

TCSS 422: OPERATING SYSTEMS

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



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February 19, 2026

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1

OBJECTIVES – 2/19

- **Questions from 2/17**
- Assignment 0 Grades Posted
- Assignment 1 Questions
- 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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2

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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Spring 2021

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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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3

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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4

MATERIAL / PACE

- Please classify your perspective on material covered in today's class (29 of 63 respondents (5 online) – 63.04%):
 - 1-mostly review, 5-equal new/review, 10-mostly new
 - **Average – 6.72** (↓ - previous **6.81**)

- 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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5

FEEDBACK FROM 2/17

- **In what way does the precise counter scale poorly?**
- **→ accuracy? speed? space/memory?**
 - Precise counter: up to n threads share a common lock to update a shared counter variable
 - As n scales, lock competition increases dramatically resulting in:
 - More threads, slower speed/runtime (performance)
 - As n scales, accuracy and space (memory) are unchanged
- **Why would you not use the approximate counter over the precise counter?**
- Approximate counter
 - Trades off accuracy for speed
 - Implementation: more complex

→ **Compare the code, which is simpler?**

Precise Counter (57 LOC):
<https://faculty.washington.edu/wlloyd/courses/tcss422/examples/ptread.c>

Sloppy Counter (183 LOC):
<https://faculty.washington.edu/wlloyd/courses/tcss422/examples/Chapter29/sloppybasic.c>

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6

FEEDBACK - 2

- **I don't understand the point of the sloppy threshold**
- Sloppy threshold (S):
- Low values:
(S=1), becomes a precise counter
 - > **all counter reads by threads are exactly the same (i.e. consistent)**
 - (S near 1), high precision, slower performance,
 - > **some counter reads between threads may disagree**
- High values:
(S=20), fewer global updates, updates to local counters happen quickly without waiting to acquire locks
 - > **more counter reads between threads disagree**
 - (S near count), only a few global updates, very inaccurate, but fast
 - > **all counter reads between threads disagree until count finishes**

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7

FEEDBACK - 3

- **Precise counter is accurate but has low performance, Sloppy counter has high performance, but can be inaccurate**
- **Is there any perfect counter?**
- See Chapter 29 Examples: `perfect.c`
- Counter implementation using atomic integer
- No locking, no blocking, no spinning !
- Increment/decrement are **WAIT-FREE** atomic operations
- **Wait-free** means every thread is guaranteed to finish its operation in bounded steps, no matter what other threads do.
- Why wait-free is hard – it requires:
 - No retry loops dependent on other threads (that change the data)
 - No locks
 - No spinning waiting on shared state

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8

FEEDBACK - 4

- **Perfect scaling is a little confusing**
- Achieve (n) performance gain with (n) additional resources
- Consider processing throughput measured in
 - Transactions per second (tps)
 - 1 core computer
 - throughput= 100 tps
 - 10 core computer (x10)
 - throughput = 1000 tps (x10)
 - 1,000,000 core computer (x1000000)
 - Throughput = 100000000 tps (x1000000)
- If the performance metric is runtime, each doubling of CPUs should halve the runtime: 1 core 60 sec, 2 cores 30 sec, 4 cores 15 sec

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9

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10

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11

GOOGLE BIG TEXTFILE

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

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12

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- Questions from 2/17
- Assignment 0 Grades Posted
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13

TUTORIAL 2

- Pthread Tutorial
- Practice using:
 - pthreads
 - Locks
 - Condition variables

- Generate and visualize prime number generation in parallel

- Now posted - due in 2 weeks

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14

CATCH UP FROM LECTURE 11

- Switch to Lecture 11 Slides
- Slides L11.33 to L11.45
(Chapter 29 –Lock Based Data Structures)

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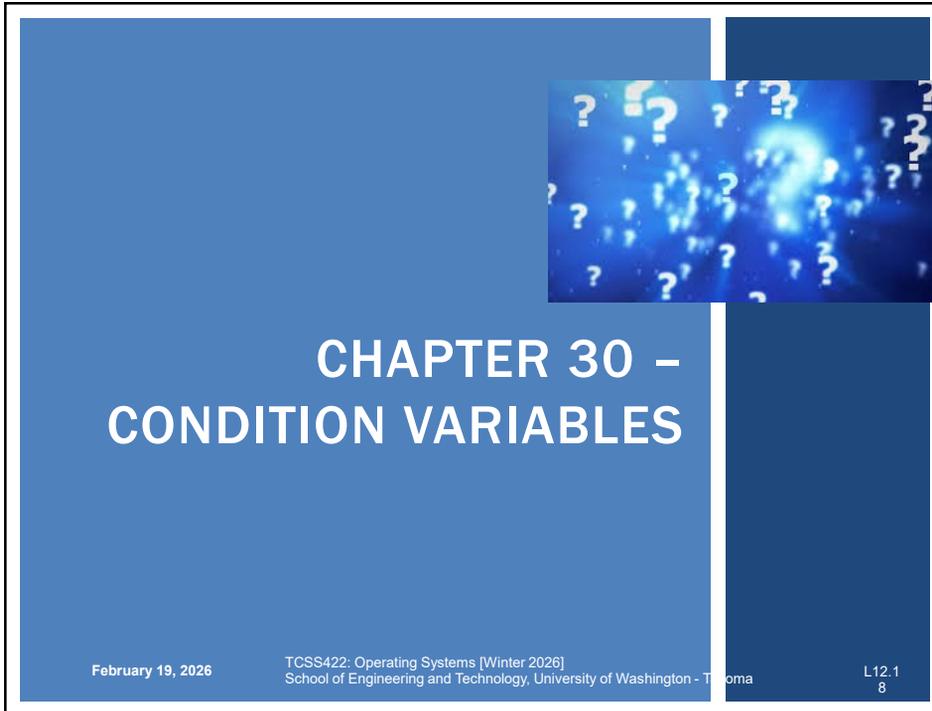
16

