Deadlock and Concurrency Bugs

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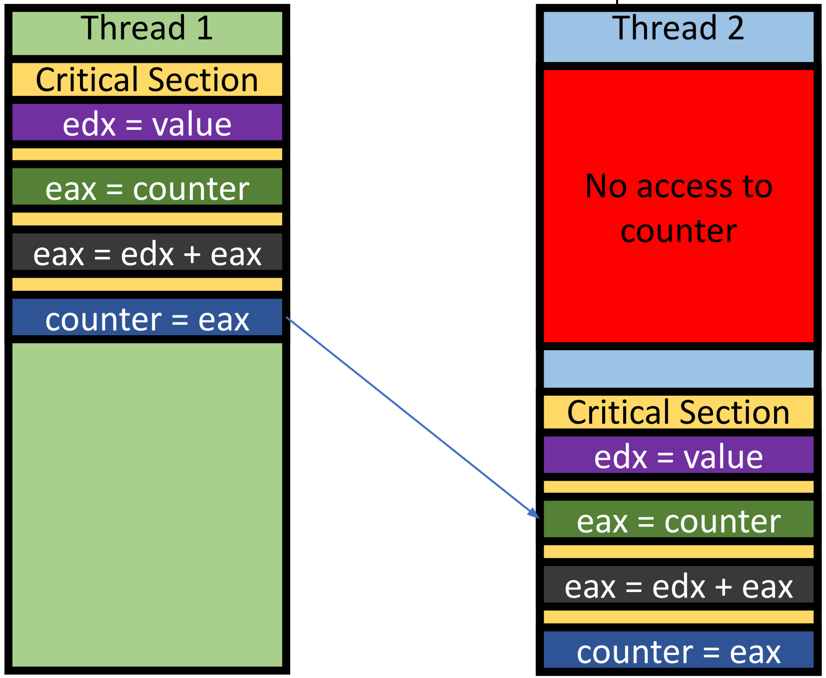
Recap: How can we prevent data races?

- *Critical section* – a section of code, or collection of operations, in which only one process shall be executing at a given time

- *Mutual exclusion (Mutex)* - mechanisms that ensure that only one person or process is doing certain things at one time (others are excluded)

Recap: How can we prevent data races?

- Mutual Exclusion / Critical Section
  - Combine multiple instructions as a chunk
  - Let only one chunk execution runs
  - Block other executions



Recap: Mutual Exclusion through locks

- Lock
  - Prevent others enter the critical section
- Unlock
  - Release the lock, let others acquire the lock

- counter += value
  - `lock()`
  - `edx = value;`
  - `eax = counter;`
  - `eax = edx + eax;`
  - `counter = eax;`
  - `unlock()`

Recap: Manual Spinlock (bad_lock)

- What will happen if we implement lock
  - As bad_lock / bad_lock?

- bad_lock
  - Wait until lock becomes 0 (loops if 1)
  - And then, set lock as 1
    - Because it was 0, we can set it as 1
  - Others must wait! **Can pass this if lock=0**

Sets lock=1 to block others

- bad_unlock
  - Just set *lock as 0

Sets lock=0 to release

Critical Section

```
void *
count_bad_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        bad_lock(&lock);
        sched_yield();
        count += 1;
        bad_unlock(&lock);
    }
}
```

```
void
bad_lock(volatile uint32_t *lock) {
    while (*lock == 1);
    *lock = 1;
}

void
bad_unlock(volatile uint32_t *lock) {
    *lock = 0;
}
```

Recap: Why does bad_lock doesn't work?

- There is a room for race condition!

LOAD

```
mov     (%rdi),%eax
cmp     $0x1,%eax
je      0x400b60 <bad_lock>
movl    $0x1,(%rdi)
```

STORE

Race condition may happen

```
void
bad_lock(volatile uint32_t *lock) {
    while (*lock == 1);
    *lock = 1;
}
```

Recap: Lock using xchg

- xchg_lock
  - Use atomic 'xchg' instruction to
  - Load and store values atomically
  - Set value to 1, and compare ret
    - If 0, then you can acquire the lock
    - If 1, lock as 1, you must wait
- xchg_unlock
  - Use atomic 'xchg'
  - Set value to 0
    - Do not need to check
    - You are the only thread that runs in the
    - Critical section..

```
void *
count_xchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        xchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

Critical Section

```
void
xchg_lock(volatile uint32_t *lock) {
    while(xchg(lock, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

Recap: Lock using test and set

- tts_xchg_lock
- Algorithm
  - Wait until lock becomes 0
  - After lock == 0
    - xchg (lock, 1)
    - This only updates lock = 1 if lock was 0

- Why xchg, why not *lock = 1 directly
  - while and xchg are not atomic
  - Load/Store must happen at
    - The same time!

Critical Section

```
void *
count_tts_xchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        tts_xchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

```
void
tts_xchg_lock(volatile uint32_t *lock) {
    while (1) {
        while(*lock == 1);
        if (xchg(lock, 1) == 0) {
            break;
        }
    }
}
```

Recap: Lock using cmpxchg_lock

- Cmpxchg_lock
  - Use cmpxchg to set lock = 1
    - Do not update if lock == 1
    - Only write 1 to lock if lock == 0

- Xchg_unlock
  - Use xchg_unlock to set lock = 0
  - Because we have 1 writer and
  - This always succeeds…

```
void *
count_cmpxchg_lock(void *args) {
    for (int i=0; i < N_COUNT; ++i) {
        cmpxchg_lock(&lock);
        sched_yield();
        count += 1;
        xchg_unlock(&lock);
    }
}
```

Critical Section

