

# TCSS 422: OPERATING SYSTEMS

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



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May 13, 2025

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## OBJECTIVES – 5/13

- **Questions from 5/6 & Midterm Distribution**
  - Assignment 0 Grades Posted
  - Assignment 1 – May 13 --> May 16
  - 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

TCSS 422 A > Assignments

Spring 2021

Home

Announcements

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Syllabus

**Assignments**

Discussions

Search for Assignment

Upcoming Assignments

TCSS 422 - Online Daily Feedback Survey - 4/1  
Available until Apr 5 at 11:59pm | Due Apr 5 at 10pm | -/1 pts

Quiz 0 - C background survey

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### TCSS 422 - Online Daily Feedback Survey - 4/1

#### Quiz Instructions

Question 1 0.5 pts

On a scale of 1 to 10, please classify your perspective on material covered in today's class:

1	2	3	4	5	6	7	8	9	10
Mostly Review To Me				Equal New and Review					Mostly New to Me

Question 2 0.5 pts

Please rate the pace of today's class:

1	2	3	4	5	6	7	8	9	10
Slow				Just Right					Fast

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## MATERIAL / PACE

- Please classify your perspective on material covered in today's class (48 of 63 respondents – 76.2%):
  - 1-mostly review, 5-equal new/review, 10-mostly new
  - **Average – 6.08** (↓ - previous **6.70**)
  
- Please rate the pace of today's class:
  - 1-slow, 5-just right, 10-fast
  - **Average – 4.90** (↓ - previous **5.24**)

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## FEEDBACK FROM 5/6

- **What exactly is the difference between the terms concurrency and parallelism?**
  
- This depends on if the computer has 1 or more CPU cores
- On a single CPU core computer:  
**Concurrency** is when multiple tasks can run in overlapping periods. It's an illusion of multiple tasks running in parallel because of a very fast switching by the CPU. The two tasks don't actually run at the same time on a single-core CPU.
- **Parallelism** is when tasks actually run in parallel in multiple CPUs (or hyperthreads)

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## FEEDBACK - 2

- What would we say the Ideal sloppy threshold is?
- It is subject to our needs?
- Or is there a way to find a mid point between accuracy and efficiency?
- The ideal sloppy threshold depends on the goal.
- If your goal is accuracy, chose a low number
- If your goal is performance, chose a high number
- If your goal is both, you'll need to pick a number in-between to balance the trade-off between accuracy and performance

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## MIDTERM RESULTS

- Statistics
- Average: 78.81
- Mode: 84.0
- Median: 80.0
- Min score: 45
- Lower quartile: 77.00
- 2<sup>nd</sup> quartile: 80.0
- 3<sup>rd</sup> quartile: 84
- Max score: 91
- Standard deviation: 8.93
- Curve: +7
- Question 2 Correction: +4

Score	# of students
100	0
97	0
94	1
91	0
88	7
85	6
82	11
79	14
76	9
73	4
70	4
67	3
64	1
61	1
58	0
55	0
52	0
49	1
46	1
43	0
40	0
37	0

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## GOOGLE BIG TEXTFILE

- <https://faculty.washington.edu/wlloyd/courses/tcss422/assignments/googlebig.txt.gz>

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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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## QUIZ 3

- Build a synchronized array thread-safe data structure
- As a class activity (~30 min allocated)
- Thursday May 15
- Bring Laptops
- Groups of 1 or 2

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## CATCH UP FROM LECTURE 11

- Switch to Lecture 11 Slides
- Slides L11.20 to L11.40  
(Chapter 29 –Lock Based Data Structures)

