# TCSS 422: OPERATING SYSTEMS

## Condition Variables

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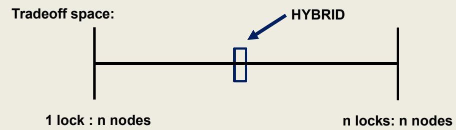
## FEEDBACK – 4/25

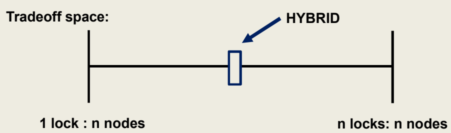
- Quiz: How to create a thread safe data struct
  - Quizzes like these are great, I learn a lot!
- How hybrid approach is implemented?
- Hybrid approach: presumably for linked-list locking






## FEEDBACK - 2

- Consider the tradeoff space: Concurrent Linked List
- Ratio of locks : Nodes




- Which design is best for fast list traversal?
- Which design is best for optimal concurrency?
  - *Many threads working within the structure at same time*
- If we add locks:

  How does list traversal change?
  How does concurrency change?



## FEEDBACK - 3

- Quiz 3 verifications
- Program 2
  - Posted
- Midterm: Thursday May 4 – Primary Coverage:
  - CPU Scheduling (Virtualizing the CPU)
  - Chapters 4, 6, 7, 8, 9
  - Concurrency
  - Chapters 26, 27, 28, 29, 30, 32*
    - ** - deadlocks: common causes, how to avoid*



## OBJECTIVES

- Sloppy Counter, demo
- Condition variables
- Consumer/Producer
- Covering condition



## SLOPPY COUNTER

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

## SLOPPY COUNTER - 2

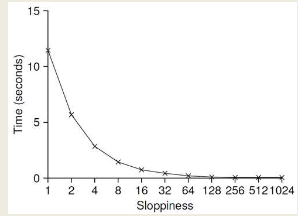
- Update threshold (S) = 5
- Synchronized across four CPU cores
- Threads update local CPU counters

| Time | $L_1$ | $L_2$ | $L_3$ | $L_4$ | G |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 1 | 1 | 0 |
| 2 | 1 | 0 | 2 | 1 | 0 |
| 3 | 2 | 0 | 3 | 1 | 0 |
| 4 | 3 | 0 | 3 | 2 | 0 |
| 5 | 4 | 1 | 3 | 3 | 0 |
| 6 | 5 → 0 | 1 | 3 | 4 | 5 (from $L_1$) |
| 7 | 0 | 2 | 4 | 5 → 0 | 10 (from $L_4$) |



## THRESHOLD VALUE S

- Consider 4 threads increment a counter 1000000 times each
- Low *S* → What is the consequence?
- High S → What is the consequence?






## SLOPPY COUNTER - EXAMPLE

- Example implementation (sloppybasic.c)
- Also with CPU affinity (sloppy.c)



## CONDITION VARIABLES

- There are many cases where a thread wants to wait for another thread before proceeding with execution
- Consider when a precondition must be fulfilled before it is meaningful to proceed …



## CONDITION VARIABLES - 2


- Support a signaling mechanism to alert threads when preconditions have been satisfied
- Eliminate busy waiting
- Alert one or more threads to "consume" a result, or respond to state changes in the application
- Threads are placed on an **explicit queue** (FIFO) to wait for signals
- **Signal**: wakes one thread
  **broadcast** wakes all (ordering by the OS)



## CONDITION VARIABLES - 3

- Condition variable

```
pthread cond t c;
```

  - Requires initialization
- Condition API calls

```
pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);    // wait()
pthread_cond_signal(pthread_cond_t *c);                      // signal()
```

- wait() accepts a mutex parameter
  - Releases lock, puts thread to sleep
- signal()
  - Wakes up thread, awakening thread acquires lock

## CONDITION VARIABLES - QUESTIONS

- Why would we want to put waiting threads on a queue… why not use a stack?
- Using condition variables eliminates busy waiting by putting a thread "sleep" and yielding the CPU. Why do we want to not busily wait for the lock to become available?
- A program has 10-threads, where 9 threads are waiting. The working thread finishes and broadcasts that the lock is available. What happens next?



## MATRIX GENERATOR

Matrix generation example

Chapter 30
signal.c



## MATRIX GENERATOR

- The main thread, and worker thread (generates matrices) share a single matrix pointer.
- What would happen if we don't use a condition variable to coordinate exchange of the lock?
- Let's try "nosignal.c"



## SUBTLE RACE CONDITION: WITHOUT A WHILE

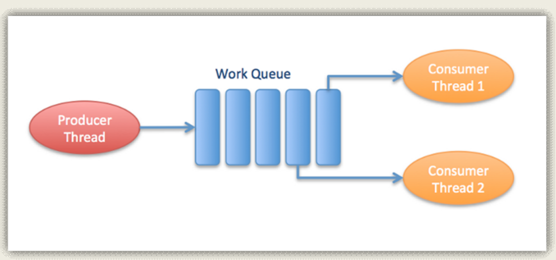
```
void thr_exit() {
        done = 1;
        Pthread_cond_signal(&c);
}

void thr_join() {
        if (done == 0)
                Pthread_cond_wait(&c);
}
```

- Parent thread calls thr_join() and executes the comparison
- The context switches to the child
- The child runs thr_exit() and signals the parent, but the parent is not waiting yet.
- **The signal is lost**
- The parent deadlocks



## PRODUCER / CONSUMER






## PRODUCER / CONSUMER

- **Producer**
  - Produces items – consider the child matrix maker
  - Places them in a buffer
    - Example: the buffer 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

## 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



## PUT/GET ROUTINES

- Buffer is a one element shared data structure (int)
- Producer "puts" data
- Consumer "gets" data
- Shared data structure requires synchronization

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

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

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



## PRODUCER / CONSUMER - 3

- Producer adds data
- Consumer removes data (busy waiting)
- **Will this code work (spin locks) with 2-threads?**
  1. Producer 2. Consumer

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

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



## PRODUCER / CONSUMER - 3

- The shared data structure needs synchronization!