```
void
cmpxchg_lock(volatile uint32_t *lock) {
    while(cmpxchg(lock, 0, 1));
}

void
xchg_unlock(volatile uint32_t *lock) {
    xchg(lock, 0);
}
```

Recap: Using hardware features smartly

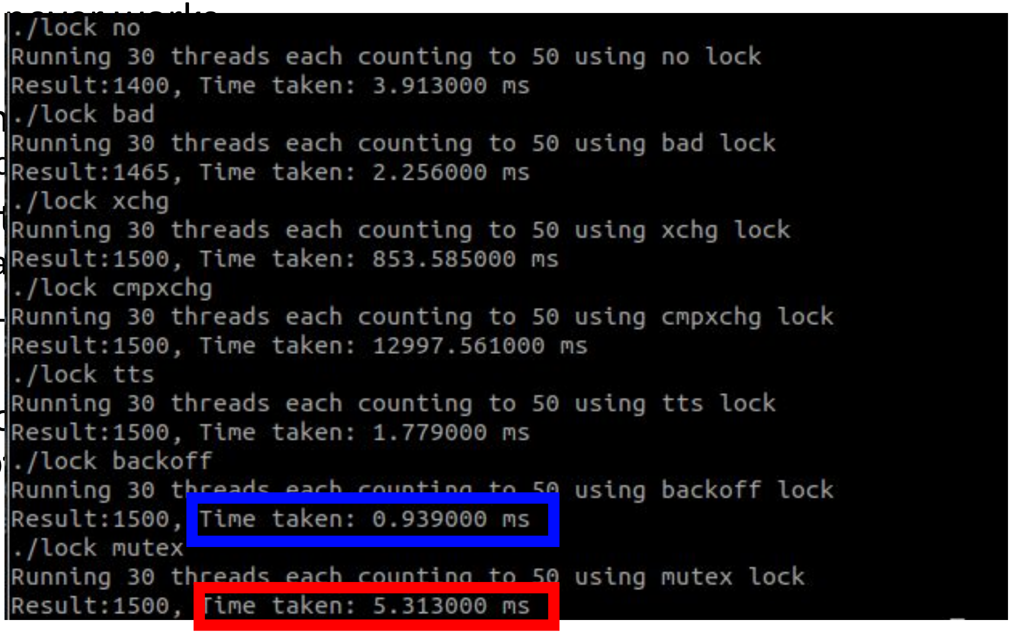
- backoff_cmpxchg_lock(lock)
- Try cmpxchg
  - If succeeded, acquire the lock.
  - If failed
    - Wait 1 cycle (pause) for 1^{st} trial
    - Wait 2 cycles for 2^{nd} trial
    - Wait 4 cycles for 3^{rd} trial
    - …
    - Wait 65536 cycles for 17^{th} trial..
    - Wait 65536 cycles for 18^{th} trial..

```c
void
backoff_cmpxchg_lock(volatile uint32_t *lock) {
    uint32_t backoff = 1;
    while(cmpxchg(lock, 0, 1)) {
        for (int i=0; i<backoff; ++i) {
            __asm volatile("pause");
        }
        if (backoff < 0x10000) {
            backoff <<= 1;
        }
    }
}
```

- https://en.wikipedia.org/wiki/Exponential_backoff

Recap: Summary

- Mutex is implemented with Spinlock
  - Waits until lock == 0 with a while loop (that’s why it’s called spin)
- Naïve code implementation
  - Load/Store must be atomic
- xchg is a “test and set” atom
  - Consistent, however, many c
- Lock cmpxchg is a ”test and
  - But Intel implemented this a
- We can implement test-and-
  - Faster!
- We can also implement expo
  - Much faster! **Faster Than p**



Other synchronization primitives

- We may want to have more than one thread/process to execute at same time

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

How many producers/consumers can run at a given time?

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

What we want!

- To be more efficient we want to be able to allow **more than one producer/consumer, i.e., equal to the number of items that can be inserted into/removed from the pool**

Producer

```
while (1) {

        produce an item;

        lock();
        insert(item to pool);
        unlock();
}
```

Consumer

```
While (1) {

        lock();
        remove(item from pool);
        unlock();

    consume the item;
}
```

Semaphore

A semaphore is like an **integer**, with three differences:

When you create the semaphore, you can initialize its value to any integer, but after that the only operations you are **allowed to perform** are **increment** (increase by one) and **decrement** (decrease by one). *You cannot read the current value of the semaphore.*

When a thread **decrements** the semaphore, if the **result is negative**, the **thread blocks itself** and cannot continue until another thread increments the semaphore.

When a thread **increments** the semaphore, if there are **other threads waiting, one of the waiting threads gets unblocked**.

Semaphore operations

```
wait(S) {
  while (S<=0);
   S--;
}
```

```
signal(S) {
        S++;
}
```

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;

    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    wait(FULL);
    lock();
    remove(item from pool);
    unlock();

    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Producers/consumers using Semaphores

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock();
    insert(item to pool);
    unlock();
    signal(FULL);
}
```

Consumer

```
While (1) {

    wait(FULL);
    lock();
    remove(item from pool);
    unlock();
    signal(EMPTY);
    consume the item;
}
```

Init: FULL = 0; **EMPTY = N**;

Is Semaphore good for producers/consumers?

Need to know the size of buffer!

How to accommodate dynamic pool size?

Revising Producers/consumers

Producer

```
while (1) {

    produce an item;
    wait(EMPTY);
    lock(m);
    insert(item to pool);
    unlock(m);
    signal(FULL);
}
```

Consumer

```
While (1) {

    wait(FULL);
    lock(m);
    remove(item from pool);
    unlock(m);
    signal(EMPTY);
    consume the item;
}
```

Revising Producers/consumers

Producer

```
while (1) {

    produce an item;
    wait till there is space in pool
    lock(m);
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    wait till there is an item in pool
    lock(m);
    remove(item from pool);
    unlock(m);
    tell a producer that item has been removed
    consume the item;
}
```

Revising Producers/consumers

Producer

```
while (1) {

    produce an item;
    if (!pool.has_space) {
        We need to wait for consumer
    }
    lock(m);
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    if (pool.is_empty) {
        We need to wait for producer
    }
    lock(m);
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

What's wrong?

Producer

```
while (1) {

    produce an item;
    if (!pool.has_space) {
        We need to wait for consumer
    }
    lock(m);
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    if (pool.is_empty) {
        We need to wait for producer
    }
    lock(m);
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

What's wrong?

