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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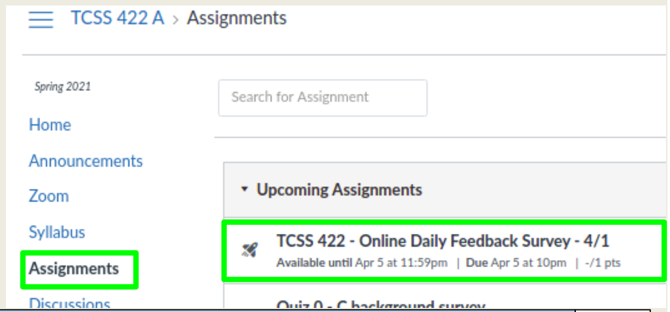
ONLINE DAILY FEEDBACK SURVEY

- 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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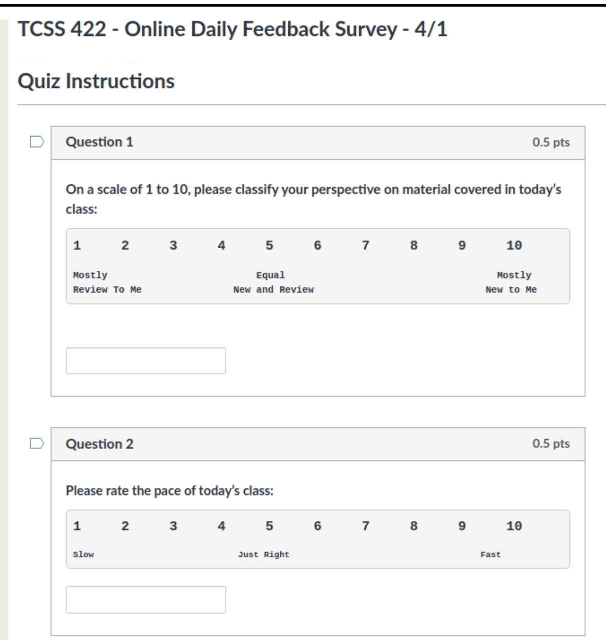

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MATERIAL / PACE

- 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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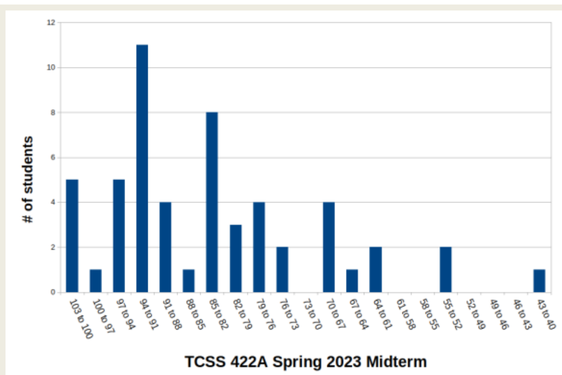
MIDTERM RESULTS

- **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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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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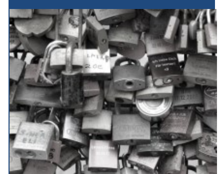
CHAPTER 29 – LOCK BASED DATA STRUCTURES



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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?

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

CONCURRENT QUEUE

- Remove from queue

```
typedef struct __node_t {
        int value;
        struct __node_t *next;
} node_t;

typedef struct __queue_t {
        node_t *head;
        node_t *tail;
        pthread_mutex_t headLock;
        pthread_mutex_t tailLock;
} queue_t;

void Queue_Init(queue_t *q) {
        node_t *tmp = malloc(sizeof(node_t));
        tmp->next = NULL;
        q->head = q->tail = tmp;
        pthread_mutex_init(&q->headLock, NULL);
        pthread_mutex_init(&q->tailLock, NULL);
}

(Cont.)
```


CONCURRENT QUEUE - 2

- Add to queue

```
(Cont.)
void Queue_Enqueue(queue_t *q, int value) {
        node_t *tmp = malloc(sizeof(node_t));
        assert(tmp != NULL);

        tmp->value = value;
        tmp->next = NULL;

        pthread_mutex_lock(&q->tailLock);
        q->tail->next = tmp;
        q->tail = tmp;
        pthread_mutex_unlock(&q->tailLock);
}
(Cont.)
```

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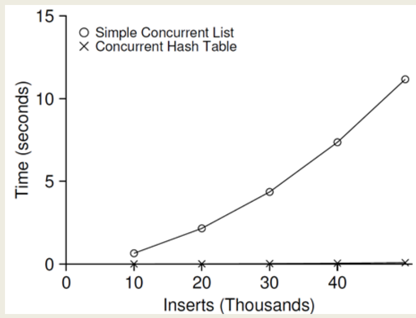
CONCURRENT HASH TABLE

- 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

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.

