Condition Variables & Concurrency

Computer Operating Systems, Spring 2024

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Administrivia

- Lecture on Thursday will be on Zoom (more threads stuff)
- Back to in-person next week!!!!!

- PennOS
  - You have the first milestone, which needs to be done sometime this week
  - Your group (or at least most of your group) needs to meet with your assigned TA and display the expectations laid out in the PennOS Specification
  - Everyone should have already contacted their group, I sent emails to every group that had to be filled by course staff (let us know if you haven't gotten this)

- Checkin to be released, due before lecture next week

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- Any questions, comments or concerns from last lecture?

Lecture Outline

- **Data Race & Mutex Practice**
- Intro to Deadlocks
- Producer & Consumer Problem
- Condition Variables
- Monitors
- Reader/Writer Problem

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What is the range of values that g can have at the end of the program?

```
int g = 0;
void *worker(void *ignore) {
  for (int k = 1; k <= 3; k++) {
    g = g + k;
  }
  printf("g = %d\n", g);
  return NULL;
}

int main() {
  pthread_t t1, t2;
  int ignore;
  ignore = pthread_create(&t1, NULL, &worker, NULL);
  ignore = pthread_create(&t2, NULL, &worker, NULL);
  pthread_join(t1, NULL);
  pthread_join(t2, NULL);
  return EXIT_SUCCESS;
}
```

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- The code below has three functions that could be executed in separate threads. Note that these are not thread entry points, just functions used by threads:
  - Assume that "lock" has been initialized

```c
1  // global variables
2  pthread_mutex_t lock;
3  int g =     0;
4  int k = 0;
5
6  void fun1() {
7    pthread_mutex_lock(&lock);
8    g += 3;
9    pthread_mutex_unlock(&lock);
10   k++;
11 }
12
13 void fun2(int a, int b) {
14   g += a;
15   a += b;
16   k = a;
17 }
18
19 void fun3() {
20   pthread_mutex_lock(&lock);
21   g = k + 2;
22   pthread_mutex_unlock(&lock);
23 }
```

- Thread-1 executes line 8 while Thread-2 executes line 21. Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

- Thread-1 executes line 15 while Thread-2 executes line 15. Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

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- The code below has three functions that could be executed in separate threads. Note that these are not thread entry points, just functions used by threads:
  - Assume that "lock" has been initialized

- Thread-1 executes line 8 while Thread-2 executes line 14
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

- Thread-1 executes line 14 while Thread-2 executes line 16.
  Choose one:
  - Could lead to a race condition.
  - There is no possible race condition.
  - The situation cannot occur.

```
1  // global variables
2  pthread_mutex_t lock;
3  int g =     0;
4  int k = 0;
5
6  void fun1() {
7    pthread_mutex_lock(&lock);
8    g += 3;
9    pthread_mutex_unlock(&lock);
10   k++;
11 }
12
13 void fun2(int a, int b) {
14   g += a;
15   a += b;
16   k = a;
17 }
18
19 void fun3() {
20   pthread_mutex_lock(&lock);
21   g = k + 2;
22   pthread_mutex_unlock(&lock);
23 }
```

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Liveness

- Liveness: A set of properties that ensure that threads execute in a timely manner, despite any contention on shared resources.

- When `pthread_mutex_lock();` is called, the calling thread blocks (stops executing) until it can acquire the lock.
  - What happens if the thread can never acquire the lock?

Liveness Failure: Releasing locks

- If locks are not released by a thread, then other threads cannot acquire that lock

- See `release_locks.c`
  - Example where locks are not released once critical section is completed.

Liveness Failure: Deadlocks

- Consider the case where there are two threads and two locks
  - Thread 1 acquires lock1
  - Thread 2 acquires lock2
  - Thread 1 attempts to acquire lock2 and blocks
  - Thread 2 attempts to acquire lock1 and blocks

Neither thread can make progress ☹

- See `milk_deadlock.c`

- Note: there are many algorithms for detecting/preventing deadlocks

Liveness Failure: Mutex Recursion

- What happens if a thread tries to re-acquire a lock that it has already acquired?
- See `recursive_deadlock.c`
- By default, a mutex is not re-entrant.
  - The thread won't recognize it already has the lock, and block until the lock is released

Aside: Recursive Locks

- Mutex’s can be configured so that you it can be re-locked if the thread already has locked it. These locks are called *recursive locks* (sometimes called *re-entrant locks*).