Producer

Data Race

```
while (1) {

    produce an item;
    if (!pool.has_space) {
        We need to wait for consumer
    }
    lock(m);
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    if (pool.is_empty) {
        We need to wait for producer
    }
    lock(m);
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

Lets move the lock up!

Producer

```
while (1) {

    produce an item;
    lock(m);
    if (!pool.has_space) {
        We need to wait for consumer
    }
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    lock(m);
    if (pool.is_empty) {
        We need to wait for producer
    }
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

What's wrong?

Producer

Producer may never get to run

```
while (1) {

    produce an item;
    lock(m);
    if (!pool.has_space) {
        We need to wait for consumer
    }
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    lock(m);
    if (pool.is_empty) {
        We need to wait for producer
    }
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

Lets release the lock and wait!

Producer

```
while (1) {

    produce an item;
    lock(m);
    if (!pool.has_space) {
        unlock(m);
        We need to wait for consumer
        lock(m);
    }
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Consumer

```
While (1) {

    lock(m);
    if (pool.is_empty) {
        unlock(m);
        We need to wait for producer
        lock(m);
    }
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

Release, wait and reacquire

Producer

```
while (1) {

    produce an item;
    lock(m);
    if (!pool.has_space) {
        unlock(m);
        We need to wait for consumer
        lock(m);
    }
    insert(item to pool);
    unlock(m);
    tell a waiting consumer
}
```

Release lock, waiting for a condition and acquire lock

Consumer

```
While (1) {

    lock(m);
    if (pool.is_empty) {
        unlock(m);
        We need to wait for producer
        lock(m);
    }
    remove(item from pool);
    unlock(m);
    tell a waiting producer
    consume the item;
}
```

Condition Variable (CV)

CV full; full->lock = m;
CV empty; empty->lock = m;

Producer

```
while (1) {

    produce an item;
    lock(m);
    if (!pool.has_space) {
        wait(full);
    }
    insert(item to pool);
    signal(empty);
    unlock(m);
}
```

unlock(m);
We need to wait for consumer
lock(m);

Consumer

```
While (1) {

    lock(m);
    if (pool.is_empty) {
        wait(empty);
    }
    remove(item from pool);
    signal(full);
    unlock(m);
    consume the item;
}
```

Condition Variable operations

```
wait(S) {
 unlock(s->lock);
 block and add into s->queue
 lock(s->lock);
}
```

```
signal(S) {
 unlock(s->lock);
 p = remove process from s->queue
 unblock process p
 lock(s->lock);
}
```

Condition Variables

- Wait (condition)
  - Block on “condition”

- Signal (condition)
  - Wakeup one or more processes blocked on “condition”

- Conditions are like semaphores but:
  - signal is no-op if none blocked
  - There is no counting!

CVs for Ordering - Order 1

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

Thread 2::
void mMain(...) {
     ...
     mState = mThread->State;
     ...
}
```

CVs for Ordering - Order 2

```
Thread 2::
void mMain(...) {
    ...
    mState = mThread->State;
    ...
}
```

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

CVs for Ordering - Order 2

```
Thread 2::
void mMain(...) {
     ...
     mState = mThread->State;
     ...
}
```

Not Initialized…

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

CVs for Ordering

- 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;
    ...
}
```

CVs for Ordering

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

Waits for condition..

```
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;
    ...
}
```

CVs for Ordering

- 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 for condition..

Wait free synchronization

- Can we ensure our programs run fine in presence of possible race conditions without explicitly using synchronization primitives (or waiting for critical section)?
  - Root cause of Data races:
    - Hint: Concurrent use of shared data.
      - Can we make this safe?

Wait free synchronization

- Design data structures in a way that allows safe concurrent accesses
    - no mutual exclusion (lock acquire & release) necessary
    - no possibility of deadlock

- Approach: use a single *atomic* operation to
    - commit all changes
        - move the shared data structure from one consistent state to another

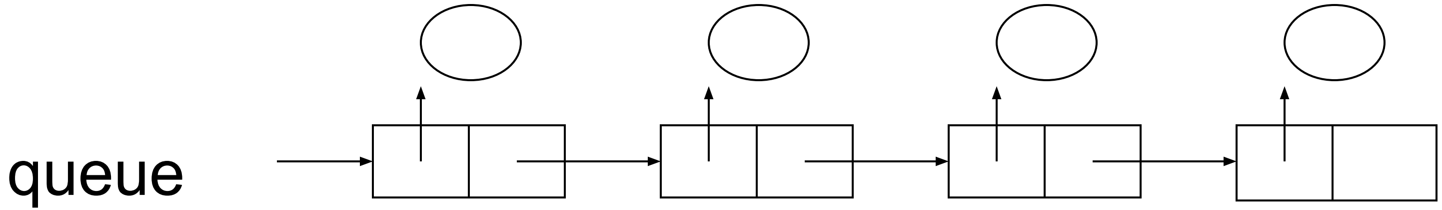
Simple queue insertion

```
QElem *queue;


void Insert(item) {
   QElem *new = malloc(sizeof(QElem));
   new->item = item;
   new->next = queue;
   queue = new;
}
```

Simple queue insertion