CONCURRENT HASH TABLE

```
#define BUCKETS (101)

typedef struct __hash_t {
        list_t lists[BUCKETS];
} hash_t;

void Hash_Init(hash_t *H) {
        int i;
        for (i = 0; i < BUCKETS; i++) {
                List_Init(&H->lists[i]);
        }
}

int Hash_Insert(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Insert(&H->lists[bucket], key);
}

int Hash_Lookup(hash_t *H, int key) {
        int bucket = key % BUCKETS;
        return List_Lookup(&H->lists[bucket], key);
}
```

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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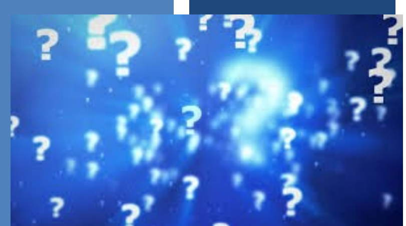

CHAPTER 30 – CONDITION VARIABLES

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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 …

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

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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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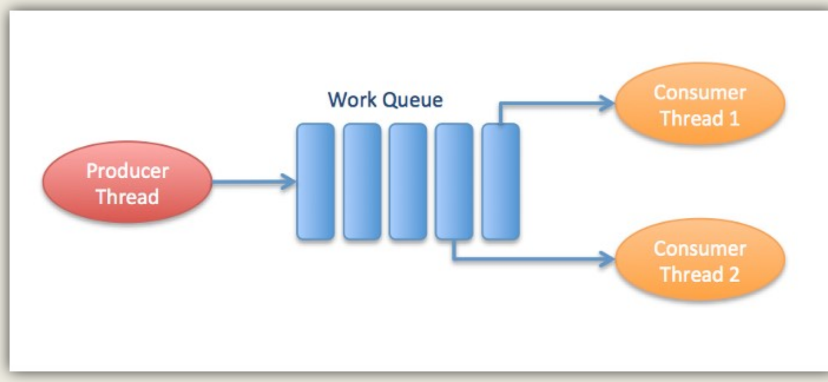
PRODUCER / CONSUMER



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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***

```
int buffer;
int count = 0;    // initially, empty

void put(int value) {
        assert(count == 0);
        count = 1;
        buffer = value;
}

int get() {
        assert(count == 1);
        count = 0;
        return buffer;
}
```


PRODUCER / CONSUMER - 3

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

```
void *producer(void *arg) {
        int i;
        int loops = (int) arg;
        for (i = 0; i < loops; i++) {
                put(i);
        }
}

void *consumer(void *arg) {
        int i;
        while (1) {
                int tmp = get();
                printf("%d\n", tmp);
        }
}
```

PRODUCER / CONSUMER - 3

- The shared data structure needs synchronization!

Producer

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        if (count == 1)                        // p2
            Pthread_cond_wait(&cond, &mutex);  // p3
        put(i);                                // p4
        Pthread_cond_signal(&cond);            // p5
        Pthread_mutex_unlock(&mutex);          // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // c1
```


PRODUCER/CONSUMER - 4

```
        if (count == 0)                        // c2
            Pthread_cond_wait(&cond, &mutex);  // c3
        int tmp = get();                       // c4
        Pthread_cond_signal(&cond);            // c5
        Pthread_mutex_unlock(&mutex);          // c6
        printf("%d\n", tmp);
    }
}
```

Consumer

- This code as-is works with just:
  - (1) Producer
  - (1) Consumer
- <u>PROBLEM</u>: 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}**

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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

```
cond_t empty, full;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 1)
            Pthread_cond_wait(&empty, &mutex);
        put(i);
        Pthread_cond_signal( &full);
        Pthread_mutex_unlock(&mutex);
    }
}
```

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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

```
int buffer[MAX];
int fill = 0;
int use = 0;
int count = 0;

void put(int value) {
    buffer[fill] = value;
    fill = (fill + 1) % MAX;
    count++;
}

int get() {
    int tmp = buffer[use];
    use = (use + 1) % MAX;
    count--;
    return tmp;
}
```

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FINAL P/C - 2

