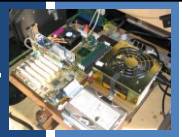
TCSS 422: OPERATING SYSTEMS



Lock-based data structures II, Condition Variables, Concurrency Problems

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OBJECTIVES – 5/9

- **Questions from 5/2 & Midterm Review**
- Assignment 0 Grades Posted
- Assignment 1 – May 11
- Tutorial 2: Pthread Tutorial - to be posted
- Chapter 29: Lock Based Data Structures
  - Approximate Counter (Sloppy Counter)
  - Concurrent Structures: Linked List, Queue, Hash Table
- Chapter 30: Condition Variables
  - Producer/Consumer
  - Covering Conditions
- Chapter 32: Concurrency Problems
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention

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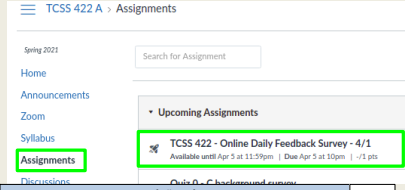
ONLINE DAILY FEEDBACK SURVEY

- Daily Feedback Quiz in Canvas – Available After Each Class
- Extra credit available for completing surveys ***ON TIME***
- Tuesday surveys: due by ~ Wed @ 11:59p
- Thursday surveys: due ~ Mon @ 11:59p



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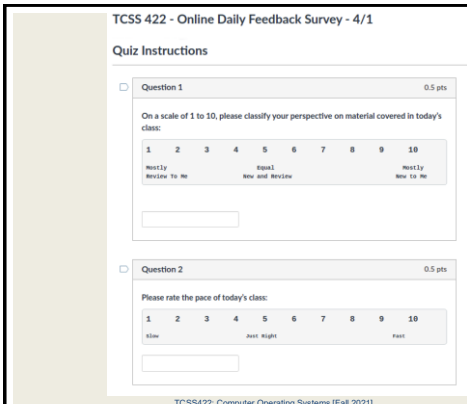

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MATERIAL / PACE

- Please classify your perspective on material covered in today's class (48 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- **Average – 6.52 (↓ - previous 6.98)**

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- **Average – 5.48 (↓ - previous 6.07)**

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FEEDBACK FROM 5/2

- ***From the practice midterm, in the FIFO example, A and C are both 10 time slices, but why there were 10 As but only 4 Cs on the diagram?***
  - There are actually 9 Cs, there should be 10

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FIFO EXAMPLE

- Operation of CPU schedulers can be visualized with timing graphs.
- The graph below depicts a FIFO scheduler where three jobs arrive in the sequence A, B, C, where job A runs for 10 time slices, job B for 5 time slices, and job C for 10 time slices.

```
      |
FIFO |AAAAAAAAAABBBBBCCCCCCCCCC
      |_____________________________________
      0          10    15        25
```


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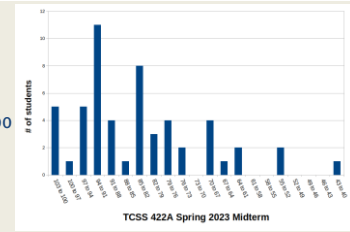
MIDTERM RESULTS

- **Statistics**
- Average: 83.28
- Mode: 92.0
- Median: 85.0
- Min score: 41
- Lower quartile: 77.00
- 2nd quartile: 85.0
- 3rd quartile: 93
- Max score: 102
- Standard deviation: 13.49
- Curve: +2
- Missing: 4



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MIDTERM REVIEW

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OBJECTIVES – 5/9

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TUTORIAL 2

- Pthread Tutorial
- Practice using:
  - pthreads
  - Locks
  - Condition variables
- Generate and visualize prime number generation in parallel
- To be posted in next couple of days

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CHAPTER 29 – LOCK BASED DATA STRUCTURES

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APPROXIMATE (SLOPPY) COUNTER

- Provides single logical shared counter
  - Implemented using local counters for each ~CPU core
    - 4 CPU cores = 4 local counters & 1 global counter
    - Local counters are synchronized via local locks
  - Global counter is updated periodically
    - Global counter has lock to protect global counter value
    - Update threshold (*S*) – *referred to as sloppiness threshold:* How often to push local values to global counter
    - Small (*S*): more updates, more overhead
    - Large (*S*): fewer updates, more performant, less synchronized
- Why this implementation?
  Why do we want counters local to each CPU Core?