```
typedef struct {
  QItem *item;
  QElem *next;
} QElem;
```



Simple queue insertion

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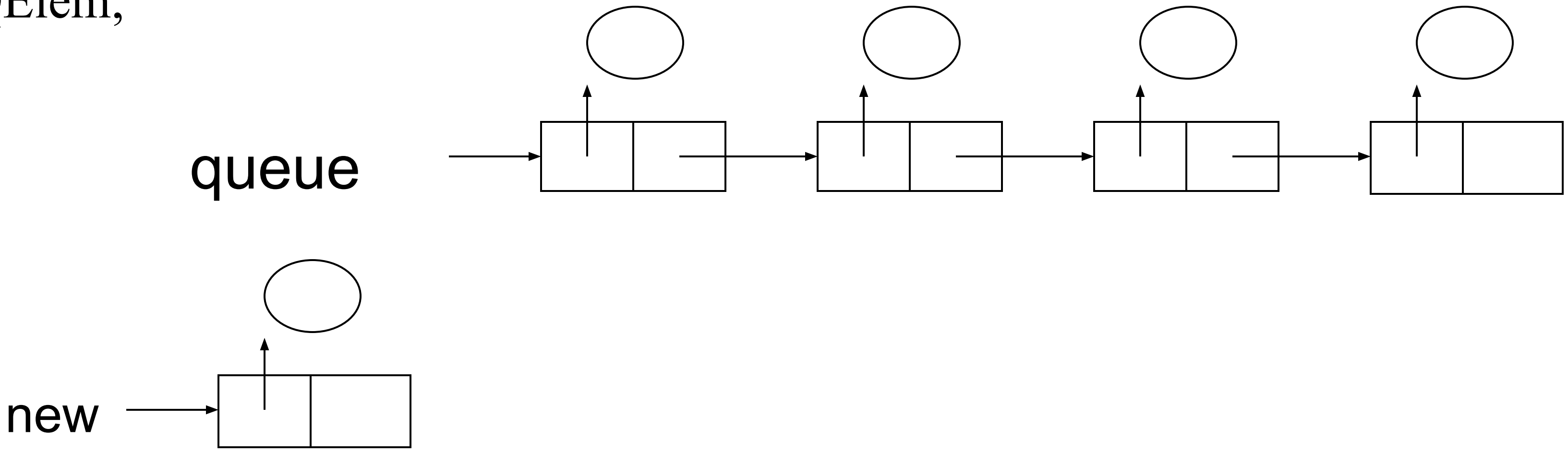

Simple queue insertion

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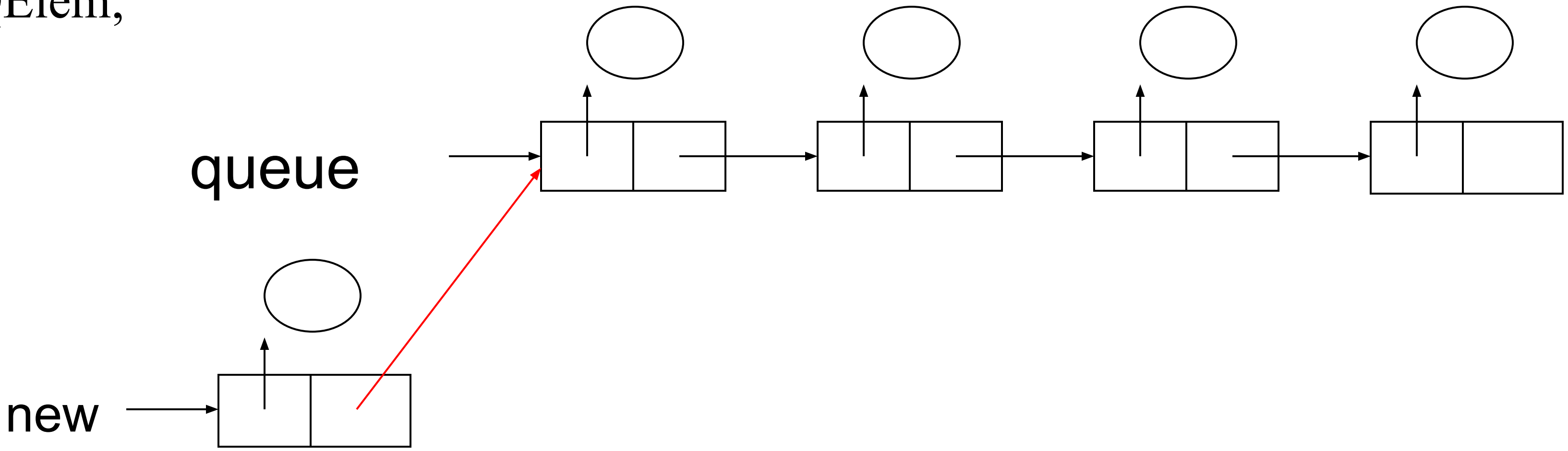

Simple queue insertion

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typedef struct {
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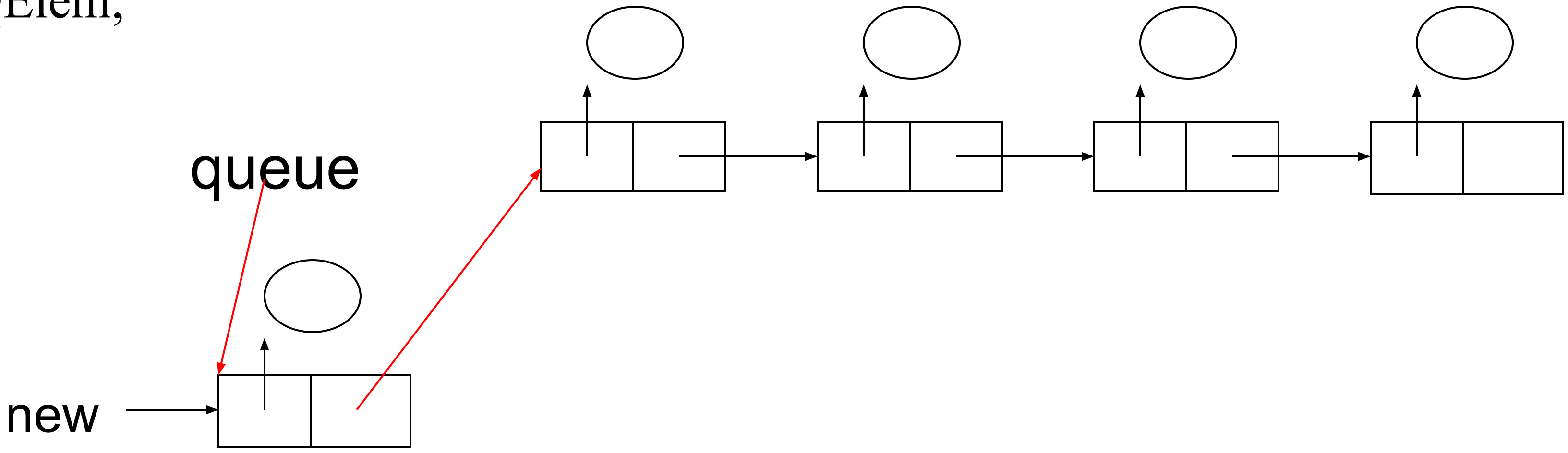


Possible data races?