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-------------------	---	--------

17



CHAPTER 30 – CONDITION VARIABLES

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8

18

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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19

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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20

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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21

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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22

MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c

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23

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24

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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25

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

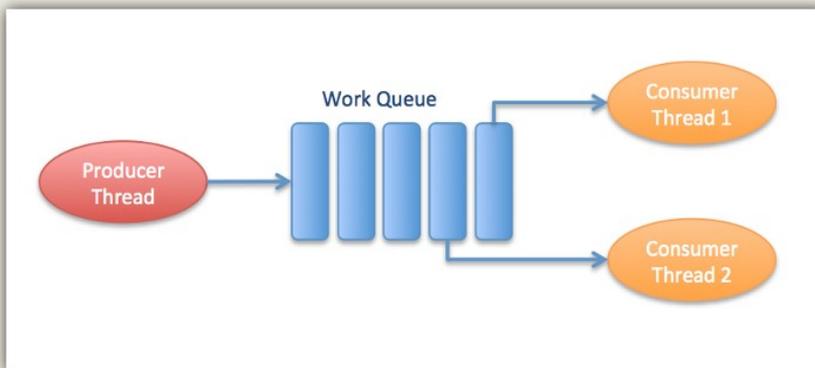
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26

PRODUCER / CONSUMER



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27

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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28

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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-------------------	---	--------

29

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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30

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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31

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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32

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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33

EXECUTION TRACE: NO WHILE, 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		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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34

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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35

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	Oops! Woke T_{c2}

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36

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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37

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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38

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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39

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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40

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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41

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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42

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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43

**WE WILL RETURN AT
5:00PM**



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4

44

OBJECTIVES – 2/19

- Questions from 2/17
- Assignment 0 Grades Posted
- Assignment 1 Questions
- 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
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45

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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46

COVERING CONDITIONS - 2

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

Check available memory (points to line 11)

Broadcast (points to line 22)

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47

COVER CONDITIONS - 3

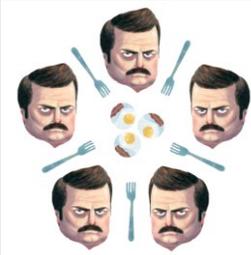
- Broadcast awakens all blocked threads requesting memory
- Each thread evaluates if there's enough memory: (bytesLeft < size)
 - Reject: requests that cannot be fulfilled- go back to sleep
 - *Insufficient memory*
 - Run: requests which **can** be fulfilled
 - with newly available memory!
- **Another 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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48

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 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
 - Asymmetric solution: number the philosophers. Odd #s pick up left fork 1st, Even #s pick up right. This breaks circular symmetry and prevents deadlock. At most $\lfloor N/2 \rfloor$ can eat at same time.



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49

OBJECTIVES – 2/19

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50



CHAPTER 32 – CONCURRENCY PROBLEMS

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51

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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52

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53

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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-------------------	---	--------

54

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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55

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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56

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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57

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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-------------------	---	--------

58

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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-------------------	---	--------

59

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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60

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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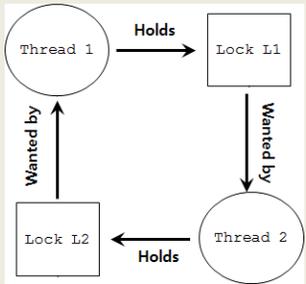
61

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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-------------------	---	--------

62

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 - Deadlock prevention

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-------------------	---	--------

63

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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64

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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65

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-------------------	---	--------

66

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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67

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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68

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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69

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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70

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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71

CONDITIONS FOR DEADLOCK

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72

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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73

CONDITIONS FOR DEADLOCK

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74

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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75

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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-------------------	---	--------

76

CONDITIONS FOR DEADLOCK

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77

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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78

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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79

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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80

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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81

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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82

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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83

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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-------------------	---	--------

84

QUESTIONS



85