thread synchronization.

True. Page table is for virtual memory, and thus is not relevant to thread sync.

Sample Questions

- In JOS lab, which value will the fork() returns to the child environment if the function has been executed successfully?
  - 0
  - 1
  - The envid of the parent env
  - The envid of the child env
  - The address of the page table of the child env

Sample Questions

- In JOS lab, which value will the fork() returns to the child environment if the function has been executed successfully?
  - 0
  - 1
  - The envid of the parent env
  - The envid of the child env
  - The address of the page table of the child env

Fork returns:

Parent: child envid

Child: 0

Sample Questions

- Which of the following stores the information about the reason of a page fault?
  - EAX
  - CR2
  - CR3
  - eflags
  - Trapframe

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  - EAX
  - CR2
  - CR3
  - eflags
  - Trapframe

Error code in trapframe

Sample Questions

- Will this implementation cause deadlock (assuming no infinite loop in the critical section)?

```
Thread 1:
pthread_mutex_lock(L1);
pthread_mutex_lock(L2);
```

Yes

```
Thread 2:
pthread_mutex_lock(L2);
pthread_mutex_lock(L1);
```

Sample Questions

- Will this implementation cause deadlock (assuming no infinite loop in the critical section)?

Thread 1:

```
spin_lock(&meta);
spin_lock(&l1);
spin_lock(&l2);
spin_unlock(&meta);
…
spin_unlock(&l2);
spin_unlock(&l1);
```

Thread 2:

```
spin_lock(&meta);
spin_lock(&l2);
spin_lock(&l1);
spin_unlock(&meta);
…
spin_unlock(&l1);
spin_unlock(&l2);
```

No