```
cond_t empty, full
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // p1
        while (count == MAX)                        // p2
            Pthread_cond_wait(&empty, &mutex);      // p3
        put(i);                                     // p4
        Pthread_cond_signal (&full);                // p5
        Pthread_mutex_unlock(&mutex);               // p6
    }
}

void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);                 // c1
        while (count == 0)                          // c2
            Pthread_cond_wait( &full, &mutex);      // c3
        int tmp = get();                            // c4
```


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FINAL P/C - 3

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

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

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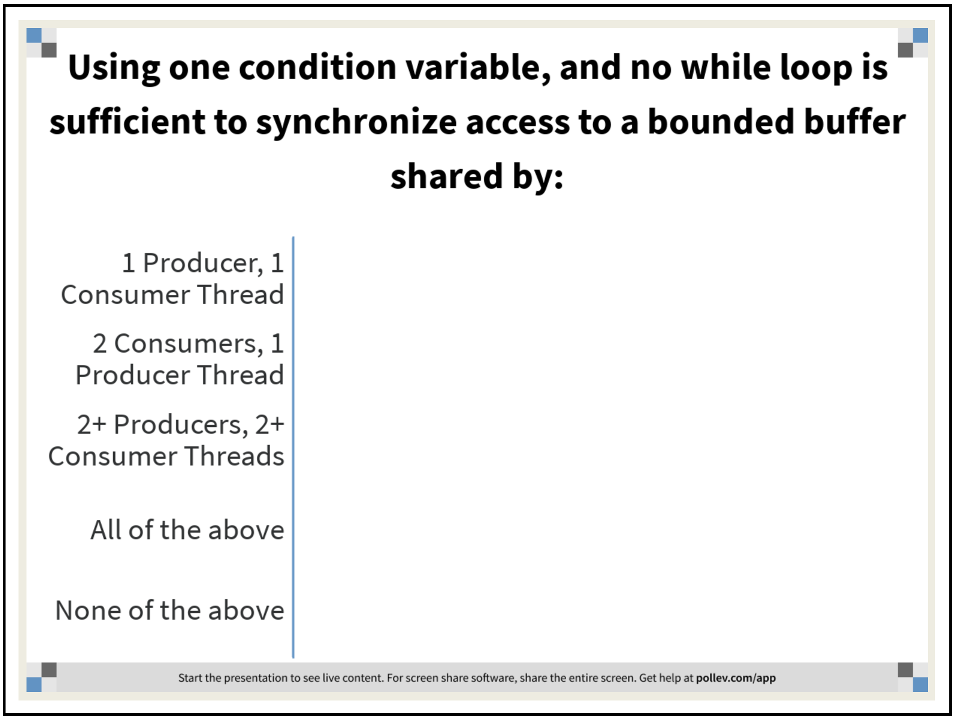
Using one condition variable, and no while loop is sufficient to synchronize access to a bounded buffer shared by:
1 Producer, 1 Consumer Thread
2 Consumers, 1 Producer Thread
2+ Producers, 2+ Consumer Threads
All of the above
None of the above
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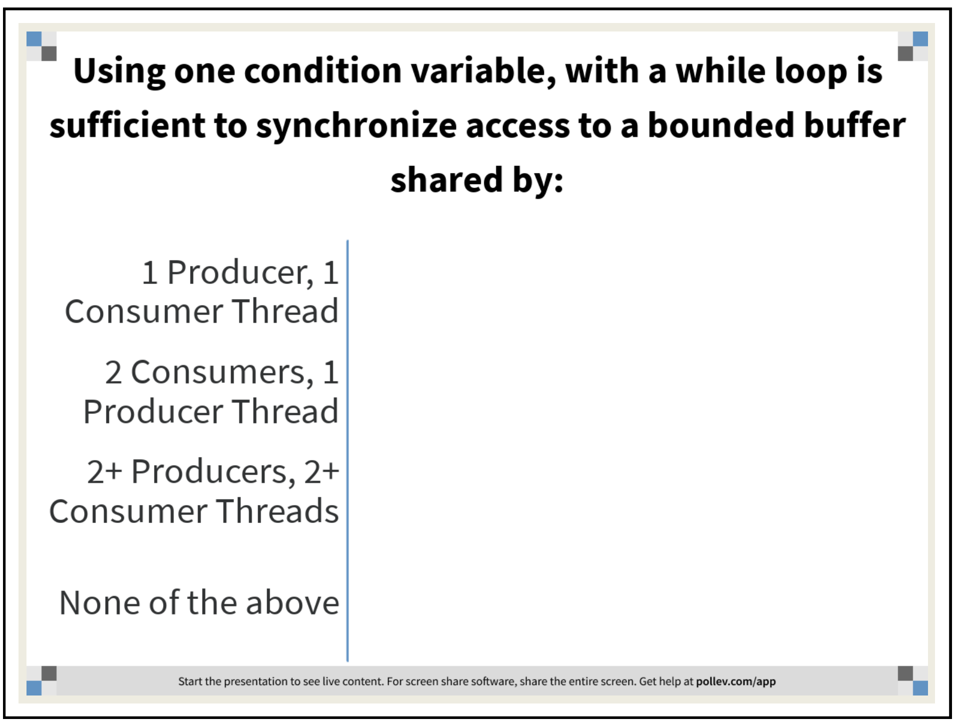
Using one condition variable, with a while loop is sufficient to synchronize access to a bounded buffer shared by:
1 Producer, 1 Consumer Thread
2 Consumers, 1 Producer Thread
2+ Producers, 2+ Consumer Threads
None of the above
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Using two condition 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
- Chapter 30: Condition Variables
  - 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