- Acquiring a lock that is already held will succeed
- To release a lock, it must be released the same number of times it was acquired

- Has its uses, but generally discouraged.

Lecture Outline

- Data Race & Mutex Practice
- Intro to Deadlocks
- **Producer & Consumer Problem**
- Condition Variables
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Producer & Consumer Problem

- Common design pattern in concurrent programming.
  - There are at least two threads, at least one producer and at least one consumer.
  - The producer threads create some data that is then added to a shared data structure
  - Consumers will process and remove data from the shared data structure

- We need to make sure that the threads play nice

Aside: C++ deque

- I am using a c++ **`deque`** for this example so that we don't have to write our own data structure. This is not legal C

- Deque is a double ended queue, you can push to the front or back and pop from the front or back

```
// global deque of integers
// will be initialized to be empty
deque<int> dq {};

int main() {
  dq.push_back(3);        // adds 3
  int val = dq.at(0);     // access index 0
  dq.pop_front()          // delete first element
  printf("%d\n", val);    // should print 3
}
```

Producer Consumer Example

- Does this work?
- Assume that two threads are created, one assigned to each function

```
deque<int> dq {};

void* producer_thread(void* arg) {
  while (true) {
    dq.push_back(long_computation());
  }
}

void* consumer_thread(void* arg) {
  while (true) {
    while (dq.size() == 0) {
      // do nothing
    }
    int val = dq.at(0);
    dq.pop_front();
    do_something(val);
  }
}
```

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- How do we use mutex to fix this? To make sure that the threads access dq safely.
  - You are only allowed to add calls to pthread_mutex_lock and pthread_mutex_unlock
  - Can add other mutexes if needed

```
deque<int> dq {};
pthread_mutex_t dq_lock;

void* producer_thread(void* arg) {
  while (true) {
    dq.push_back(long_computation());
  }
}

void* consumer_thread(void* arg) {
  while (true) {
    while (dq.size() == 0) {
      // do nothing
    }
    int val = dq.at(0);
    dq.pop_front();
    do_something(val);
  }
}
```

Any issue?

- The code is correct, but do we notice anything wrong with this code?

- Maybe a common inefficiency that I have told you about several times before (just in other contexts?)

- Then consumer code "busy waits" when there is nothing for it to consume.
  - It is particularly bad if we have multiple consumers, the locks make the busy waiting of the consumers sequential and use more CPU resources.

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- **Condition Variables**
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Condition Variables

- Variables that allow for a thread to wait until they are notified to resume

- Avoids waiting clock cycles “spinning”

- Done in the context of mutual exclusion
  - a thread must already have a lock, which it will temporarily release while waiting
  - Once notified, the thread will re-acquire a lock and resume execution

Condition Variables

- Condition Variables exist so that:
  - Threads can wait for a shared variable to change
  - Threads can notify waiting threads that a change has been made to the shared variable, and that they can stop waiting

- Since condition variables are used to manage access of a shared variable, it is utilized with a mutex (lock).
  - For a thread to wait, it must first have the associated lock. While the thread waits, it gives up the lock
  - For a thread to signal threads sleeping on a condition variable, it must also have the associated lock.
  - When a thread is notified, it will resume executing once it can re-acquire the lock.

