TCSS 422: OPERATING SYSTEMS

Concurrency Problems

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OBJECTIVES

- Non-deadlock concurrency bugs
- Deadlock causes
- Deadlock prevention

CONCURRENCY BUGS IN OPEN SOURCE SOFTWARE

- "Learning from Mistakes – A Comprehensive Study on Real World Concurrency Bug Characteristics"
  - Shan Lu et al.
  - Architectural Support For Programming Languages and Operating Systems (ASPLOS 2008), Seattle WA

Application	What it does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
Open Office	Office Suite	6	2
Total		**74**	**31**

NON-DEADLOCK BUGS

- Majority of concurrency bugs
- Most common:
  - Atomicity violation
  - Order violation

ATOMICITY VIOLATION - MYSQL

- Two threads access the proc_info field in struct thd
- NULL is 0 in C
- Serialized access to shared memory among separate threads is not enforced (e.g. non-atomic)
- Simple example:

Programmer intended variable to be accessed atomically…

```
1   Thread1::
2   if(thd->proc_info){
3     …
4     fputs(thd->proc_info , …);
5     …
6   }
7
8   Thread2::
9   thd->proc_info = NULL;
```


ATOMICITY VIOLATION - SOLUTION

- Add locks whereever thd->proc_info is used

```
1   pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;
2
3   Thread1::
4   pthread_mutex_lock(&lock);
5   if(thd->proc_info){
6     …
7     fputs(thd->proc_info , …);
8     …
9   }
10  pthread_mutex_unlock(&lock);
11
12  Thread2::
13  pthread_mutex_lock(&lock);
14  thd->proc_info = NULL;
15  pthread_mutex_unlock(&lock);
```

ORDER VIOLATION BUGS

- Desired order between memory accesses is flipped
- E.g. something is checked before it is set
- Example:

```
1   Thread1::
2   void init(){
3       mThread = PR_CreateThread(mMain, …);
4   }
5
6   Thread2::
7   void mMain(…){
8       mState = mThread->State
9   }
```

- What if mThread is not initialized?

ORDER VIOLATION - SOLUTION

- Use condition variable to enforce order

```
1   pthread_mutex_t mtLock = PTHREAD_MUTEX_INITIALIZER;
2   pthread_cond_t mtCond = PTHREAD_COND_INITIALIZER;
3   int mtInit = 0;
4
5   Thread 1::
6   void init(){
7       …
8       mThread = PR_CreateThread(mMain,…);
9
10      // signal that the thread has been created.
11      pthread_mutex_lock(&mtLock);
12      mtInit = 1;
13      pthread_cond_signal(&mtCond);
14      pthread_mutex_unlock(&mtLock);
15      …
16  }
17
18  Thread2::
19  void mMain(…){
20      …
```


ORDER VIOLATION – SOLUTION 2

```
21      // wait for the thread to be initialized …
22      pthread_mutex_lock(&mtLock);
23      while(mtInit == 0)
24              pthread_cond_wait(&mtCond, &mtLock);
25      pthread_mutex_unlock(&mtLock);
26
27      mState = mThread->State;
28      …
29  }
```


NON-DEADLOCK BUGS - 1

- 97% of Non-Deadlock Bugs were
  - Atomicity
  - Order violations
- Consider what is involved in "spotting" these bugs in code
- Desire for automated tool support (IDE)

NON-DEADLOCK BUGS - 2

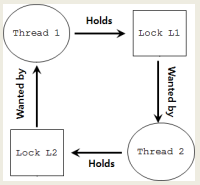
- Atomicity
  - How can we tell if a given variable is shared?
    - Can search the code for uses
  - How do we know if all instances of its use are shared?
    - Can some non-synchronized uses be legal?
    - Before threads are created, after threads exit
    - Must verify the scope
- Order violation
  - Must consider all variable accesses
  - Must known desired order

DEADLOCK BUGS

- Presence of a cycle in code
- Thread 1 acquires lock L1, waits for lock L2
- Thread 2 acquires lock L2, waits for lock L1

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

- Both threads can block, unless one manages to acquire both locks



REASONS FOR DEADLOCKS

- Complex code
  - Must avoid circular dependencies
- Encapsulation hides potential locking conflicts
  - Easy-to-use APIs embed locks inside
  - Programmer doesn't know they are there
  - Consider the Java Vector class:

```
1   Vector v1,v2;
2   v1.AddAll(v2);
```

  - Vector is thread safe (synchronized) by design
  - If there is a v2.AddAll(v1); call at nearly the same time deadlock could result

CONDITIONS FOR DEADLOCK

- **Four conditions** are required for dead lock to occur

Condition	Description
Mutual Exclusion	Threads claim exclusive control of resources that they require.
Hold-and-wait	Threads hold resources allocated to them while waiting for additional resources
No preemption	Resources cannot be forcibly removed from threads that are holding them.
Circular wait	There exists a circular chain of threads such that each thread holds one more resources that are being requested by the next thread in the chain