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APPROXIMATE COUNTER – MAIN POINTS

- Idea of the Approximate Counter is to ***RELAX*** the synchronization requirement for counting
  - Instead of synchronizing global count variable each time: `counter=counter+1`
  - Synchronization occurs only every so often: e.g. *every **1000** counts*
- Relaxing the synchronization requirement ***drastically*** reduces locking API overhead by trading-off split-second accuracy of the counter
- Approximate counter: trade-off accuracy for speed
  - It's approximate because it's not so accurate (until the end)

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CONCURRENT LINKED LIST PERFORMANCE

- Using a single lock for entire list is not very performant
- Users must "wait" in line for a single lock to access/modify any item
- Hand-over-hand-locking (lock coupling)
  - Introduce a lock for each node of a list
  - Traversal involves handing over previous node's lock, acquiring the next node's lock…
  - Improves lock granularity
  - Degrades traversal performance
- Consider hybrid approach
  - Fewer locks, but more than 1
  - Best lock-to-node distribution?

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MICHAEL AND SCOTT CONCURRENT QUEUES

- Improvement beyond a single master lock for a queue (FIFO)
- Two locks:
  - One for the **head** of the queue
  - One for the **tail**
- Synchronize enqueue and dequeue operations
- Add a dummy node
  - Allocated in the queue initialization routine
  - Supports separation of head and tail operations
- Items can be added and removed by separate threads at the same time

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CONCURRENT QUEUE

- Remove from queue

```
1       typedef struct __node_t {
2               int value;
3               struct __node_t *next;
4       } node_t;
5
6       typedef struct __queue_t {
7               node_t *head;
8               node_t *tail;
9               pthread_mutex_t headLock;
10              pthread_mutex_t tailLock;
11      } queue_t;
12
13      void Queue_Init(queue_t *q) {
14              node_t *tmp = malloc(sizeof(node_t));
15              tmp->next = NULL;
16              q->head = q->tail = tmp;
17              pthread_mutex_init(&q->headLock, NULL);
18              pthread_mutex_init(&q->tailLock, NULL);
19      }
20
(Cont.)
```


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CONCURRENT QUEUE - 2

- Add to queue

```
(Cont.)
21      void Queue_Enqueue(queue_t *q, int value) {
22              node_t *tmp = malloc(sizeof(node_t));
23              assert(tmp != NULL);
24
25              tmp->value = value;
26              tmp->next = NULL;
27
28              pthread_mutex_lock(&q->tailLock);
29              q->tail->next = tmp;
30              q->tail = tmp;
31              pthread_mutex_unlock(&q->tailLock);
32      }
(Cont.)
```


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CONCURRENT HASH TABLE

- Consider a simple hash table
  - Fixed (static) size
  - Hash maps to a bucket
    - Bucket is implemented using a concurrent linked list
    - One lock per hash (bucket)
    - Hash bucket is a linked lists

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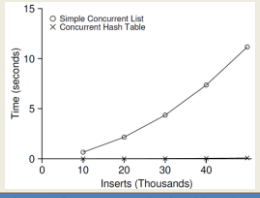
INSERT PERFORMANCE – CONCURRENT HASH TABLE

- Four threads – 10,000 to 50,000 inserts
  - iMac with four-core Intel 2.7 GHz CPU



The simple concurrent hash table scales magnificently

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CONCURRENT HASH TABLE

```
1   #define BUCKETS (101)
2
3   typedef struct __hash_t {
4           list_t lists[BUCKETS];
5   } hash_t;
6
7   void Hash_Init(hash_t *H) {
8           int i;
9           for (i = 0; i < BUCKETS; i++) {
10                  List_Init(&H->lists[i]);
11          }
12  }
13
14  int Hash_Insert(hash_t *H, int key) {
15          int bucket = key % BUCKETS;
16          return List_Insert(&H->lists[bucket], key);
17  }
18
19  int Hash_Lookup(hash_t *H, int key) {
20          int bucket = key % BUCKETS;
21          return List_Lookup(&H->lists[bucket], key);
22  }
```


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Which is a major advantage of using concurrent data structures in your programs?

