CS3281 / CS5281

Concurrency Bugs

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**Some lecture slides borrowed and adapted from "Operating Systems: 3 Easy Pieces" and CMU's "Computer Systems: A Programmer's Perspective"*

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Non-Deadlock Bugs: Atomicity Violation

- Thread 1 is interrupted before it runs fputs() function
- Dereference the null pointer exception inside fputs()
- Memory access (thd->proc_info) needs to be protected

```
Thread1::
if(thd->proc_info){
   …
   fputs(thd->proc_info , …);
   …
}

Thread2::
thd->proc_info = NULL;
```

Non-Deadlock Bugs: Atomicity Violation

- Fix: place thd->proc_info within lock and unlock routines

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

Thread1::
pthread_mutex_lock(&lock);
if(thd->proc_info){
     …
     fputs(thd->proc_info , …);
     …
}
pthread_mutex_unlock(&lock);

Thread2::
pthread_mutex_lock(&lock);
thd->proc_info = NULL;
pthread_mutex_unlock(&lock);
```

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Non-Deadlock Bugs: Order Violation

- Thread 2 runs before Thread 1
  - mThread is not initialized
  - Null-pointer dereference

```
Thread1::
void init(){
     mThread = PR_CreateThread(mMain, …);
}

Thread2::
void mMain(…){
     mState = mThread->State
}
```

Non-Deadlock Bugs: Order Violation

- Fix: Use condition variables
- Enforce the order of execution between memory accesses

```
pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
int mtInit = 0;

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);
    …
}

Thread2::
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;
    …
}
```

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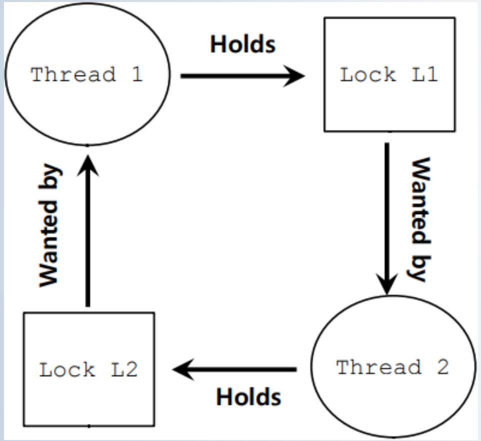
Deadlock

- Def: A process is *deadlocked* iff it is waiting for a condition that will never be true

- Typical Scenario
  - Processes 1 and 2 needs two resources (A and B) to proceed
  - Process 1 acquires A, waits for B
  - Process 2 acquires B, waits for A
  - Both will wait forever!

Deadlock Bugs

- Deadlock: A thread holds a lock and waits for another lock.



Thread 1:
pthread_mutex_lock (L1);
context switch to Thread 2
pthread_mutex_lock (L2);

Thread 2;
pthread_mutex_lock (L2);

pthread_mutex_lock (L1);

Deadlock Bugs

- Encapsulation does not work well with locking
- Vector class in Java

Thread 1:	*Thread 2*:
Vector v1, v2;	
v1.addAll (v2);	v2.addAll (v1);

- *addAll*() needs to be thread safe.
- Thread 1 acquires a lock for v1.
- Thread 2 acquires a lock for v2 at the same time.

Deadlock Bugs

- Conditions for deadlocks
  - Mutual exclusion: Thread grabs a lock
  - Hold-and-wait: Thread holds the lock and waits to acquire an additional lock
  - No preemption: Lock that is held cannot be taken away from the thread
  - Circular wait: *hold-and-wait* for a circular chain of threads

- Deadlock does not occur if ***any*** of the above conditions is not met

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Deadlock Bugs

- Prevention for: Circular Wait
  - Total ordering (two locks): acquire L1 before L2
  - Partial ordering (multiple locks): group lock acquisition ordering
    - E.g., acquire L1 before L2, acquire L3 before L4

- Prevention for: Hold-and-Wait
  - Acquire all locks at once
    - pthread_mutex_lock (prevention);
    - pthread_mutex_lock (L1);
    - pthread_mutex_lock (L2);
    - …
    - pthread_mutex_unlock (prevention);
  - Disadvantage: decrease concurrency

Deadlock Bugs

- Prevention for: No Preemption
- Use pthread_mutex_trylock()
  - Acquire lock if it is available or return an error code (lock is already held)
  - Preemption: release the ownership of a lock