pthreads and condition variables

- `pthread.h` defines datatype `pthread_cond_t`

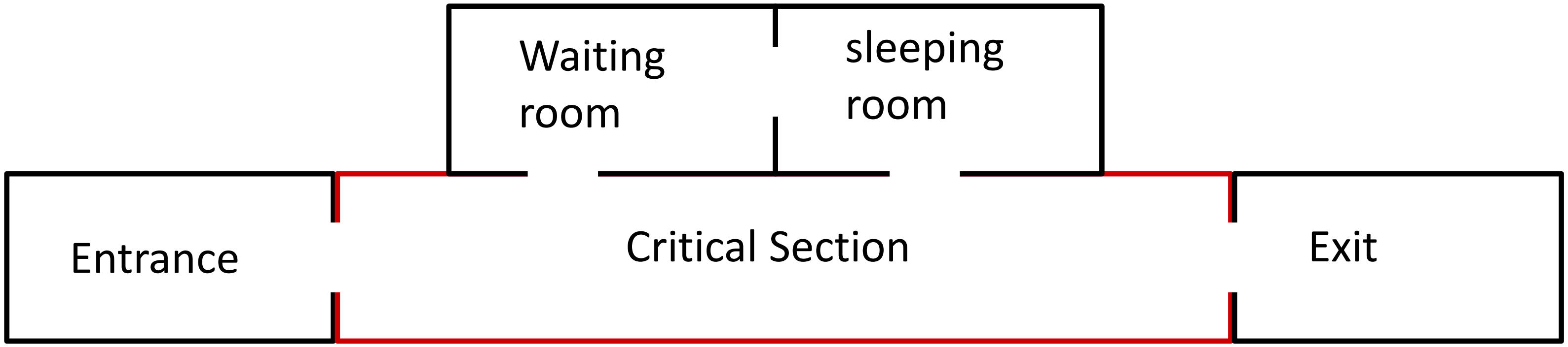
- ```
  int pthread_cond_init(pthread_cond_t* cond,
                        const pthread_condattr_t* attr);
  ```
  - Initializes a condition variable with specified attributes
- ```
  int pthread_cond_destroy(pthread_cond_t* cond);
  ```
  - "Uninitializes" a condition variable – clean up when done

