Operating Systems

Lecture 26: Semaphores Revision + Common Concurrency Problems

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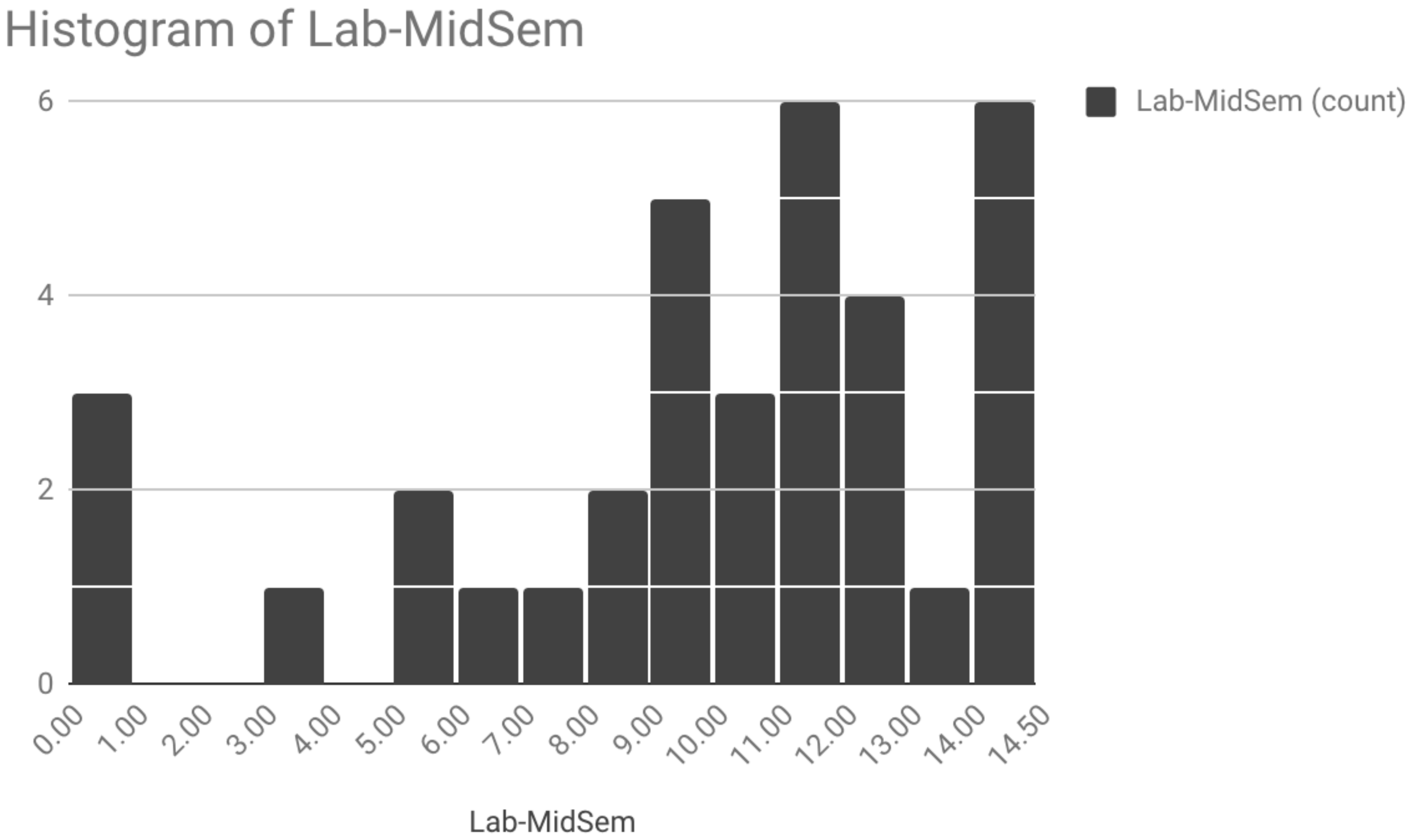
Nov 1, 2018


Histogram of Lab-MidSem
Lab-MidSem (count)
0
2
4
6
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
14.00
14.50
Lab-MidSem