```
top:
    lock(L1);
    if( tryLock(L2) == -1 ){
            unlock(L1);
            goto top;
    }
```

- Livelock
  - Another thread holds L2 and attempts to acquire L1.
  - Both threads execute their code blocks at the same time.
- Solution: adding a random delay before jumping back

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Deadlock Bugs

- Problems with trylock
  - Memory allocated after acquiring L1 should be released when acquiring L2 fails.
  - trylock does not preempt the ownership of a lock. It allows a thread to give back the ownership voluntarily.

Deadlock Bugs

- Prevention for: Mutual Exclusion
  - Lock-free data structures
- Create atomic functions based on hardware instructions

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

```
void AtomicIncrement(int *value, int amount){
    do{
            int old = *value;
    }while( CompareAndSwap(value, old, old+amount)==0);
}
```

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Deadlock Bugs

- List insertion
- Race condition occurs if called by multiple threads

```
void insert(int value){
     node_t * n = malloc(sizeof(node_t));
     assert( n != NULL );
     n->value = value ;
     n->next  = head;
     head     = n;
}
```

interrupt

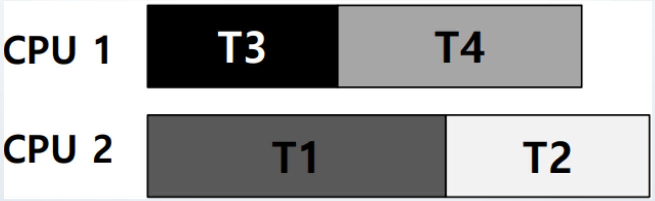