- Locks are encapsulated within data structure code ensuring thread safety.
- Lock granularity tradeoff already optimized inside data structurew
- Multiple threads can more easily share data
- All of the above
- None of the above

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LOCK-FREE DATA STRUCTURES

- Lock-free data structures in Java
- Java.util.concurrent.atomic package
- Classes:
  - AtomicBoolean
  - AtomicInteger
  - AtomicIntegerArray
  - AtomicIntegerFieldUpdater
  - AtomicLong
  - AtomicLongArray
  - AtomicLongFieldUpdater
  - AtomicReference
- See: https://docs.oracle.com/en/java/javase/11/docs/api/java.base/java/util/concurrent/atomic/package-summary.html

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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 …

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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)

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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

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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

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MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c

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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"

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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

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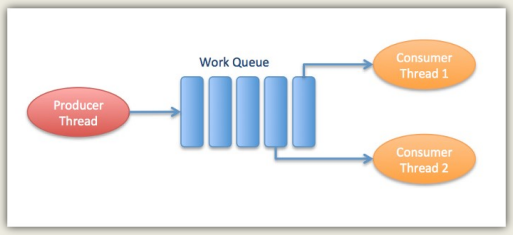
PRODUCER / CONSUMER



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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

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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

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WE WILL RETURN AT 2:50PM

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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      }
```


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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      }
```


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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

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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 ?

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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

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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}

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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}

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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 …

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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
```


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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      }
```


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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
```


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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

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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

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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

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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

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OBJECTIVES – 5/9

- Questions from 5/2 & Midterm Review
- Assignment 0 Grades Posted
- Assignment 1 – Nov 12
- Tutorial 2: Pthread Tutorial - to be posted
- Chapter 29: Lock Based Data Structures
  - Sloppy Counter
  - Concurrent Structures: Linked List, Queue, Hash Table
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  - Producer/Consumer
  - **Covering Conditions**
- Chapter 32: Concurrency Problems
  - Non-deadlock concurrency bugs
  - Deadlock causes
  - Deadlock prevention

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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?

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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);  //
23      Pthread_mutex_unlock(&m);
24  }
```

Check available memory

Broadcast

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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

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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

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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**

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NON-DEADLOCK BUGS

- Majority of concurrency bugs
- Most common:
  - Atomicity violation: forget to use locks
  - Order violation: failure to initialize lock/condition before use

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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;
```


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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);
```


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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?

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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      …
```


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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  }
```


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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)

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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

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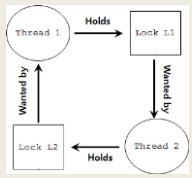
DEADLOCK BUGS

- 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



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  - **Deadlock causes**
  - Deadlock prevention

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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

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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

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OBJECTIVES – 5/9

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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   }
```


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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)

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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   }
```


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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   }
```


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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

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CONDITIONS FOR DEADLOCK

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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…

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CONDITIONS FOR DEADLOCK

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

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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

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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!

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CONDITIONS FOR DEADLOCK

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

Condition	Description
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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

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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

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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

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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

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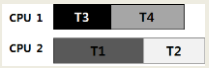
INTELLIGENT SCHEDULING - 2

- Scheduler produces schedule:



- No deadlock can occur
- Consider:

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

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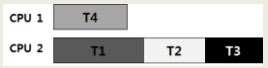
INTELLIGENT SCHEDULING - 3

- Scheduler produces schedule



- 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

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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.

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QUESTIONS

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