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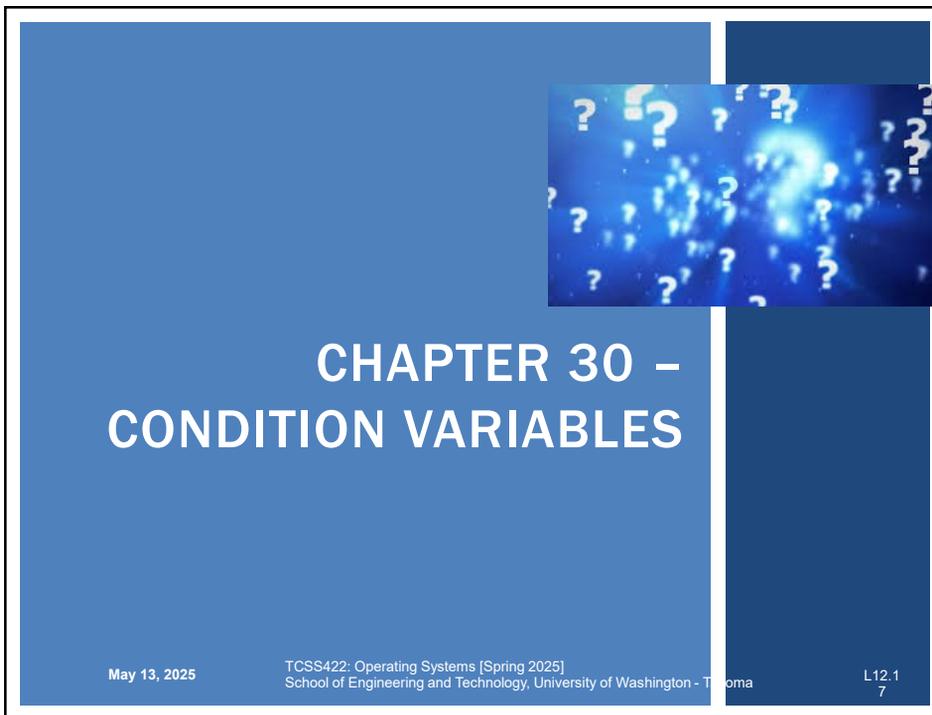
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# CHAPTER 30 – CONDITION VARIABLES

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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

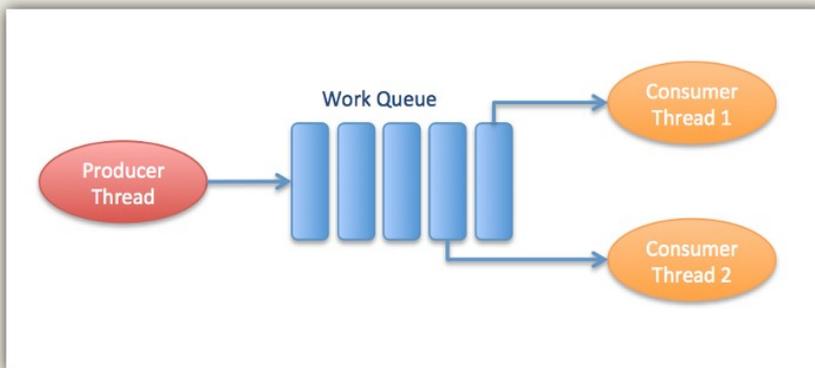
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## PRODUCER / CONSUMER



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## PRODUCER / CONSUMER

- **Producer**
  - Produces items – e.g. child the makes matrices
  - 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  
5:00PM**



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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
```

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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

	$T_{c1}$	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

**Legend**

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

**No while can result in second consumer having no data to consume**

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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

**One condition can result in waking up wrong thread (consumer instead of producer)**

$T_{c1}$	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	<b>Oops! Woke <math>T_{c2}</math></b>

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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 matrices

```
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
23     }
24 }
```

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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 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 – 5/13

- Questions from 5/6 & Midterm Distribution
- Assignment 0 Grades Posted
- Assignment 1 – May 13 --> May 16
- 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

```
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 }
```

Annotations in the code block:  
- A blue arrow points to line 11: `while (bytesLeft < size)`. A box labeled "Check available memory" is positioned to the right.  
- A blue arrow points to line 22: `pthread_cond_signal(&c);`. A box labeled "Broadcast" is positioned to the right.

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## COVER CONDITIONS - 3

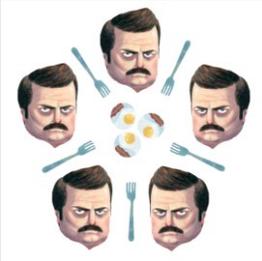
- Broadcast awakens all blocked threads requesting memory
- Each thread evaluates if there's enough memory: (bytesLeft < size)
  - Reject: requests that cannot be fulfilled- go back to sleep
    - *Insufficient memory*
  - Run: requests which **can** be fulfilled
    - with newly available memory!
- **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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  - Non-deadlock concurrency bugs
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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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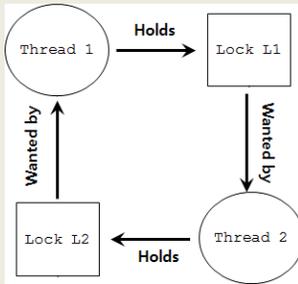
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## DEADLOCK BUGS



- 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 – 5/13

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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

- **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*)

```

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

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.
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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

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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:

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

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## 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

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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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