pthreads and condition variables

- `pthread.h` defines datatype `pthread_cond_t`
- ```
  int pthread_cond_wait(pthread_cond_t* cond,
                        pthread_mutex_t* mutex);
  ```
  - Atomically releases the mutex and blocks on the condition variable. Once unblocked (by one of the functions below), function will return and calling thread will have the mutex locked
- ```
  int pthread_cond_signal(pthread_cond_t* cond);
  ```
  - Unblock at least one of the threads on the specified condition
- ```
  int pthread_cond_broadcast(pthread_cond_t* cond);
  ```
  - Unblock all threads blocked on the specified condition
  ```

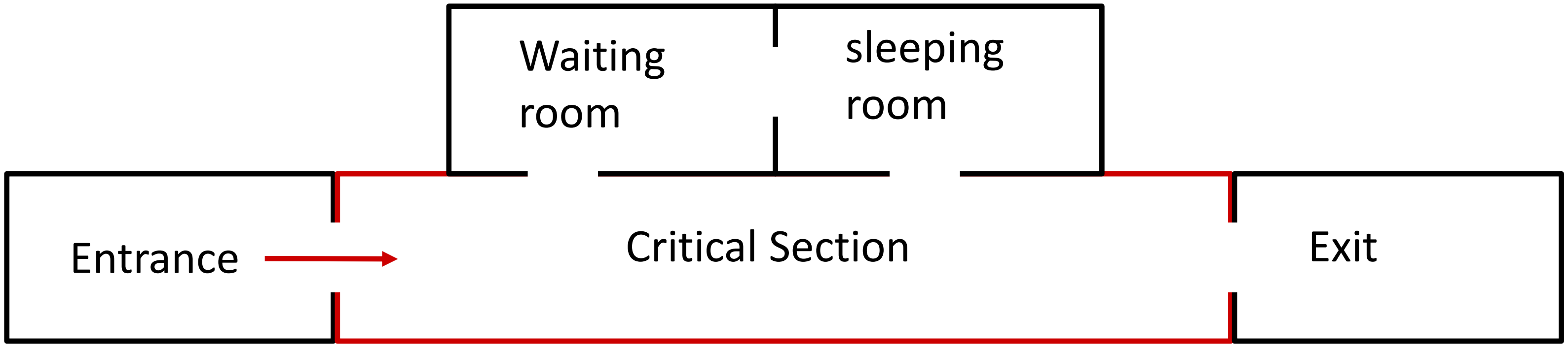
Condition Variable & Mutex Visualization

- This is to visualize how we are using condition variables in this example



Condition Variable & Mutex Visualization

- This is to visualize how we are using condition variables in this example



`pthread_mutex_lock`

A thread enters the critical section by acquiring a lock

Condition Variable & Mutex Visualization

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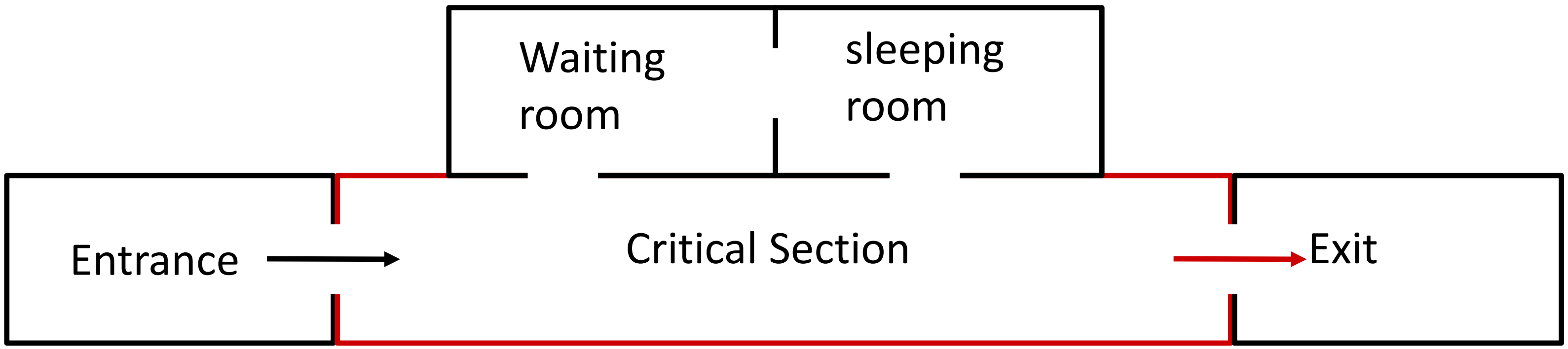


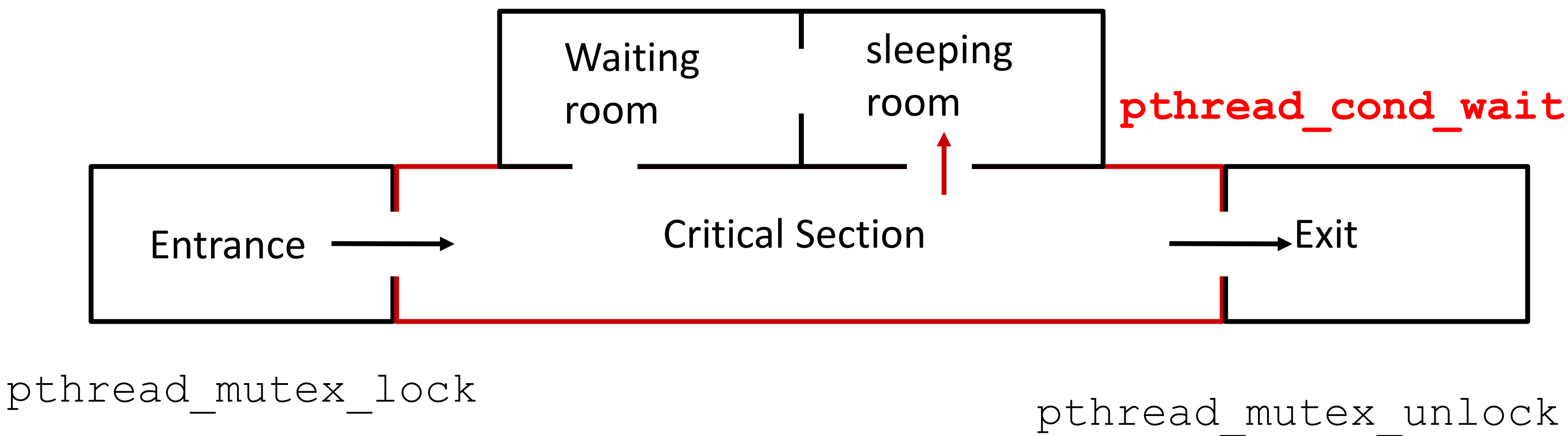
`pthread_mutex_lock`

`pthread_mutex_unlock`

A thread can exit the critical section by acquiring a lock

Condition Variable & Mutex Visualization

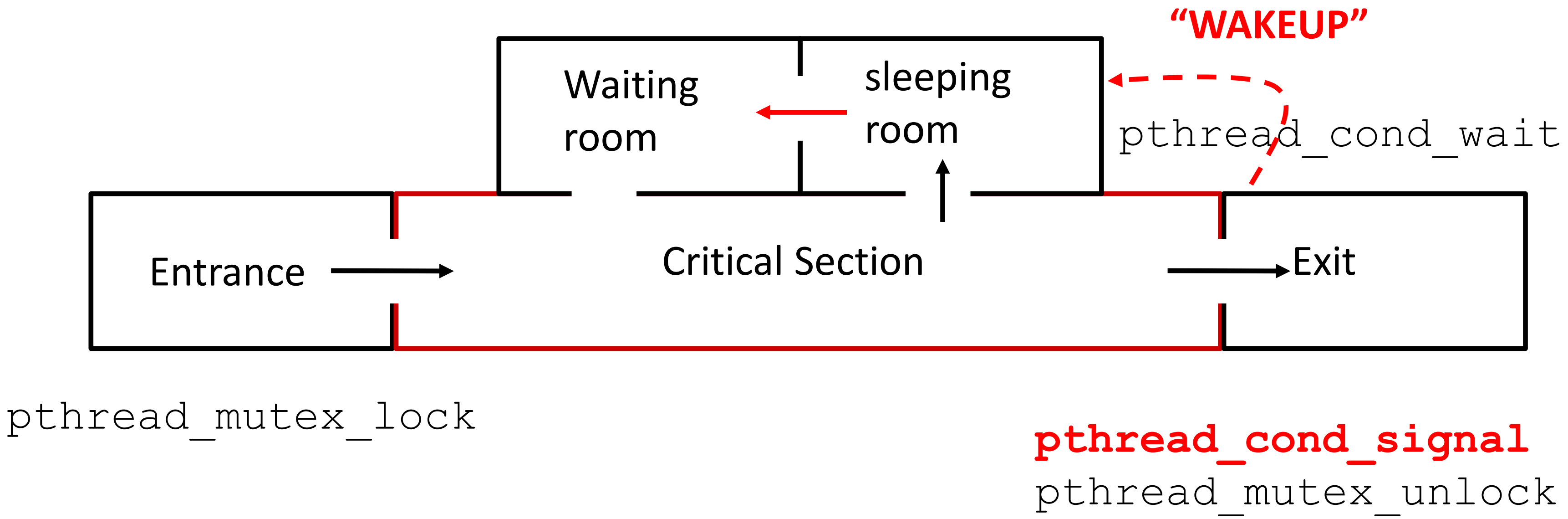
- This is to visualize how we are using condition variables in this example