Administrative

- Feedback from lab quiz?
  - How to run it better?
  - Automated checkers?
    - How?
- Assignment deadline postponed to 6th noon
- Quiz 3 on Mon, 12th November?
  - Will give the syllabus in writing, no additional questions entertained
- Project grading:
  - Second round of project grading:
    - 12th and 16th Nov
  - Third and final round:
    - 19th and 23rd Nov

Condition Variables

- **wait (cond_t *cv, mutex_t *lock)**
  - Assumes lock is held when wait() is called
  - Puts caller to sleep + atomically releases lock
  - When awoken, reacquires lock before returning
- **signal (cond_t *cv)**
  - Wake a single waiting thread
  - If there is no waiting thread, just return, do nothing

Condition Variables **wait** Pseudocode

- **wait (cond_t *cv, mutex_t *lock)**
  - Assume lock is held initially
  - pthread_mutex_unlock(lock)
  - block_on_condition(cv)
  - Move from Ready to Waiting/Blocked State
  - Move to Ready State
  - pthread_mutex_lock(lock)

Condition Variables **wait** Pseudocode

Which of these are atomic?

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Atomic

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Atomic

Signal

When does wait return?

Condition Variables **wait** Pseudocode

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When does wait return?
When lock has been acquired.

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When does wait return?
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What if some other thread holds the lock — block!

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Atomic

Signal

When does wait return?
When lock has been acquired.
What if some other thread holds the lock — block!

Why do we need to lock again?

Exercise: order using condition variables
Correct Solution

```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    thread_join()
    printf("parent: end\n");
    return 0; }
```

Exercise: order using condition variables Correct Solution

```
void thread_exit {
    mutex_lock(&m)
    Done  = 1
    cond_signal(&c)
    mutex_unlock(&m)
```

```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
      Pthread_create(&c, NULL, child, NULL); // create child
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      printf("parent: end\n");
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```

Exercise: order using condition variables
Correct Solution

```
void thread_exit {
    mutex_lock(&m)
    Done  = 1
    cond_signal(&c)
    mutex_unlock(&m)
```

```
void thread_join {
    mutex_lock(&m)              //w
    while (done==0)             //x
        cond_wait(&c, &m)       //y
    mutex_unlock(&m) }          //z
```

```
void *child(void *arg) {
    printf("child\n");
    thread_exit()
    return NULL; }

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    thread_join()
    printf("parent: end\n");
    return 0; }
```

Exercise: Build a lock using semaphores

```
sem_t m;
sem_init(&m, 0, 1);

sem_wait(&m);
//critical section here
sem_post(&m);
```

Refresher Notes

```
int sem_wait(sem_t *s) {
  s->value -= 1
    wait if s->value <0
}
```

```
int sem_post(sem_t *s) {
    s->value += 1
    wake one waiting thread if any
}
```

Value	Thread 0	State	Thread 1	State	T2	State

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1		Running		Ready		Ready

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Can T1 run before sem_post returns?

NO!

Semaphores Implementation

Semaphores Implementation

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API	Our implementation

`#include <semaphore.h>`
`sem_t s;`	

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API

```
#include <semaphore.h>
sem_t s;
```

Our implementation

```
typedef struct __Zem_t {
  int value;
  pthread_cond_t cond;
  pthread_mutex_t lock;
} Zem_t;

```

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API

```
int sem_init(sem_t *s, int init_val) {
  s->value=init_val;
  }
```

Our implementation

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API

```
int sem_init(sem_t *s,
int init_val) {
    s->value=init_val;
    }
```

Our implementation

```
// only one thread can call this
void Zem_init(Zem_t *s, int value) {
    s->value = value;
    Cond_init(&s->cond);
    Mutex_init(&s->lock);
}
```

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API

```
int sem_post(sem_t *s) {
    s->value += 1
    wake one waiting thread if any
}
```

Our implementation

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Atomic operation

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int sem_post(sem_t *s) {
    s->value += 1
    wake one waiting thread if any
}
```

Atomic operation

Our implementation

```
void Zem_post(Zem_t *s) {
    Mutex_lock(&s->lock);
    s->value++;
    Cond_signal(&s->cond);
    Mutex_unlock(&s->lock);
}
```

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- Any critical section should require **locking**
- **Signal** and **Wait** on condition
- Don’t maintain the invariant that the value of the semaphore, when negative, reflects the number of waiting threads