```
QElem *queue;


void Insert(item) {
   QElem *new = malloc(sizeof(QElem));
   new->item = item;
   new->next = queue;
   queue = new;
}
```

Possible data races?

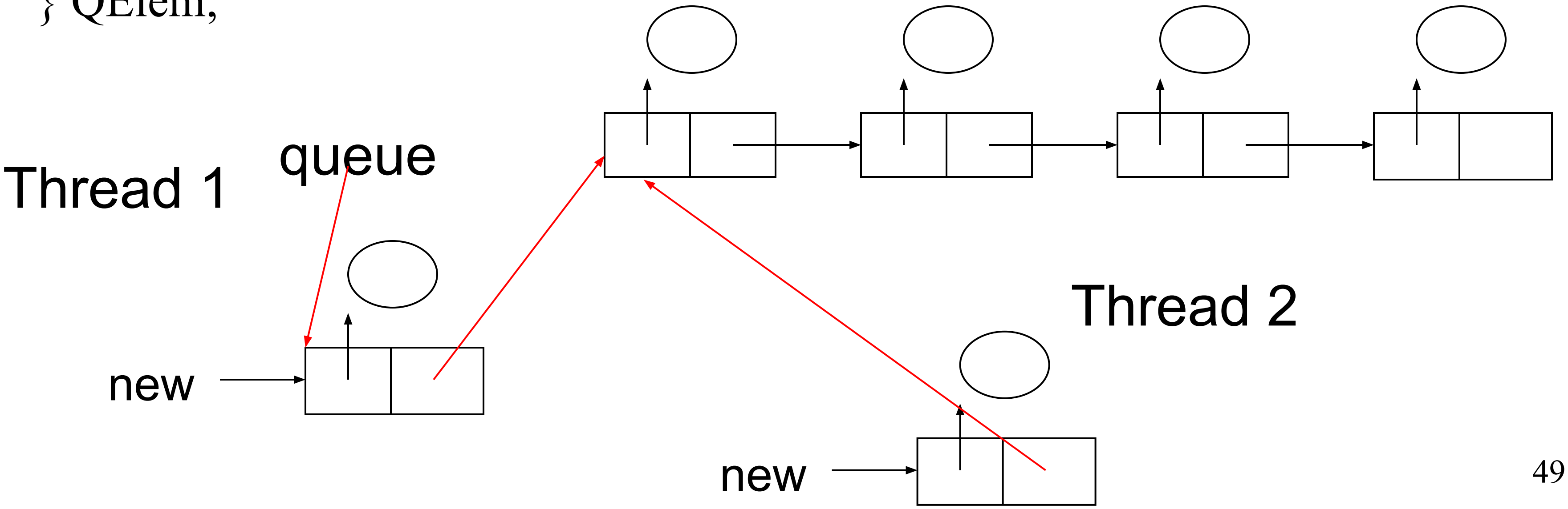
```
QElem *queue;


void Insert(item) {
   QElem *new = malloc(sizeof(QElem));
   new->item = item;
   new->next = queue;
   queue = new;
}
```

Data race

Simple queue insertion

```
typedef struct {
  QItem *item;
  QElem *next;
} QElem;
```



Simple queue insertion with xchg

```
QElem *queue;


void Insert(item) {
   QElem *new = malloc(sizeof(QElem));
   new->item = item;
   do {
         new->next = queue;
   } while (xchg(&queue, new) != new->next);
}
```

Wait free synchronization

- Example only works for simple data structures where changes can be committed with *one store instruction*

- Complex data structures need synchronization

Concurrency Bugs

Defects that occur because of not using or improperly using synchronization primitives.

- TOCTOU:
  - Time of check to time of use

TOCTOU

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

TOCTOU

Read

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

Write!

TOCTOU

Read

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

Write!

Time-of-check-to-time-of-use bug

TOCTTOU

TOCTOU

Read

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

Time of check

Write!

Time-of-check-to-time-of-use bug

TOCTTOU

TOCTOU

Read

```
Thread 1::
if (thd->proc_info) {   Time of check
  ...
  fputs(thd->proc_info, ...);   Time of use
  ...
}