If a thread can't complete its action, or must wait for some change in state, it can "go to sleep" until someone wakes it up later.

Condition Variable & Mutex Visualization

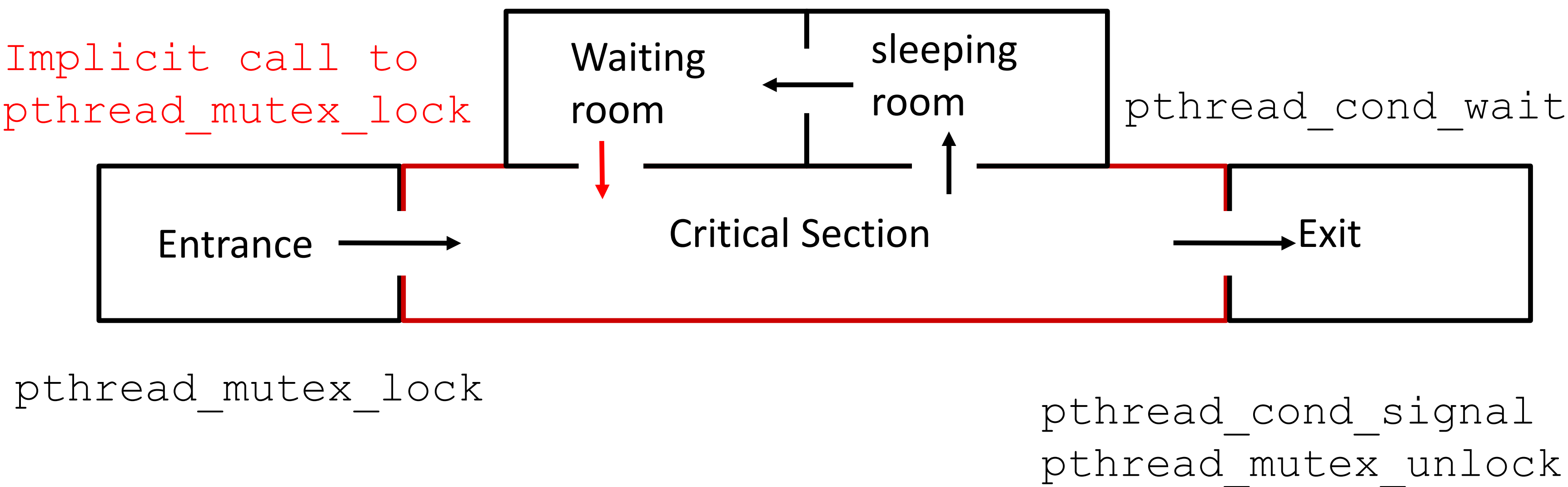
- This is to visualize how we are using condition variables in this example



When a thread modifies state and then leaves the critical section, it can also call pthread_cond_signal to wake up threads sleeping on that condition variable

Condition Variable & Mutex Visualization

- This is to visualize how we are using condition variables in this example



One or more sleeping threads wake up and attempt to acquire the lock.
Like a normal call to pthread_mutex_lock the thread will block until it can acquire the lock

Revisiting Producer Consumer

- Demo: producer_and_consumer.cpp
  - Original producer and consumer code
  - One thread reads a line from stdin and puts it in the deque
  - The other thread gets that string and prints it
  - The consumer thread spins while doing this

- Demo: cond.cpp
  - Consumer and producer uses condition variable
  - Consumer waits if there is no value to process
  - Producer notifies any sleeping threads
  - No more spinning ☺

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- We still need a while loop in the consumer, even with condition variables.
- Why is this needed? Why may our code be incorrect if we don't have one?