API	Our implementation

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API	Our implementation

`int sem_wait(sem_t *s) {`
`  s->value -= 1`
`   wait if s->value <0`
`}`	

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Atomic operation

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```
int sem_wait(sem_t *s) {
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   wait if s->value <0
}
```

Atomic operation

Our implementation

```
void Zem_wait(Zem_t *s) {

  Mutex_lock(&s->lock);
  while (s->value <= 0)
    Cond_wait(&s->cond, &s->lock);
  s->value--;
  Mutex_unlock(&s->lock);
}
```

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- Any critical section should require **locking**
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```

Should it be ==0?

Value	Thread 0	State	Thread 1	State	T2	State

Value	Thread 0	State	Thread 1	State	T2	State
1		Running		Ready		Ready

Value	Thread 0	State	Thread 1	State	T2	State
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1	call zem_wait()	Running		Ready		Ready

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1	Increments zem	Running				

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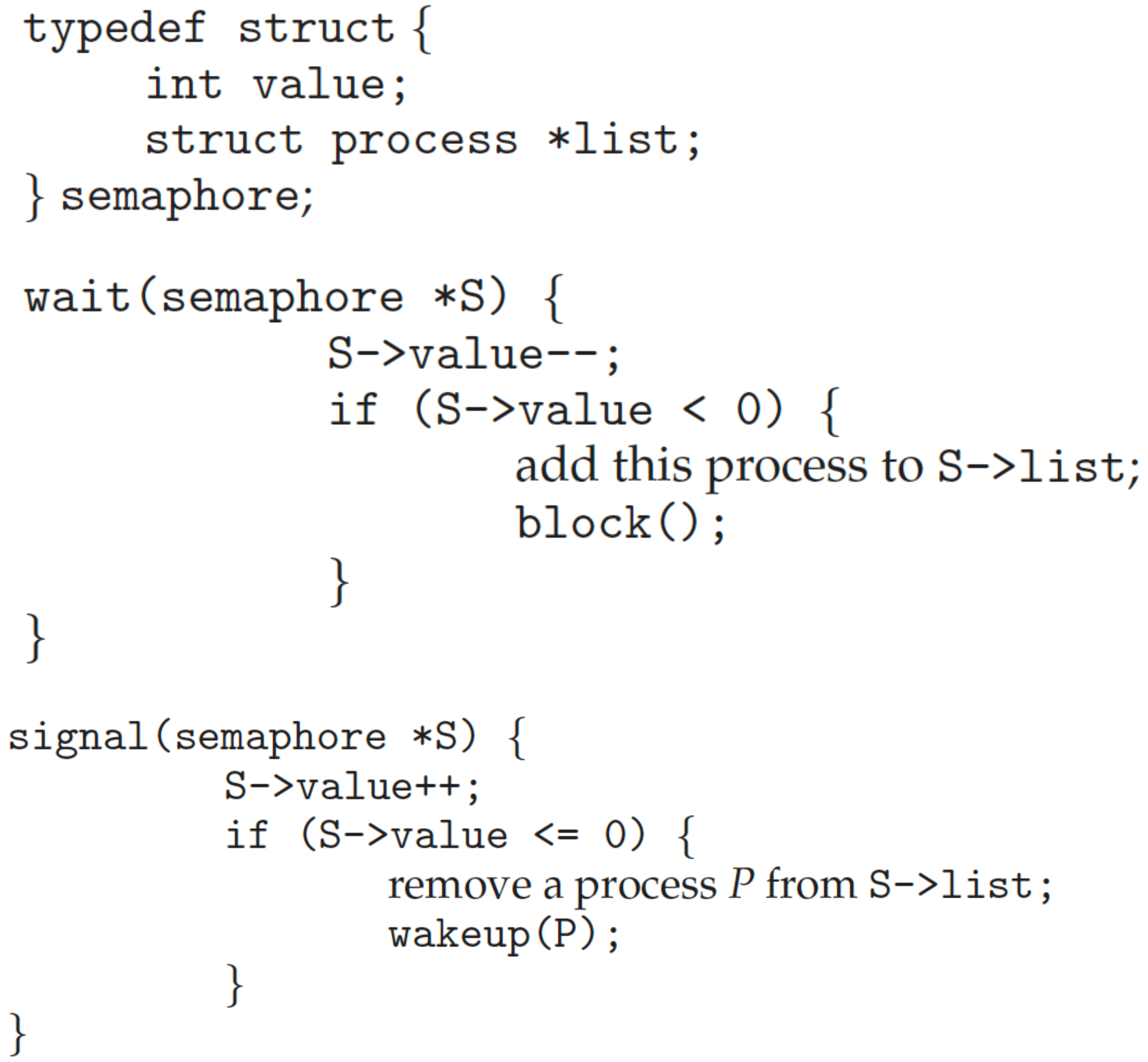
0	call sem_post()	Running		sleeping		
	Acquires lock	Running				
1	Increments zem	Running				
1	Wakes up thread T1	Running		Ready		
			Condition wait will return once it gets lock	Ready		
1	zem_post() returns	Running		Ready		
0			Zem = zem - 1	Running		

Another Implementation …

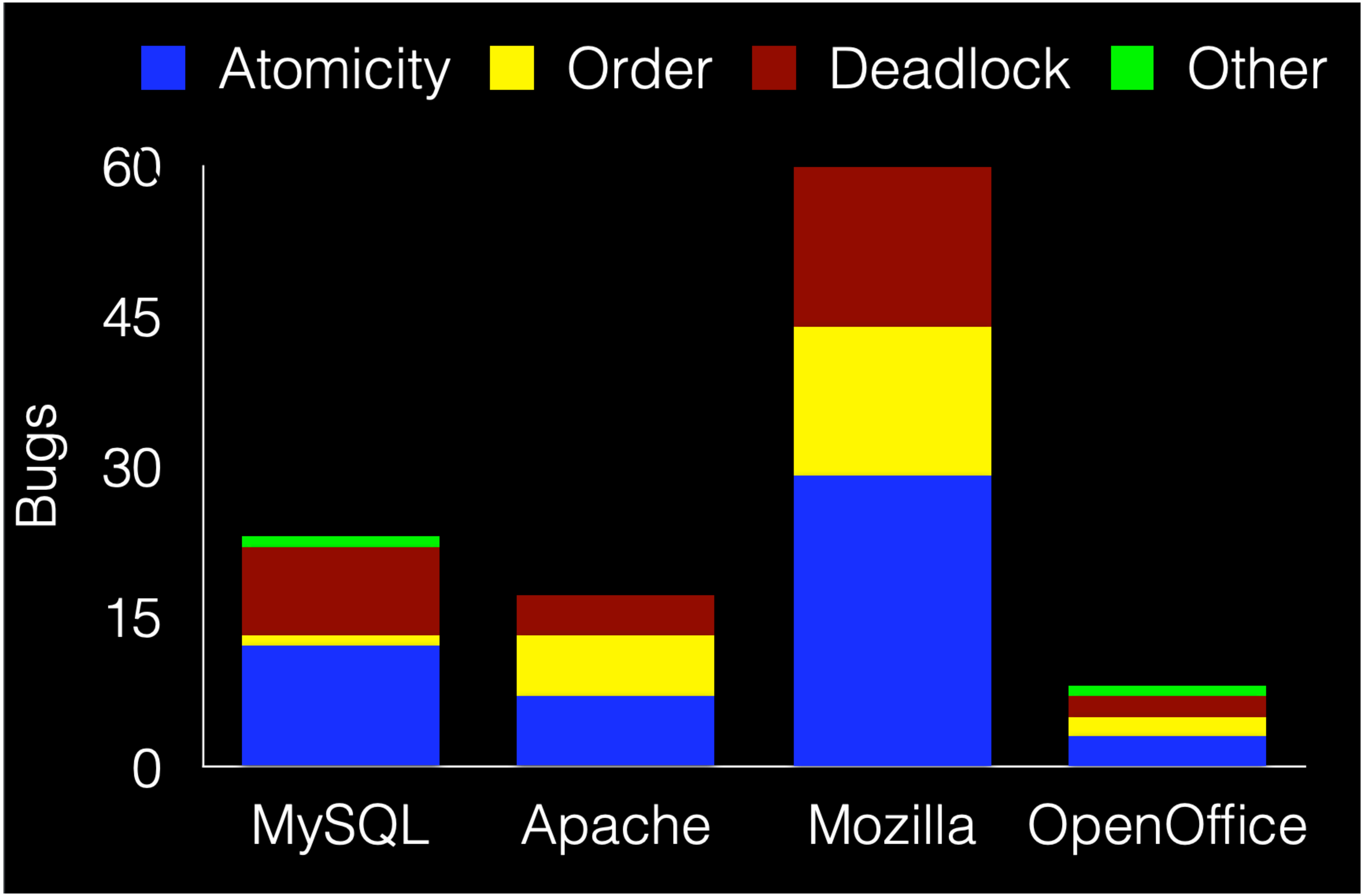