Thread 2::
thd->proc_info = NULL;
```

Write!

Time-of-check-to-time-of-use bug

TOCTTOU

TOCTOU

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

thd_proc_info was not NULL

TOCTOU

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

thd_proc_info was not NULL

thd_proc_info becomes NULL

TOCTOU

```
Thread 1::
if (thd->proc_info) {
   ...
   fputs(thd->proc_info, ...);
   ...
}

Thread 2::
thd->proc_info = NULL;
```

thd_proc_info was not NULL

Uh-oh

...

thd_proc_info becomes NULL

Concurrency Bugs

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

Deadlocks

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

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

Deadlocks

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

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

Deadlocks

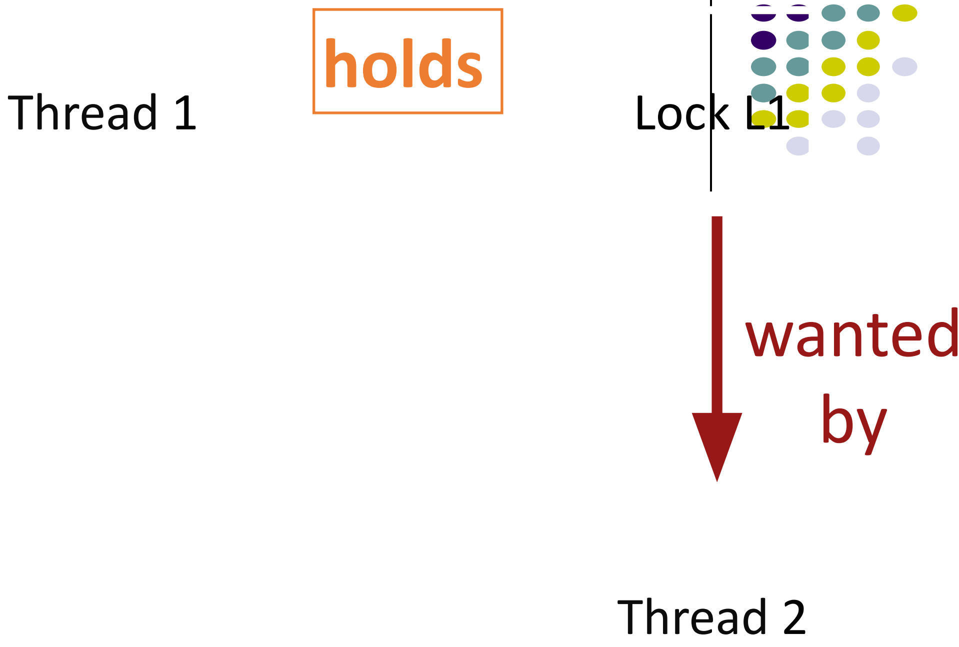
Thread 1 **holds** Lock L1

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

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

Deadlocks

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

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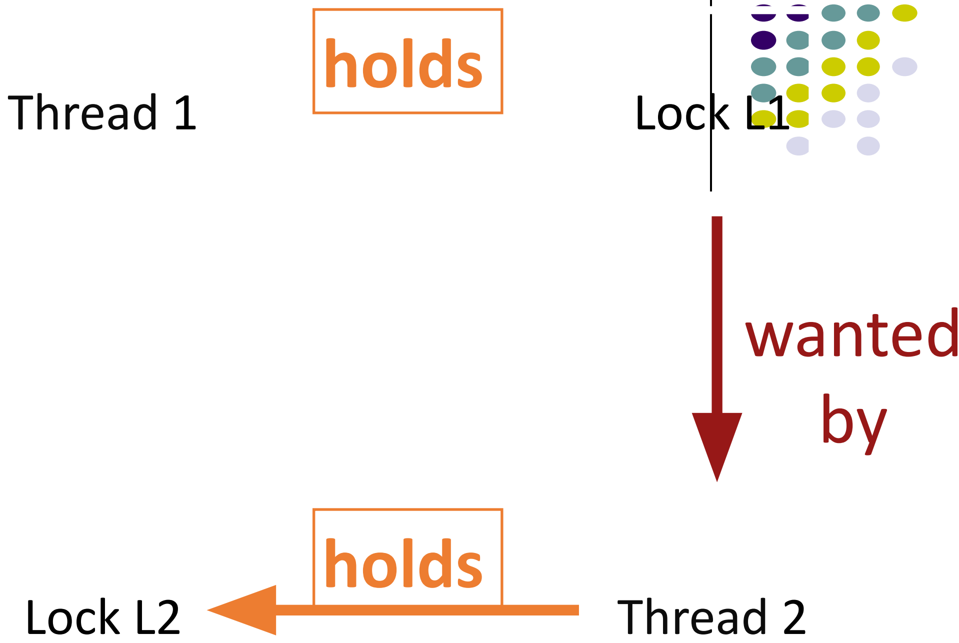
```

Deadlocks



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Thread 1:                  Thread 2:
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Deadlocks