PREVENTION – CIRCULAR WAIT

- Provide **total ordering** of lock acquisition throughout code
  - Always acquire locks in same order
  - L1, L2, L3, …
  - Never mix: L2, L1, L3; L2, L3, L1; L3, L1, L2….
- Must carry out same ordering through entire program

PREVENTION – HOLD AND WAIT

- Acquire all locks atomically
- Use a "lock" "lock"

```
1   lock(prevention);
2   lock(L1);
3   lock(L2);
4   …
5   unlock(prevention);
```

- Effective solution – guarantees no race conditions while acquiring L1, L2, etc.
- Order doesn't matter for L1, L2
- Prevention (GLOBAL) lock decreases concurrency of code
  - Acts Lowers lock granularity
- Encapsulation: consider the Java Vector class…

PREVENTION – NO PREEMPTION

- When acquiring locks, don't BLOCK forever if unavailable…
- pthread_mutex_trylock() - try once
- pthread_mutex_timedlock() - try and wait awhile

```
1   top:
2       lock(L1);
3       if( tryLock(L2) == -1 ){
4               unlock(L1);
5               goto top;
6       }
```

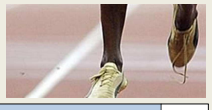
- Eliminates deadlocks

NO PREEMPTION - LIVELOCKS

- Can lead to livelock

```
1   top:
2       lock(L1);
3       if( tryLock(L2) == -1 ){
4               unlock(L1);
5               goto top;
6       }
```

- Two threads execute code in parallel → always fail to obtain both locks
- Add random delay
  - Allows one thread to win livelock race!



PREVENTION – MUTUAL EXCLUSION

- Build wait-free data structures
  - Eliminate locks altogether
  - Build structures using CompareAndSwap atomic CPU (HW) instruction
- C pseudo code for CompareAndSwap
- Hardware executes this code atomically

```
1   int CompareAndSwap(int *address, int expected, int new){
2       if(*address == expected){
3               *address = new;
4               return 1; // success
5       }
6       return 0;
7   }
```


PREVENTION – MUTUAL EXCLUSION - 2

- Recall atomic increment

```
1   void AtomicIncrement(int *value, int amount){
2       do{
3               int old = *value;
4       }while( CompareAndSwap(value, old, old+amount)==0);
5   }
```

- Compare and Swap tries over and over until successful
- CompareAndSwap is guaranteed to be atomic
- When it runs it is **ALWAYS** atomic (at HW level)

MUTUAL EXCLUSION: LIST INSERTION

- Consider list insertion

```
1   void insert(int value){
2       node_t * n = malloc(sizeof(node_t));
3       assert( n != NULL );
4       n->value = value ;
5       n->next  = head;
6       head     = n;
7   }
```


MUTUAL EXCLUSION – LIST INSERTION - 2

- Lock based implementation

```
1   void insert(int value){
2       node_t * n = malloc(sizeof(node_t));
3       assert( n != NULL );
4       n->value = value ;
5       lock(listlock); // begin critical section
6       n->next  = head;
7       head     = n;
8       unlock(listlock) ;  //end critical section
9   }
```


MUTUAL EXCLUSION – LIST INSERTION - 3

- Wait free (no lock) implementation

```
1   void insert(int value) {
2       node_t *n = malloc(sizeof(node_t));
3       assert(n != NULL);
4       n->value = value;
5       do {
6               n->next = head;
7       } while (CompareAndSwap(&head, n->next, n));
8   }
```

- Assign &head to n (new node ptr)
- Only when head = n->next

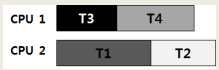
DEADLOCK AVOIDANCE VIA INTELLIGENT SCHEDULING

- Consider a smart scheduler
  - Scheduler knows which locks threads use
- Consider this scenario:
  - 4 Threads (T1, T2, T3, T4)
  - 2 Locks (L1, L2)
- Lock requirements of threads:

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

INTELLIGENT SCHEDULING - 2

- Scheduler produces schedule:

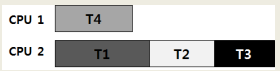


- No deadlock can occur
- Consider:

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

INTELLIGENT SCHEDULING - 3

- Scheduler produces schedule



- Scheduler must be conservative and not task risks
- Slows down execution – many threads
- There has been limited use of these approaches given the difficulty having intimate lock knowledge about every thread

DETECT AND RECOVER

- Allow deadlock to occasionally occur and then take some action.
  - Example: When OS freezes, reboot…
- How often is acceptable?
- Many database systems employ deadlock detection and recovery technique.

QUESTIONS