Producer

```
cond_t cond;
mutex_t mutex;

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

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



## PRODUCER/CONSUMER - 4

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

Consumer

- This code as-is works with just:
  (1) Producer
  (1) Consumer
- If we scale to (2+) consumer's it fails
  - How can it be fixed ?



## EXECUTION TRACE:
### NO WHILE, 1 PRODUCER, 2 CONSUMERS

- Two threads

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

| $T_{c1}$ | State | $T_{c2}$ | State | $T_p$ | State | Count | Comment |
|---|---|---|---|---|---|---|---|
| c1 | Running | | Ready | | Ready | 0 | |
| c2 | Running | | Ready | | Ready | 0 | |
| c3 | Sleep | | Ready | | Ready | 0 | Nothing to get |
| | Sleep | | Ready | p1 | Running | 0 | |
| | Sleep | | Ready | p2 | Running | 0 | |
| | Sleep | | Ready | p4 | Running | 1 | Buffer now full |
| | Ready | | Ready | p5 | Running | 1 | $T_{c1}$ awoken |
| | Ready | | Ready | p6 | Running | 1 | |
| | Ready | | Ready | p1 | Running | 1 | |
| | Ready | | Ready | p2 | Running | 1 | |
| | Ready | | Ready | p3 | Sleep | 1 | Buffer full; sleep |
| | Ready | c1 | Running | | Sleep | 1 | $T_{c2}$ sneaks in ... |
| | Ready | c2 | Running | | Sleep | 1 | |
| | Ready | c4 | Running | | Sleep | 0 | ... and grabs data |
| | Ready | c5 | Running | | Ready | 0 | $T_p$ awoken |
| | Ready | c6 | Running | | Ready | 0 | |
| c4 | Running | | Ready | | Ready | 0 | **Oh oh! No data** |

## PRODUCER/CONSUMER SYNCHRONIZATION

- When producer threads awake, they do not check if there is any data in the buffer…
  - Need while, not if
- What if $T_p$ puts a value, wakes $T_{c1}$ whom consumes the value
- Then $T_p$ has a value to put, but $T_{c1}$'s signal on &cond wakes $T_{c2}$
- There is nothing for $T_{c2}$ consume, so $T_{c2}$ sleeps
- $T_{c1}$, $T_{c2}$, and $T_p$ all sleep forever
- $T_{c1}$ needs to wake $T_p$ to $T_{c2}$



## EXECUTION TRACE:
### WHILE, 1 CONDITION, 1 PRODUCER, 2 CONSUMERS

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

| $T_{c1}$ | State | $T_{c2}$ | State | $T_p$ | State | Count | Comment |
|---|---|---|---|---|---|---|---|
| c1 | Running | | Ready | | Ready | 0 | |
| c2 | Running | | Ready | | Ready | 0 | |
| c3 | Sleep | | Ready | | Ready | 0 | Nothing to get |
| | Sleep | c1 | Running | | Ready | 0 | |
| | Sleep | c2 | Running | | Ready | 0 | |
| | Sleep | c3 | Sleep | | Ready | 0 | Nothing to get |
| | Sleep | | Sleep | p1 | Running | 0 | |
| | Sleep | | Sleep | p2 | Running | 0 | |
| | Sleep | | Sleep | p4 | Running | 1 | Buffer now full |
| | Ready | | Sleep | p5 | Running | 1 | $T_{c1}$ awoken |
| | Ready | | Sleep | p6 | Running | 1 | |
| | Ready | | Sleep | p1 | Running | 1 | |
| | Ready | | Sleep | p2 | Running | 1 | |
| | Ready | | Sleep | p3 | Sleep | 1 | Must sleep (full) |
| c2 | Running | | Sleep | | Sleep | 1 | Recheck condition |
| c4 | Running | | Sleep | | Sleep | 0 | $T_{c1}$ grabs data |
| c5 | Running | | Ready | | Sleep | 0 | Oops! Woke $T_{c2}$ |



## 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 … |



## TWO CONDITIONS

- Use two condition variables: empty & full
  - One condition handles the producer
  - the other the consumer

```
cond_t empty, full;
mutex_t mutex;

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

```



## FINAL PRODUCER/CONSUMER

- Change buffer from int, to int buffer[MAX]
- Add indexing variables

```
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;
}
```



## 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
```

## 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



## COVERING CONDITIONS

- A condition that covers ***all*** cases (conditions):
- Excellent use case for pthread_cond_broadcast

- Consider memory allocation:
  - What if 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



## 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



## 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!

- **Overhead**
  - Many threads may be awoken which can't execute



## QUESTIONS