TCSS 422: OPERATING SYSTEMS

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

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

1

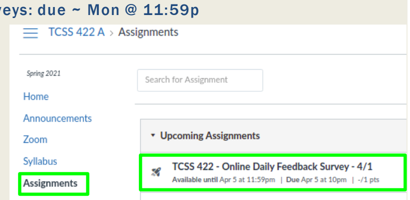
OBJECTIVES – 5/13

- 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

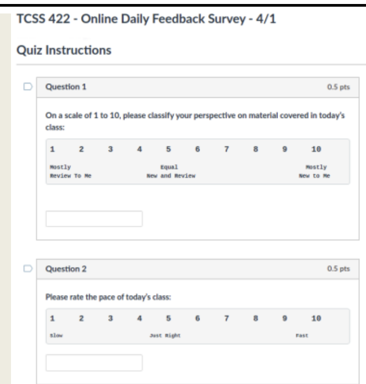
2

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



3



4

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)**

5

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)

6

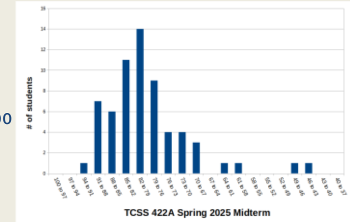
FEEDBACK - 2

- ***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

7

MIDTERM RESULTS

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



8

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

9

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

10

GOOGLE BIG TEXTFILE

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

11

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

12

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

13

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

14

CATCH UP FROM LECTURE 11

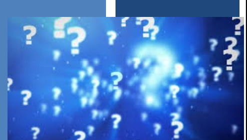
- Switch to Lecture 11 Slides
- Slides L11.20 to L11.40
  (Chapter 29 –Lock Based Data Structures)

15

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

16



CHAPTER 30 – CONDITION VARIABLES

17

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 ...

18

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)

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.19

19

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.20

20

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.21

21

MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.22

22

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.23

23

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"

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.24

24

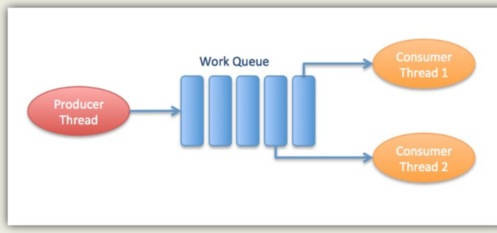
ATTEMPT TO USE CONDITION VARIABLE WITHOUT A WHILE STATEMENT

```
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

25

PRODUCER / CONSUMER



26

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

27

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

28

WE WILL RETURN AT 5:00PM

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***

```
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;
}
```


30

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);
        }
}
```


31

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
```


32

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
- PROBLEM: no while. If thread wakes up it MUST execute
- If we scale to (2+) consumer's it fails
  - How can it be fixed ?

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

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

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

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}

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}

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 ...

37

TWO CONDITIONS

- Required w/ multiple producer and consumer threads
- Use two condition variables: <u>**empty**</u> & <u>**full**</u>
  - 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);
    }
}
```


38

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;
}
```


39

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
```


40

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

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

Start the presentation to see live content. For screen share software, share the entire screen. Get help at pollev.com/app

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

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

43

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.44

44

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?

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.45

45

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

Check available memory

Broadcast

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.46

46

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.47

47

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.48

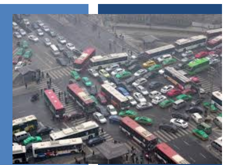
48

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.49

49



CHAPTER 32 – CONCURRENCY PROBLEMS

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.50

50

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**

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.51

51

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.52

52

NON-DEADLOCK BUGS

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.53

53

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;
```

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.54

54

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);
```


55

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?

56

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(…){
    …
```


57

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;
    …
}
```


58

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)

59

NON-DEADLOCK BUGS - 2

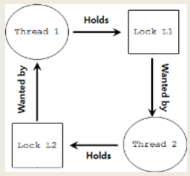
- Atomicity
  - How can we tell if a given variable is shared?
    - Can search the code for uses
  - How do we know if all instances of its use are shared?
    - Can some non-synchronized, non-atomic uses be legal?
      - Legal uses: before threads are created, after threads exit
    - Must verify the scope
- Order violation
  - Must consider all variable accesses
  - Must know desired order

60

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.61

61

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.62

62

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.63

63

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.64

64

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**

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.65

65

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;
}
```

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.66

66

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)

67

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;
}
```


68

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
}
```


69

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

70

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

71

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…

72

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

73

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

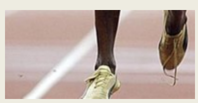
74

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!



75

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

76

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

77

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

78

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

Start the presentation to see live content. For screen share software, share the entire screen. Get help at **pollev.com/app**

79

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.80

80

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.81

81

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

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.82

82

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.

May 13, 2025 | TCSS422: Operating Systems [Spring 2025] School of Engineering and Technology, University of Washington - Tacoma | L12.83

83

QUESTIONS

84