# TCSS 422: OPERATING SYSTEMS

## Condition Variables, Concurrency Problems

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## OBJECTIVES – 5/7

- Questions from 4/30
- Quiz 2 (available until May 11, 11:59p AOE)
- Assignment 1 (May 7 → May 10, 11:59p AOE)
- Assignment 2 (based on Ch. 30, posted ~May 11)
- Chapter 30: Condition Variables
  - Producer/Consumer
  - Covering Conditions
- Chapter 32: Concurrency Problems
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention



## MATERIAL / PACE

- Please classify your perspective on material covered in today's class (43 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.27 (↓ *from* 7.30)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.77 (↓ from 5.92)**



## FEEDBACK FROM 4/30



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## CHAPTER 30 – CONDITION VARIABLES



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## CONDITION VARIABLES

- There are many cases where a thread wants to wait for another thread before proceeding with execution
- Consider when a precondition must be fulfilled before it is meaningful to proceed …



## CONDITION VARIABLES - 2


- Support a signaling mechanism to alert threads when preconditions have been satisfied
- Eliminate busy waiting
- Alert one or more threads to "consume" a result, or respond to state changes in the application
- Threads are placed on **(FIFO) queue** to ***WAIT*** for signals
- **Signal**: wakes one thread (thread waiting longest)
  **broadcast** wakes all threads (ordering by the OS)



## CONDITION VARIABLES - 3

- Condition variable

```
pthread_cond_t c;
```

  - Requires initialization
- Condition API calls

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);    // wait()
pthread_cond_signal(pthread_cond_t *c);                      // signal()
```

- wait() accepts a mutex parameter
  - Releases lock, puts thread to sleep, thread added to FIFO queue
- signal()
  - Wakes up thread, awakening thread acquires lock

## CONDITION VARIABLES - QUESTIONS

- **Why would we want to put waiting threads on a queue? *why not use a stack?***
  - Queue (FIFO), Stack (LIFO)
- **Why do we want to not busily wait for the lock to become available?**
  - Using condition variables eliminates busy waiting by putting threads to "sleep" and yielding the CPU.
- A program has 10-threads, where 9 threads are waiting. The working thread finishes and broadcasts that the lock is available. **What happens next?**
  - All threads woken up in FIFO order - based on when started to wait



## MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c



## MATRIX GENERATOR

- The worker thread produces a matrix
  - Matrix stored using shared global pointer
- The main thread consumes the matrix
  - Calculates the average element
  - Display the matrix
- What would happen if we don't use a condition variable to coordinate exchange of the lock?
- Example program: "nosignal.c"



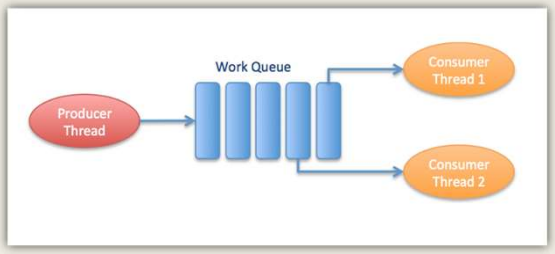
## ATTEMPT TO USE CONDITION VARIABLE WITHOUT A WHILE STATEMENT