```
void insert(int value) {
    node_t *n = malloc(sizeof(node_t));
    assert(n != NULL);
    n->value = value;
    do {
            n->next = head;
    } while (CompareAndSwap(&head, n->next, n) == 0);
}
```

Deadlock Bugs

- Avoid deadlock
- Find out what locks are acquired by what threads

	T1	T2	T3	T4
L1	yes	yes	no	no
L2	yes	yes	yes	no

- Scheduler does not run T1 and T2 at the same time.
- T3 grabs only one lock. It can run with T1.



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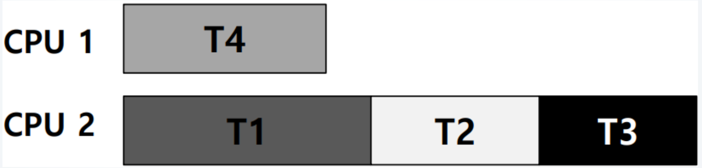
Deadlock Bugs

	T1	T2	T3	T4
L1	yes	yes	yes	no
L2	yes	yes	yes	no



- Decrease concurrency
- Trade-off between performance and deadlock avoidance
- It's impractical to gain a priori knowledge of lock acquisition for most applications.

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Deadlocking with Semaphores

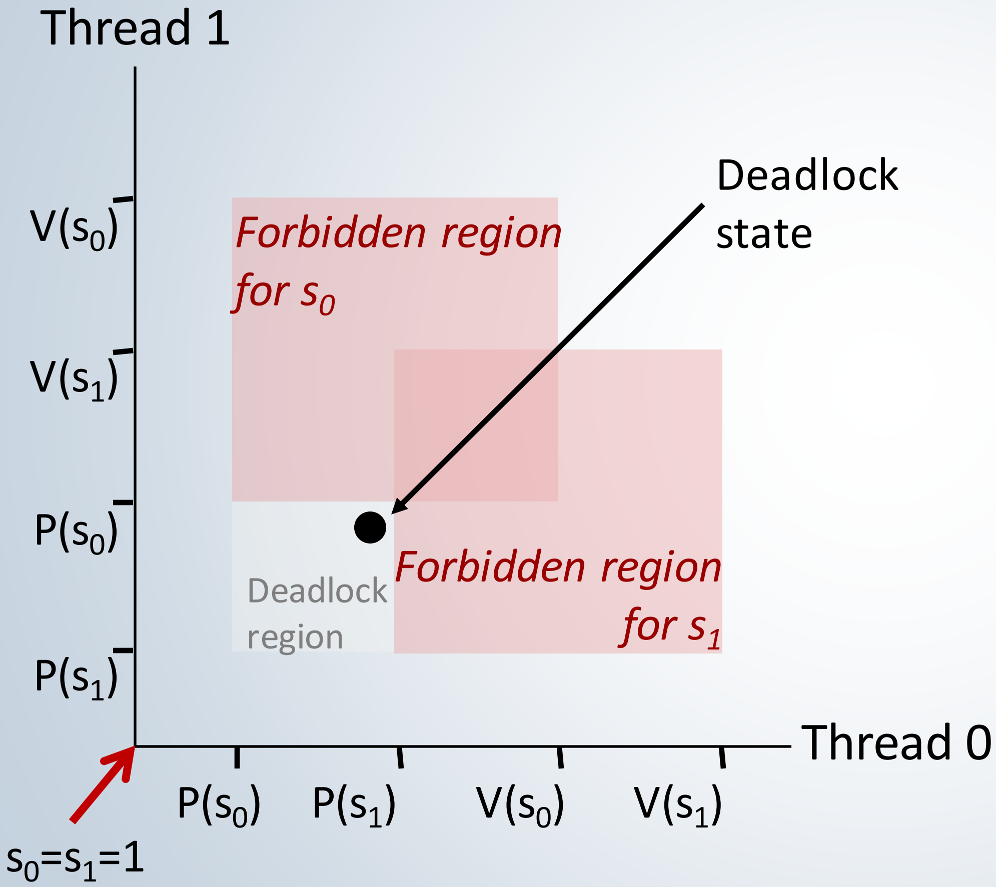
```
int main()
{
   pthread_t tid[2];
   Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
   Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
   Pthread_create(&tid[0], NULL, count, (void*) 0);
   Pthread_create(&tid[1], NULL, count, (void*) 1);
   Pthread_join(tid[0], NULL);
   Pthread_join(tid[1], NULL);
   printf("cnt=%d\n", cnt);
   exit(0);
}
```