```
typedef struct {
     int value;
     struct process *list;
} semaphore;

wait(semaphore *S) {
             S->value--;
             if (S->value < 0) {
                     add this process to S->list;
                     block();
             }
}

signal(semaphore *S) {
          S->value++;
          if (S->value <= 0) {
                  remove a process P from S->list;
                  wakeup(P);
          }
}
```

Concurrency Bugs



Types of bugs in 4 major projects from 500K bug reports

Concurrency Bugs — Atomicity

Concurrency Bugs — Atomicity

MySQL bug …

Concurrency Bugs — Atomicity

MySQL bug …

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

Concurrency Bugs — Atomicity

MySQL bug …

```
Thread1::
if(thd->proc_info){
  …
  fputs(thd->proc_info , …);
…
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```
Thread2::
thd->proc_info = NULL;
```

Concurrency Bugs — Atomicity

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- Is this problematic?

Concurrency Bugs — Atomicity

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- Is this problematic?
    - Yes, else we wouldn’t be discussing …

Concurrency Bugs — Atomicity

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```

- Is this problematic?
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  - How?

Concurrency Bugs — Atomicity

```
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);
```

Concurrency Bugs — Atomicity

Simple Solution

```
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);
```

Concurrency Bugs — Order Violation

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

```

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

Concurrency Bugs — Order Violation

Mozilla bug …

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void mMain(...){
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Concurrency Bugs — Order Violation

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

Concurrency Bugs — Order Violation

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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);
  ...
}
```

Concurrency Bugs — Order Violation

```
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;
}
```

Concurrency Bugs — Deadlock

Concurrency Bugs — Deadlock

Thread 1

Lock(L1);

Lock(L2);

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1

Concurrency Bugs — Deadlock

Thread 1

```
Lock(L1);
Lock(L2);
```

Thread 2

```
Lock(L2);
Lock(L1);
```

- Thread T1 gets Lock L1
- Thread T1 gets Lock L2

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Thread T1 gets Lock L2
- Thread T1 completes critical section

Concurrency Bugs — Deadlock

Thread 1

```
Lock(L1);
Lock(L2);
```

Thread 2

```
Lock(L2);
Lock(L1);
```

- Thread T1 gets Lock L1
- Thread T1 gets Lock L2
- Thread T1 completes critical section
- Context Switch

Concurrency Bugs — Deadlock

Thread 1

```
Lock(L1);
Lock(L2);
```

Thread 2

```
Lock(L2);
Lock(L1);
```

- Thread T1 gets Lock L1
- Thread T1 gets Lock L2
- Thread T1 completes critical section
- Context Switch
- Thread T2 gets Lock L2 and Lock L1

Concurrency Bugs — Deadlock

Thread 1

```
Lock(L1);
Lock(L2);
```

Thread 2

```
Lock(L2);
Lock(L1);
```

- Thread T1 gets Lock L1
- Thread T1 gets Lock L2
- Thread T1 completes critical section
- Context Switch
- Thread T2 gets Lock L2 and Lock L1
- Works :)

Concurrency Bugs — Deadlock

Concurrency Bugs — Deadlock

Thread 1