```
1       void thr_exit() {                ← Child calls
2               done = 1;
3               Pthread_cond_signal(&c);
4       }
5
6       void thr_join() {                ← Parent calls
7               if (done == 0)
8                       Pthread_cond_wait(&c);
9       }
```

- Subtle race condition introduced
- **Parent** thread calls **thr_join()** and executes comparison (line 7)
- Context switches to the child
- The **child** runs **thr_exit()** and signals the parent, but the parent is not waiting yet. *(parent has not reached line 8)*
- **The signal is lost !**
- The parent deadlocks



## PRODUCER / CONSUMER






## PRODUCER / CONSUMER

- **Producer**
  - Produces items – e.g. child the makes matricies
  - Places them in a buffer
    - Example: the buffer size is only 1 element (single array pointer)
- **Consumer**
  - Grabs data out of the buffer
  - Our example: parent thread receives dynamically generated matrices and performs an operation on them
    - Example: calculates average value of every element (integer)
- Multithreaded web server example
  - Http requests placed into work queue; threads process

## PRODUCER / CONSUMER - 2

- Producer / Consumer is also known as **Bounded Buffer**
- Bounded buffer
  - Similar to piping output from one Linux process to another
  - grep pthread signal.c | wc –l
  - Synchronized access:
    sends output from grep → wc as it is produced
  - File stream



## PUT/GET ROUTINES

- Buffer is a one element shared data structure (int)
- Producer "puts" data, Consumer "gets" data
- "Bounded Buffer" shared data structure requires ***synchronization***

```
1       int buffer;
2       int count = 0;   // initially, empty
3
4       void put(int value) {
5               assert(count == 0);
6               count = 1;
7               buffer = value;
8       }
9
10      int get() {
11              assert(count == 1);
12              count = 0;
13              return buffer;
14      }
```



## PRODUCER / CONSUMER - 3

- Producer adds data
- Consumer removes data (busy waiting)
- **Without synchronization:**
  1. Producer Function 2. Consumer Function

```
1       void *producer(void *arg) {
2               int i;
3               int loops = (int) arg;
4               for (i = 0; i < loops; i++) {
5                       put(i);
6               }
7       }
8
9       void *consumer(void *arg) {
10              int i;
11              while (1) {
12                      int tmp = get();
13                      printf("%d\n", tmp);
14              }
15      }
```



## PRODUCER / CONSUMER - 3

- The shared data structure needs synchronization!

```
1       cond_t cond;
2       mutex_t mutex;
3
4       void *producer(void *arg) {
5           int i;
6           for (i = 0; i < loops; i++) {
7               Pthread_mutex_lock(&mutex);            // p1
8               if (count == 1)                        // p2
9                   Pthread_cond_wait(&cond, &mutex);  // p3
10              put(i);                                // p4
11              Pthread_cond_signal(&cond);            // p5
12              Pthread_mutex_unlock(&mutex);          // p6
13          }
14      }
15
16      void *consumer(void *arg) {
17          int i;
18          for (i = 0; i < loops; i++) {
19              Pthread_mutex_lock(&mutex);            // c1
```

Producer



## PRODUCER/CONSUMER - 4