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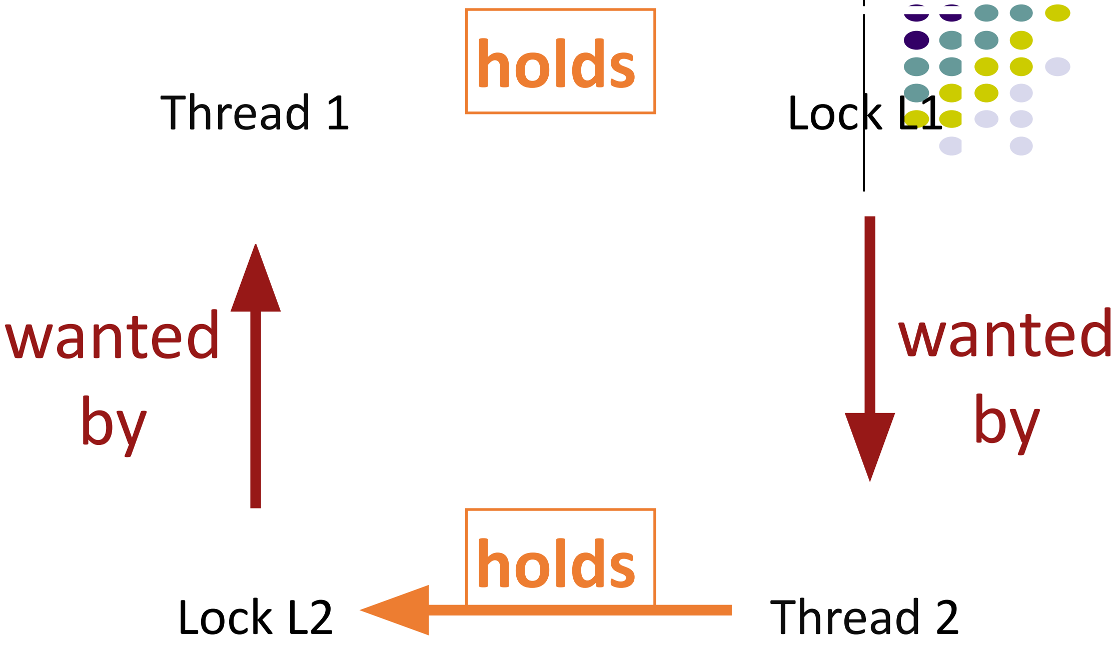


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pthread_mutex_lock(L1);    pthread_mutex_lock(L2);
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```
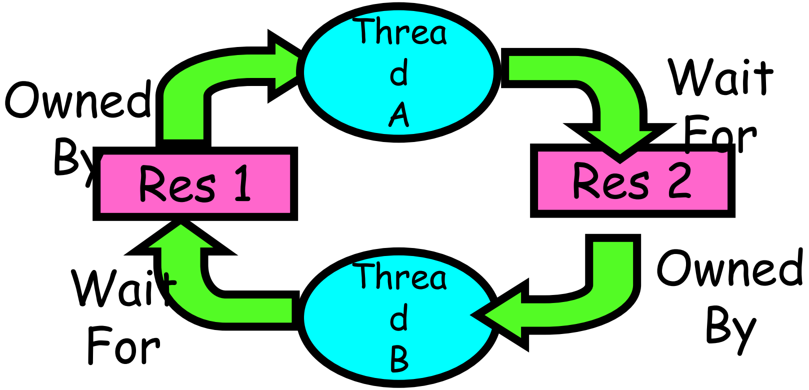

Starvation v/s Deadlock

- Starvation vs. Deadlock
  - Starvation: thread waits indefinitely
    - Example, low-priority thread waiting for resources constantly in use by high-priority threads
  - Deadlock: circular waiting for resources
    - Thread A owns Res 1 and is waiting for Res 2
      Thread B owns Res 2 and is waiting for Res 1



Starvation v/s Deadlock

- Deadlock ⇒ Starvation but not vice versa
  - Starvation can end (but doesn’t have to)
  - Deadlock can’t end without external intervention

Deadlocks can be hard to reason

```
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);
}
```

Scenario 1: Any problem?

Thread 1:

rv = set_intersection(setA, setB);

Thread 2:

rv = set_intersection(setA, setB);

Scenario 1: Any problem?

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);

Scenario 2: Any problem?

Thread 1:

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

Thread 2:

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

Scenario 2: Any 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!

Modelling Deadlock

- Resources
  - Resource types $R_1, R_2, \ldots, R_m$
    - *CPU cycles, memory space, I/O devices, mutex*
  - Each resource type R_i has W_i instances
  - *Preemptable:* can be taken away by scheduler, e.g. CPU
  - *Non-preemptable:* cannot be taken away, to be released voluntarily, e.g., mutex, disk, files, ...

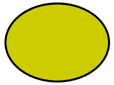
- Each process utilizes a resource as follows:
  - request
  - use
  - release

Modelling Deadlock: Resource allocation graph

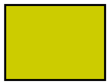
- A set of vertices V and a set of edges E
- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system
- request edge – directed edge $P_1 \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow P_i$