```
Lock(L1);
Lock(L2);
```

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2
- Context Switch

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2
- Context Switch
- Thread T1 waits since it doesn’t have Lock 2

Concurrency Bugs — Deadlock

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2
- Context Switch
- Thread T1 waits since it doesn’t have Lock 2
- Context Switch

Concurrency Bugs — Deadlock

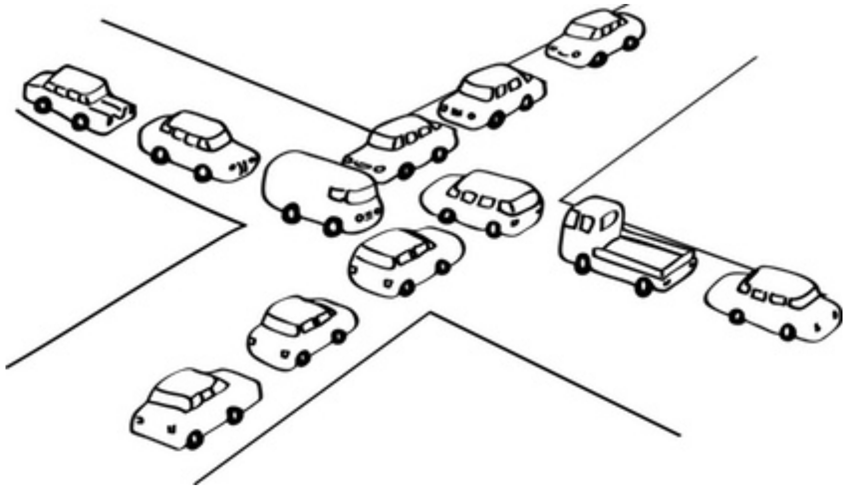
Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2
- Context Switch
- Thread T1 waits since it doesn’t have Lock 2
- Context Switch
- Thread t2 waits since it doesn’t have Lock 1

Concurrency Bugs — Deadlock

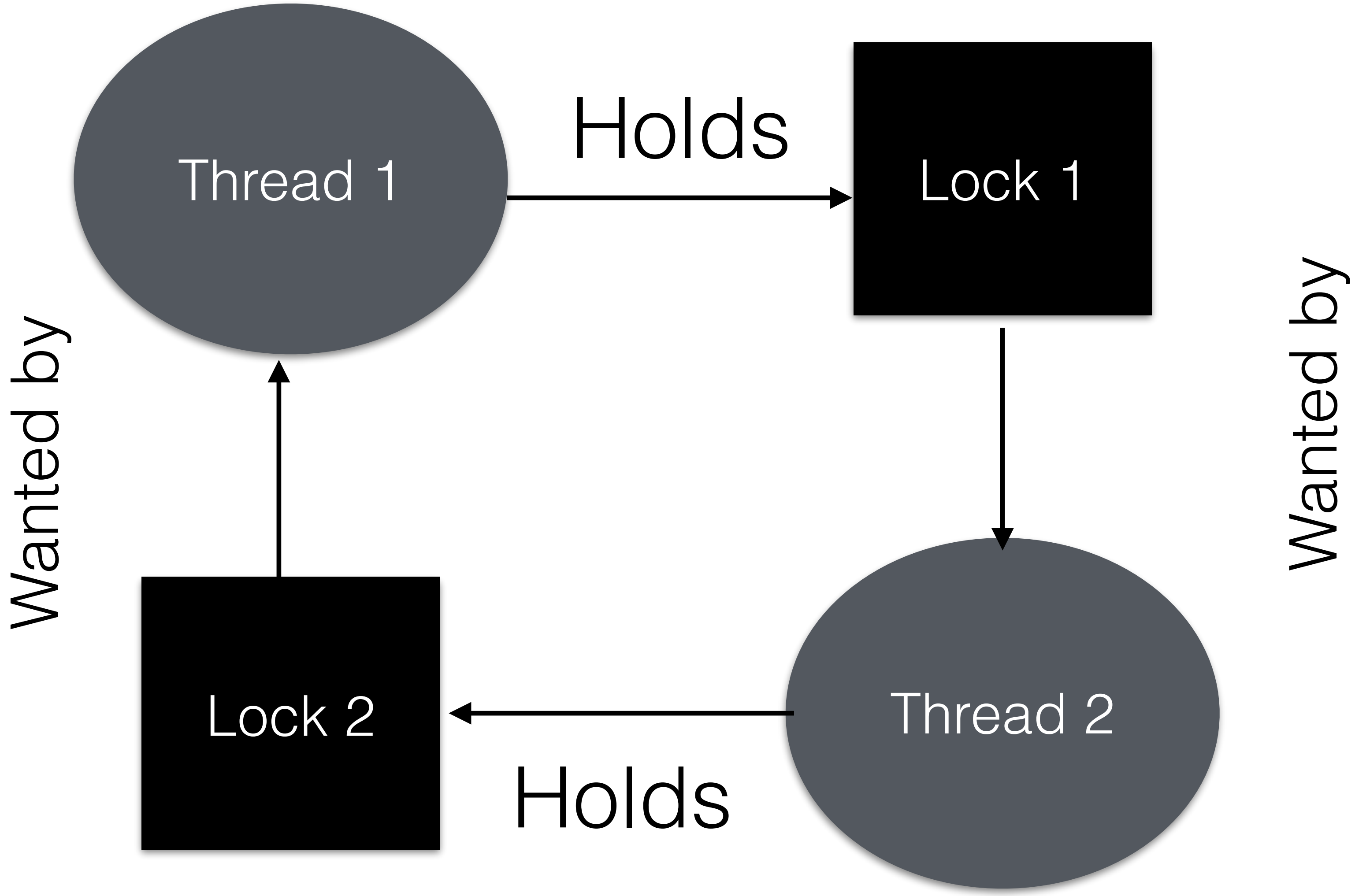
Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);

- Thread T1 gets Lock L1
- Context Switch
- Thread T2 gets Lock L2
- Context Switch
- Thread T1 waits since it doesn’t have Lock 2
- Context Switch
- Thread t2 waits since it doesn’t have Lock 1



Concurrency Bugs — Deadlock
Dependency Graphs

Thread 1	**Thread 2**
Lock(L1);	Lock(L2);
Lock(L2);	Lock(L1);



Why Deadlocks Occur

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- Encapsulation

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  - Example: Java vector addAll method

Why Deadlocks Occur

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    - V1 = [1, 4, 5]

Why Deadlocks Occur

- Encapsulation
  - Example: Java vector addAll method
    - V1 = [1, 4, 5]
    - V2 = [6, 7, 8]