```
deque<int> dq;
pthread_mutex_t dq_lock;
pthread_cond_t dq_cond;


void* consumer_thread(void* arg) {
  while (true) {
    pthread_mutex_lock(&dq_lock);
    while (dq.size() == 0) {
      pthread_cond_wait(&dq_cond,
                        &dq_lock);
      // do nothing
    }
    int val = dq.at(0);
    dq.pop_front();
    do_something(val);
    pthread_mutex_unlock(&dq_lock);
  }
}
```

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Monitors

- Monitors are a higher-level synchronization concept.
- A Monitor is associated with an object and enforces that only one thread can access data/call the functions of an object at a time.
- A monitor is made up of a mutex and a condition variable.
- Every Object in java is/has a monitor.

Java Monitor Example

```
public class obj {
  private List<String> data;

  public synchronized String get() {
     while (this.data.size() == 0) {
        wait();
        // Ommitted Java exception handling bs
     }
     return this.data.remove(0);
  }

  public synchronized void set(String new_data) {
     this.data.add(new_data);
     notifyAll();
  }

}
```

Monitor vs Condition Variables

- What we implemented with condition variables was essentially a monitor. But condition variables are not restricted to being used in that context.

- Monitors in Java work in a lot of cases and can help abstract away ***some*** of the details with synchronization

- In some cases, a monitor would not make the most sense, but you can still use condition variables to solve the issue.

- **Monitors are a concept, condition variables is an implementation detail**

Lecture Outline

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- **Reader/Writer Problem**

Readers / Writers Problem

- What if we have some shared data/object and threads can either read or write to the shared data

- How many readers can we have at a time?
  - Any number of readers, as long as no one is writing, we can have an unlimited number of readers.

- How many writers can we have at a time?
  - If a thread is writing to the shared data, then only that thread can have access to the shared data

- How do we support multiple readers but single writer?

Reader/Writers

- We need some metadata, more than just a lock and a cond. Consider the following solutions.

```
// These would normally be put
// into a rdwr_lock structure
int num_readers = 0;    // number of active readers
int writers_waiting = 0;  // number of writers waiting
bool writer_active = false;  // is there a writer active?

// lock to make sure only one thread can access &
// modify the metadata at a time
pthread_mutex_t lock;

// allows a reader/writer to wait until
// it is ok to read/write
pthread_mutex_t cond;
```

Reader/Writers Demo

- Demo: `rw_lock.c`
  - Lots of code for how we grant access to readers & writers

- Any thoughts on how we could make this better?
  - Any issues you notice? It is correct, but are there issues with starvation, wakeups, liveness, etc?
  - Hint: there are issues

pthread_rwlock

- Pthread provides a read/write lock implementation that handles this problem for us and hides many of the dirty implementation details

- Very similar to pthread_mutex, but two types of locking
  - **`pthread_rwlock_rdlock(…);`** // lock as a reader
  - **`pthread_rwlock_wrlock(…);`** // lock as a writer