```
// how many bytes of the heap are free?
int bytesLeft = MAX_HEAP_SIZE;

// need lock and condition too
cond_t c;
mutex_t m;

void *
allocate(int size) {
    Pthread_mutex_lock(&m);
    while (bytesLeft < size)          Check available memory
        Pthread_cond_wait(&c, &m);
    void *ptr = ...;                  // get mem from heap
    bytesLeft -= size;
    Pthread_mutex_unlock(&m);
    return ptr;
}

void free(void *ptr, int size) {
    Pthread_mutex_lock(&m);
    bytesLeft += size;
    Pthread_cond_signal(&c);          // Broadcast
    Pthread_mutex_unlock(&m);
}
```


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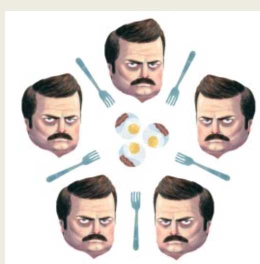
COVER CONDITIONS - 3

- 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

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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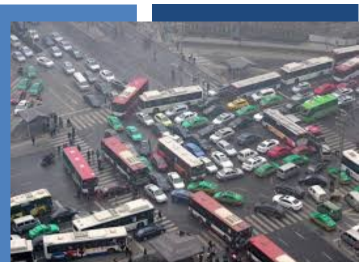

CHAPTER 32 – CONCURRENCY PROBLEMS

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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**

OBJECTIVES – 5/9

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  - Covering Conditions
- Chapter 32: Concurrency Problems
  - **Non-deadlock concurrency bugs**
  - Deadlock causes
  - Deadlock prevention

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…

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

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


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ATOMICITY VIOLATION - SOLUTION

- Add locks for all uses of: `thd->proc_info`

```
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);
```


ORDER VIOLATION BUGS

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

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

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

- What if mThread is not initialized?

ORDER VIOLATION - SOLUTION

- Use condition & signal to enforce order

```
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(…){
     …
```


ORDER VIOLATION – SOLUTION - 2

- Use condition & signal to enforce order

```
     // 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;
     …
}
```

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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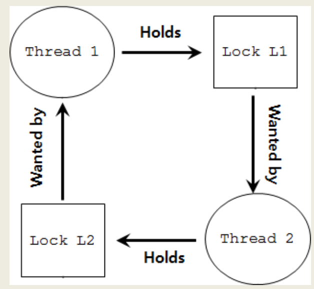
DEADLOCK BUGS

- 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 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:

```
Vector v1,v2;
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

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

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


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PREVENTION – MUTUAL EXCLUSION - 2

- Recall atomic increment

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

- 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

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

MUTUAL EXCLUSION – LIST INSERTION - 2

- Lock based implementation

```
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
}
```


MUTUAL EXCLUSION – LIST INSERTION - 3

- Wait free (no lock) implementation

```
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));
}
```

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

CONDITIONS FOR DEADLOCK

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

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PREVENTION LOCK – HOLD AND WAIT

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

```
lock(prevention);
lock(L1);
lock(L2);
…
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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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 – NO PREEMPTION

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

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

- Eliminates deadlocks

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NO PREEMPTION – LIVELOCKS PROBLEM

- Can lead to livelock

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

- 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
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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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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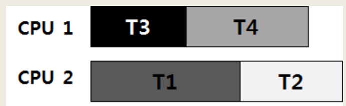
INTELLIGENT SCHEDULING - 2

- 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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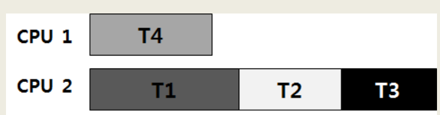
INTELLIGENT SCHEDULING - 3

- 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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