Modelling Deadlock

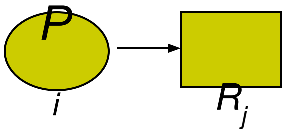
- Process



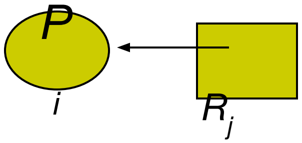
- Resource type



- P_i requests instance of R_j

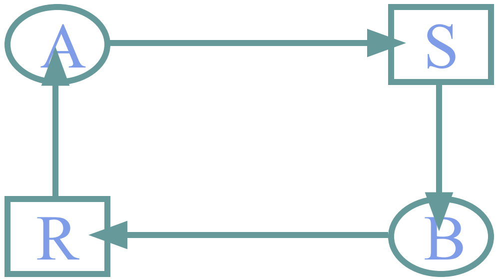


- P_i is holding an instance of R_j

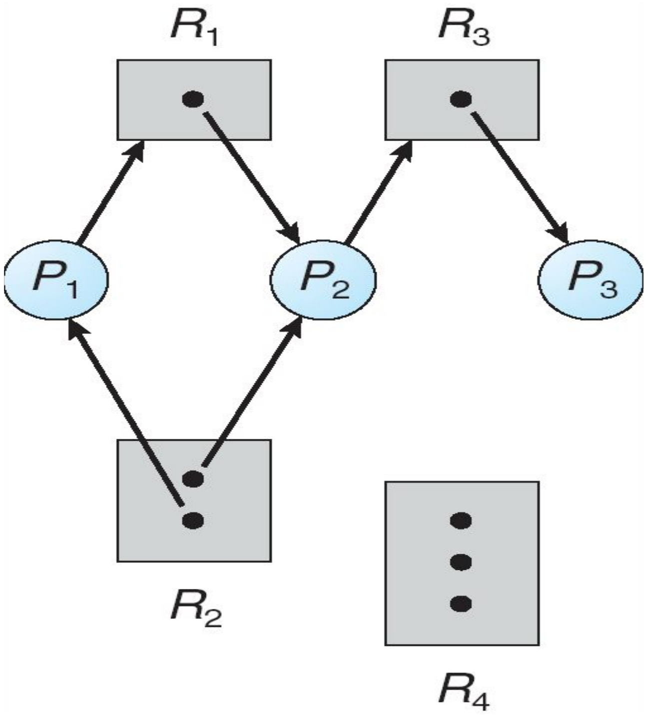


Cycle in resource allocation graph!?

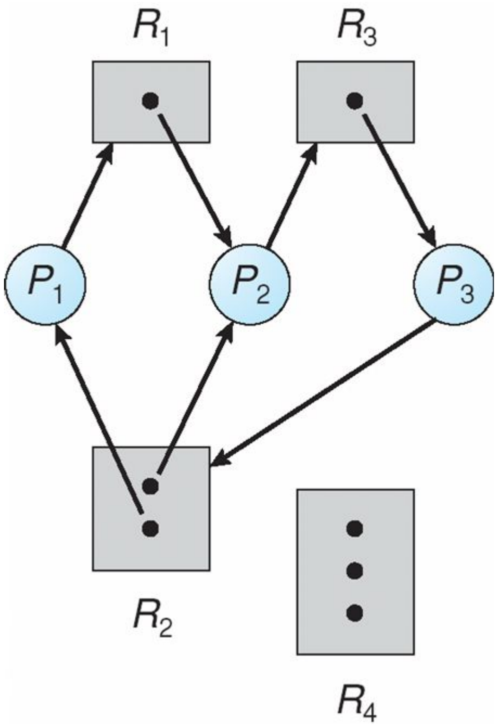
- What happens if there is a cycle in the resource allocation graph?



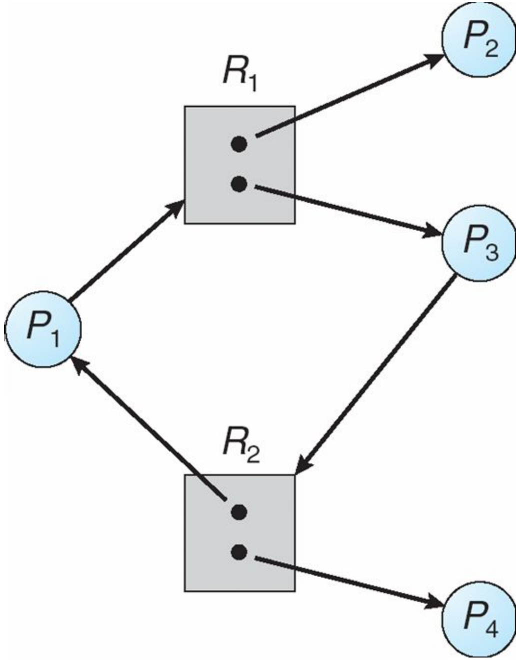
Is there a deadlock?



Is there a deadlock?



Is there a deadlock?



Modelling Deadlocks Using Resource allocation graphs

- If graph contains no cycles ⇒ no deadlock

- If graph contains a cycle ⇒
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock

Necessary conditions for a deadlock

- *Mutual exclusion*
  - Each resource instance is assigned to exactly one process
- *Hold and wait*
  - Holding at least one and waiting to acquire more
- *No preemption*
  - Resources cannot be taken away
- *Circular chain of requests*

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Resource nature

Program behavior

Necessary conditions for a deadlock

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Resource nature

Program behavior

Eliminating ***any*** condition eliminates deadlock!

Handling deadlock

1. Ignore the problem
   - It is user's fault
   - used by most operating systems, including UNIX
2. Detection and recovery (by OS)
   - Fix the problem afterwards
3. Dynamic avoidance (by OS & programmer)
   - Careful allocation
4. Prevention (by programmer & OS)
   - Negate one of the four conditions

2. Detect and Recovery

- Programmer does nothing
- Allow system to enter deadlock state
- Run some detection algorithm
  - E.g., build a resource graph to check for cycles
- Try to recover somehow
  - E.g., reboot the machine

3. Dynamic Avoidance

Definition:

An algorithm that is run by the OS whenever a process requests resources, the algorithm avoids deadlock by <u>denying or postponing</u> the request

if

it finds that accepting the request <u>could</u> put the system in an <u>unsafe state</u> (one where deadlock could occur).

3. Dynamic Avoidance

- Requirement:
  - each process <u>declares</u> the *maximum number* of resources of each type it *may* need

- Key idea:
  - The deadlock-avoidance algorithm <u>dynamically</u> examines the <u>resource-allocation state</u> to ensure there can never be a deadlock condition
  - *No matter what future requests will be*

3. Dynamic Avoidance

- Needs to know the entire set of tasks that must be run and the locks that they need
- Reduce concurrency
- Not used widely in practice
  - E.g., used in embedded systems

4. Preventing deadlock

- *Mutual exclusion*
  - Each resource instance is assigned to exactly one process
- *Hold and wait*
  - Holding at least one and waiting to acquire more
- *No preemption*
  - Resources cannot be taken away
- *Circular chain of requests*

Eliminating ***any*** condition eliminates deadlock!

Eliminating 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);
```

Eliminating 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);
}
```

Summary

- Need to be careful while using synchronization primitives
- Concurrency bugs: improper use of synchronization primitives