```
void *count(void *vargp)
{
   int i;
   int id = (int) vargp;
   for (i = 0; i < NITERS; i++) {
          P(&mutex[id]); P(&mutex[1-id]);
          cnt++;
          V(&mutex[id]); V(&mutex[1-id]);
   }
   return NULL;
}
```

Tid[0]:
$P(s_0)$;
$P(s_1)$;
cnt++;
$V(s_0)$;
$V(s_1)$;

Tid[1]:
$P(s_1)$;
$P(s_0)$;
cnt++;
$V(s_1)$;
$V(s_0)$;

Deadlock Visualization in a Progress Graph



Locking introduces the potential for *deadlock:* waiting for a condition that will never be true

Any trajectory that enters the *deadlock region* will eventually reach the *deadlock state*, waiting for either s_0 or s_1 to become nonzero

Other trajectories luck out and skirt the deadlock region

Unfortunate fact: deadlock is often nondeterministic (race)

Avoiding Deadlock

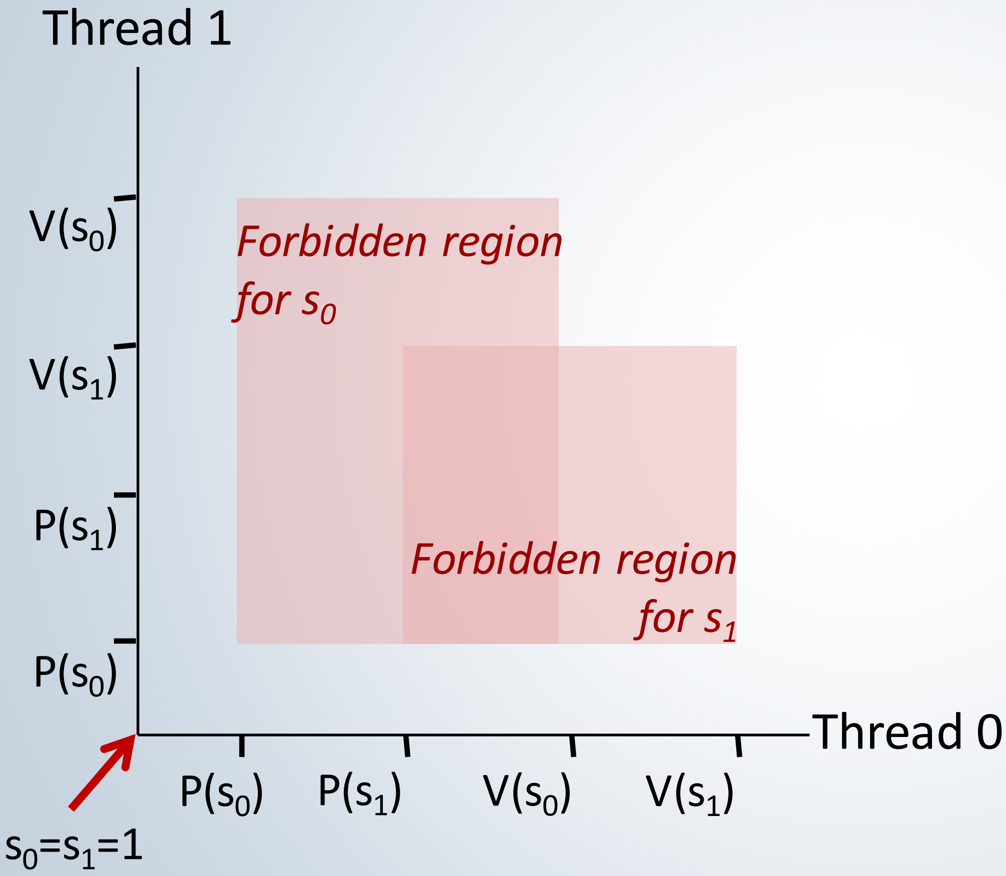
```c
int main()
{
    pthread_t tid[2];
    Sem_init(&mutex[0], 0, 1);  /* mutex[0] = 1 */
    Sem_init(&mutex[1], 0, 1);  /* mutex[1] = 1 */
    Pthread_create(&tid[0], NULL, count, (void*) 0);
    Pthread_create(&tid[1], NULL, count, (void*) 1);
    Pthread_join(tid[0], NULL);
    Pthread_join(tid[1], NULL);
    printf("cnt=%d\n", cnt);
    exit(0);
}
```

```c
void *count(void *vargp)
{
    int i;
    int id = (int) vargp;
    for (i = 0; i < NITERS; i++) {
        P(&mutex[0]); P(&mutex[1]);
     cnt++;
     V(&mutex[id]); V(&mutex[1-id]);
    }
    return NULL;
}
```

```
Tid[0]:
P(s0);
P(s1);
cnt++;
V(s0);
V(s1);
```

```
Tid[1]:
P(s0);
P(s1);
cnt++;
V(s1);
V(s0);
```

Avoiding Deadlock in a Progress Graph



No way for trajectory to get stuck

Processes acquire locks in same order

Order in which locks released immaterial

Summary

- Common solutions for deadlocks
  - Prevent deadlock
    - Order lock acquisition
    - Acquire lock atomically
    - Release lock voluntarily
    - Build lock-free atomic operations
  - Avoid deadlock
    - Schedule threads with global knowledge of lock acquisitions