```
20              if (count == 0)                        // c2
21                  Pthread_cond_wait(&cond, &mutex);  // c3
22              int tmp = get();                       // c4
23              Pthread_cond_signal(&cond);            // c5
24              Pthread_mutex_unlock(&mutex);          // c6
25              printf("%d\n", tmp);
26          }
27      }
```

Consumer

- This code as-is works with just:
  (1) Producer
  (1) Consumer
- PROBLEM: no while. If thread wakes up it MUST execute
- If we scale to (2+) consumer's it fails
  - How can it be fixed ?



## EXECUTION TRACE: NO WHILE, 1 PRODUCER, 2 CONSUMERS

- Two threads

**Legend**
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

| $T_{c1}$ | State | $T_{c2}$ | State | $T_p$ | State | Count | Comment |
|---|---|---|---|---|---|---|---|
| c1 | Running | | Ready | | Ready | 0 | |
| c2 | Running | | Ready | | Ready | 0 | |
| c3 | Sleep | | Ready | | Ready | 0 | Nothing to get |
| | Sleep | | Ready | p1 | Running | 0 | |
| | Sleep | | Ready | p2 | Running | 0 | |
| | Sleep | | Ready | p4 | Running | 1 | Buffer now full |
| | Ready | | Ready | p5 | Running | 1 | $T_{c1}$ awoken |
| | Ready | | Ready | p6 | Running | 1 | |
| | Ready | | Ready | p1 | Running | 1 | |
| | Ready | | Ready | p2 | Running | 1 | |
| | Ready | | Ready | p3 | Sleep | 1 | Buffer full; sleep |
| | Ready | c1 | Running | | Sleep | 1 | $T_{c2}$ sneaks in ... |
| | Ready | c2 | Running | | Sleep | 1 | |
| | Ready | c4 | Running | | Sleep | 0 | ... and grabs data |
| | Ready | c5 | Running | | Ready | 0 | $T_p$ awoken |
| | Ready | c6 | Running | | Ready | 0 | |
| c4 | Running | | Ready | | Ready | 0 | Oh oh! No data |

## PRODUCER/CONSUMER SYNCHRONIZATION

- When producer threads awake, they do not check if there is any data in the buffer…
  - Need "while" statement, "if" statement is ***Insufficient …***
- What if $T_p$ puts a value, wakes $T_{c1}$ whom consumes the value
- Then $T_p$ has a value to put, but $T_{c1}$'s signal on &cond wakes $T_{c2}$
- There is nothing for $T_{c2}$ consume, so $T_{c2}$ sleeps
- $T_{c1}$, $T_{c2}$, and $T_p$ all sleep forever
- $T_{c1}$ needs to wake $T_p$ to $T_{c2}$



## EXECUTION TRACE: WHILE, 1 CONDITION, 1 PRODUCER, 2 CONSUMERS

**Legend**
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

| | $T_{c1}$ | State | $T_{c2}$ | State | $T_p$ | State | Count | Comment |
|---|---|---|---|---|---|---|---|---|
| | c1 | Running | | Ready | | Ready | 0 | |
| | c2 | Running | | Ready | | Ready | 0 | |
| | c3 | Sleep | | Ready | | Ready | 0 | Nothing to get |
| | | Sleep | c1 | Running | | Ready | 0 | |
| | | Sleep | c2 | Running | | Ready | 0 | |
| | | Sleep | c3 | Sleep | | Ready | 0 | Nothing to get |
| | | Sleep | | Sleep | p1 | Running | 0 | |
| | | Sleep | | Sleep | p2 | Running | 0 | |
| | | Sleep | | Sleep | p4 | Running | 1 | Buffer now full |
| ⇨ | | Ready | | Sleep | p5 | Running | 1 | $T_{c1}$ awoken |
| | | Ready | | Sleep | p6 | Running | 1 | |
| | | Ready | | Sleep | p1 | Running | 1 | |
| | | Ready | | Sleep | p2 | Running | 1 | |
| | | Ready | | Sleep | p3 | Sleep | 1 | Must sleep (full) |
| ⇨ | c2 | Running | | Sleep | | Sleep | 1 | Recheck condition |
| ⇨ | c4 | Running | | Sleep | | Sleep | 0 | $T_{c1}$ grabs data |
| ⇨ | c5 | Running | | Ready | | Sleep | 0 | Oops! Woke $T_{c2}$ |



## EXECUTION TRACE – 2 WHILE, 1 CONDITION, 1 PRODUCER, 2 CONSUMERS

- $T_{c2}$ runs, no data to consume

**Legend**
c1/p1- lock
c2/p2- check var
c3/p3- wait
c4- put()
p4- get()
c5/p5- signal
c6/p6- unlock

| $T_{c1}$ | State | $T_{c2}$ | State | $T_p$ | State | Count | Comment |
|---|---|---|---|---|---|---|---|
| … | … | … | … | … | … | … | (cont.) |
| c6 | Running | | Ready | | Sleep | 0 | |
| c1 | Running | | Ready | | Sleep | 0 | |
| c2 | Running | | Ready | | Sleep | 0 | |
| c3 | Sleep | | Ready | | Sleep | 0 | Nothing to get |
| ⇨ | Sleep | ⇨ c2 | Running | | Sleep | 0 | |
| ⇨ | Sleep | ⇨ c3 | Sleep | | Sleep | 0 | Everyone asleep … |



## TWO CONDITIONS

- Required w/ multiple producer and consumer threads
- Use two condition variables: **empty** & **full**
  - One condition handles the producer
  - the other the consumer