Why Deadlocks Occur

- Encapsulation
  - Example: Java vector addAll method
    - V1 = [1, 4, 5]
    - V2 = [6, 7, 8]
    - V1.addAll(V2) —> [1, 4, 5, 6, 7, 8]

Why Deadlocks Occur

- Encapsulation
  - Example: Java vector addAll method
    - V1 = [1, 4, 5]
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    - V1.addAll(V2) —> [1, 4, 5, 6, 7, 8]
    - If addAll is multithreaded & assuming it locks V1, V2 in that order

Why Deadlocks Occur

- Encapsulation
    - Example: Java vector addAll method
        - V1 = [1, 4, 5]
        - V2 = [6, 7, 8]
        - V1.addAll(V2) —> [1, 4, 5, 6, 7, 8]
        - If addAll is multithreaded & assuming it locks V1, V2 in that order
        - If some thread all calls V2.add(V1), we have a deadlock!

Why Deadlocks Occur

- Encapsulation
  - Example: Java vector addAll method
    - V1 = [1, 4, 5]
    - V2 = [6, 7, 8]
    - V1.addAll(V2) —> [1, 4, 5, 6, 7, 8]
    - If addAll is multithreaded & assuming it locks V1, V2 in that order
    - If some thread all calls V2.add(V1), we have a deadlock!
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  - Filesystem calls virtual memory

Concurrency Bugs — Deadlock
Dependency Graphs

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Condition	Description

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Mutual Exclusion	Threads claim exclusive control of resources that they require.

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Preventing Circular Wait

Thread 1

```
Lock(L1);
Lock(L2);
```

Deadlock Version

Thread 2

```
Lock(L2);
Lock(L1);
```

Preventing Circular Wait

- Provide a total ordering of lock acquisition

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Thread 1

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Non-deadlock Version

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do something(mutex t *m1, mutex t *m2)
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Preventing Circular Wait

- Provide a total ordering of lock acquisition
- Define a function do_something which works correct even if two threads call it as:
  - T1 — do_something (L1, L2) and
  - T2 — do_something (L2, L1)

```
do something(mutex t *m1, mutex t *m2)
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); }
// Code assumes that m1 != m2 (it is not the same lock)
```

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Preventing Hold and Wait

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Deadlock Version

<u>Thread 2</u>

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Lock(L2);
Lock(L1);
```

Preventing Hold and Wait

- Acquire **all** locks **at once atomically**

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Thread 1

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Lock(L1);
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Preventing Hold and Wait

- Acquire **all** locks **at once atomically**

Deadlock Version

Thread 1

Lock(L1);
Lock(L2);

Thread 2

Lock(L2);
Lock(L1);

Non-deadlock Version

Thread 1

Lock(ALL)
Lock(L1);
Lock(L2);
…..
Unlock(ALL);

Thread 2

Lock(ALL)
Lock(L1);
Lock(L2);
…
Unlock(ALL)

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- Acquire **all** locks **at once atomically**

Thread 1
Lock(ALL)
Lock(L1);
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Non-deadlock Version

Thread 2
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- Acquire **all** locks **at once atomically**
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  - Requires us to know which all locks will be required ahead of time

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Preventing Hold and Wait

- Acquire **all** locks **at once atomically**
- Cons
  - Requires us to know which all locks will be required ahead of time
  - Reduction of concurrency

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…..
Unlock(ALL);

Non-deadlock Version

Thread 2
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Lock(L2);
Lock(L1);
```

Non-deadlock Version

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

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Pre-emption

- Livelock: Both threads running this sequence repeatedly

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Lock(L2);

<u>Thread 2</u>

Lock(L2);

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Pre-emption

- Livelock: Both threads running this sequence repeatedly
- How to solve?

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Pre-emption

- Livelock: Both threads running this sequence repeatedly
- How to solve?
  - Add random delay

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top:
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Prevention — Mutual exclusion

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- Use atomic instructions!

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

Prevention — Mutual exclusion

- Use atomic instructions!

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```
void AtomicIncrement(int *value, int amount){
...Fill Here
}
```

Prevention — Mutual exclusion

- Use atomic instructions!

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- Use above code to implement atomic increment: x = x+k

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

Prevention — Mutual exclusion

- List insertion using atomic instructions

Prevention — Mutual exclusion

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

Prevention — Mutual exclusion

- List insertion using atomic instructions

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void insert(int value){
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  head   = n;
}
```

- Where is the race condition?

Prevention — Mutual exclusion

- Mutex based solution

Prevention — Mutual exclusion

- Mutex based solution

```
void insert(int value){
  node_t * n = malloc(sizeof(node_t));
  assert( n != NULL );
  n->value = value ;
  lock(listlock); // begin critical section
  n->next  = head;
  head   = n;
  unlock(listlock) ;  //end critical section
}
```

Prevention — Mutual exclusion

- Atomic instruction based?

HINT

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int CompareAndSwap(int *address, int expected, int new){
  if(*address == expected){
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HINT

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}
```

```
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));
}
```

Deadlock Avoidance via Scheduling

Only one of T1 & T2 will
run at a given time …

Deadlock Avoidance via Scheduling

- Global knowledge about which threads might be acquired is needed ahead of time

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L1	yes	yes	no	no
L2	yes	yes	yes	no

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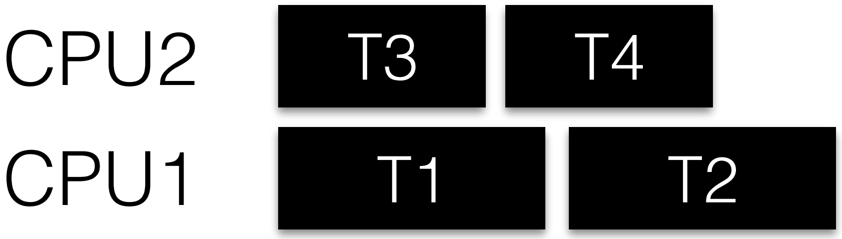

CPU2 T3 T4

CPU1 T1 T2

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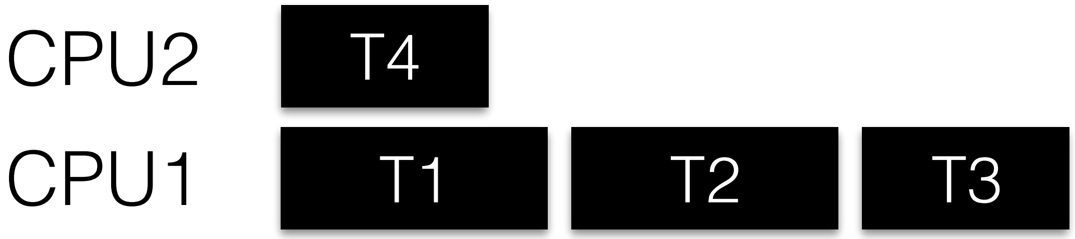

CPU2 T4

CPU1 T1 T2 T3