```
1   cond_t empty, full;
2   mutex_t mutex;
3
4   void *producer(void *arg) {
5       int i;
6       for (i = 0; i < loops; i++) {
7           Pthread_mutex_lock(&mutex);
8           while (count == 1)
9               Pthread_cond_wait(&empty, &mutex);
10          put(i);
11          Pthread_cond_signal(&full);
12          Pthread_mutex_unlock(&mutex);
13      }
14  }
15
```



## FINAL PRODUCER/CONSUMER

- Change buffer from int, to int buffer[MAX]
- Add indexing variables
- >> Becomes *BOUNDED BUFFER*, can store multiple matricies

```
1   int buffer[MAX];
2   int fill = 0;
3   int use = 0;
4   int count = 0;
5
6   void put(int value) {
7       buffer[fill] = value;
8       fill = (fill + 1) % MAX;
9       count++;
10  }
11
12  int get() {
13      int tmp = buffer[use];
14      use = (use + 1) % MAX;
15      count--;
16      return tmp;
17  }
```



## FINAL P/C - 2

```
1   cond_t empty, full
2   mutex_t mutex;
3
4   void *producer(void *arg) {
5       int i;
6       for (i = 0; i < loops; i++) {
7           Pthread_mutex_lock(&mutex);                 // p1
8           while (count == MAX)                        // p2
9               Pthread_cond_wait(&empty, &mutex);      // p3
10          put(i);                                     // p4
11          Pthread_cond_signal (&full);                // p5
12          Pthread_mutex_unlock(&mutex);               // p6
13      }
14  }
15
16  void *consumer(void *arg) {
17      int i;
18      for (i = 0; i < loops; i++) {
19          Pthread_mutex_lock(&mutex);                 // c1
20          while (count == 0)                          // c2
21              Pthread_cond_wait( &full, &mutex);      // c3
22          int tmp = get();                            // c4
```

## FINAL P/C - 3

```
(Cont.)
23              Pthread_cond_signal(&empty);            // c5
24              Pthread_mutex_unlock(&mutex);           // c6
25              printf("%d\n", tmp);
26          }
27      }
```

- Producer: only sleeps when buffer is full
- Consumer: only sleeps if buffers are empty



**Using one condition variable, and no while loop is sufficient to synchronize access to a bounded buffer shared by:**

- 1 Producer, 1 Consumer Thread
- 2 Consumers, 1 Producer Thread
- 2+ Producers, 2+ Consumer Threads
- All of the above
- None of the above



**Using one condition variable, with a while loop is sufficient to synchronize access to a bounded buffer shared by:**

- 1 Producer, 1 Consumer Thread
- 2 Consumers, 1 Producer Thread
- 2+ Producers, 2+ Consumer Threads
- None of the above



**Using two condition variables, and a while loop is sufficient to synchronize access to a bounded buffer shared by:**

- 1 Producer, 1 Consumer Thread
- 2 Consumers, 1 Producer Thread
- 2+ Producers, 2+ Consumer Threads
- All of the above
- None of the above



## COVERING CONDITIONS

- A condition that covers ***all*** cases (conditions):
- Excellent use case for **pthread_cond_broadcast**
- Consider memory allocation:
  - When a program deals with huge memory allocation/deallocation on the heap
  - Access to the heap must be managed when memory is scarce

  PREVENT: Out of memory:
  - queue requests until memory is free
  - Which thread should be woken up?



## COVERING CONDITIONS - 2

```
1       // how many bytes of the heap are free?
2       int bytesLeft = MAX_HEAP_SIZE;
3
4       // need lock and condition too
5       cond_t c;
6       mutex_t m;
7
8       void *
9       allocate(int size) {
10          Pthread_mutex_lock(&m);
11          while (bytesLeft < size)
12              Pthread_cond_wait(&c, &m);
13          void *ptr = ...;                // get mem from heap
14          bytesLeft -= size;
15          Pthread_mutex_unlock(&m);
16          return ptr;
17      }
18
19      void free(void *ptr, int size) {
20          Pthread_mutex_lock(&m);
21          bytesLeft += size;
22          Pthread_cond_signal(&c);        // Broadcast
23          Pthread_mutex_unlock(&m);
24      }
```

Check available memory

## COVER CONDITIONS - 3

- Broadcast awakens all blocked threads requesting memory
- Each thread evaluates if there's enough memory: (bytesLeft < size)
  - Reject: requests that cannot be fulfilled- go back to sleep
    - *Insufficient memory*
  - Run: requests which **can** be fulfilled
    - with newly available memory!
- **Another use case**: coordinate a group of busy threads to gracefully end, to EXIT the program
- **Overhead**
  - Many threads may be awoken which can't execute

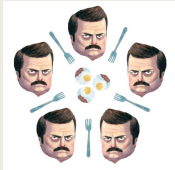


## TCSS 422 WILL RETURN AT ~2:40PM



## CHAPTER 31: SEMAPHORES

- Offers a combined C language construct that can assume the role of a lock or a condition variable depending on usage
  - Allows fewer concurrency related variables in your code
  - Potentially makes code more ambiguous
  - For this reason, with limited time in a 10-week quarter, we do not cover
- **Ch. 31.6 – Dining Philosophers Problem**
  - Classic computer science problem about sharing eating utensils
  - Each philosopher tries to obtain two forks in order to eat
  - Mimics deadlock as there are not enough forks
  - Solution is to have one left-handed philosopher that grabs forks in opposite order





## CHAPTER 32 – CONCURRENCY PROBLEMS



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## 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: forget to use locks
  - Order violation: failure to initialize lock/condition before use



## ATOMICITY VIOLATION - MYSQL

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

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 for all uses of: `thd->proc_info`

```
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 & signal 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

- Use condition & signal to enforce order

```
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
  - >> *no use of locking constructs to search for*
- 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, non-atomic uses be legal?
      - Legal uses: before threads are created, after threads exit
    - Must verify the scope
- Order violation
  - Must consider all variable accesses
  - Must know desired order

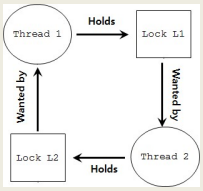


## DEADLOCK BUGS

- 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 – can be hard to find…
- 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 – 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



## 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 LOCK – HOLD AND WAIT

- Problem: acquire all locks atomically
- Solution: use a "lock" "lock"… (*like a guard 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…

## CONDITIONS FOR DEADLOCK

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## 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

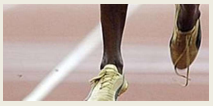


## NO PREEMPTION – LIVELOCKS PROBLEM

- 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
- Fix: add random delay
  - Allows one thread to win the livelock race!





## CONDITIONS FOR DEADLOCK

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## 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



## CONDITIONS FOR DEADLOCK

- **If any of the following conditions DOES NOT EXSIST, describe why deadlock can not 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 |

**The dining philosophers problem where 5 philosophers compete for 5 forks, and where a philosopher must hold two forks to eat involves which deadlock condition(s)?**

- Mutual Exclusion
- Hold-and-wait
- No preemption
- Circular wait
- All of the above

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## 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:

| | | |
|---|---|---|
| CPU 1 | T3 | T4 |
| CPU 2 | T1 | T2 |

- 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

| | | | |
|---|---|---|---|
| CPU 1 | T4 | | |
| CPU 2 | T1 | T2 | T3 |

- Scheduler must be conservative and not take 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 this acceptable?
  - Once per year
  - Once per month
  - Once per day
  - *Consider the effort tradeoff of finding every deadlock bug*
- Many database systems employ deadlock detection and recovery techniques.



## QUESTIONS

## WILL RETURN IN A FEW MINUTES