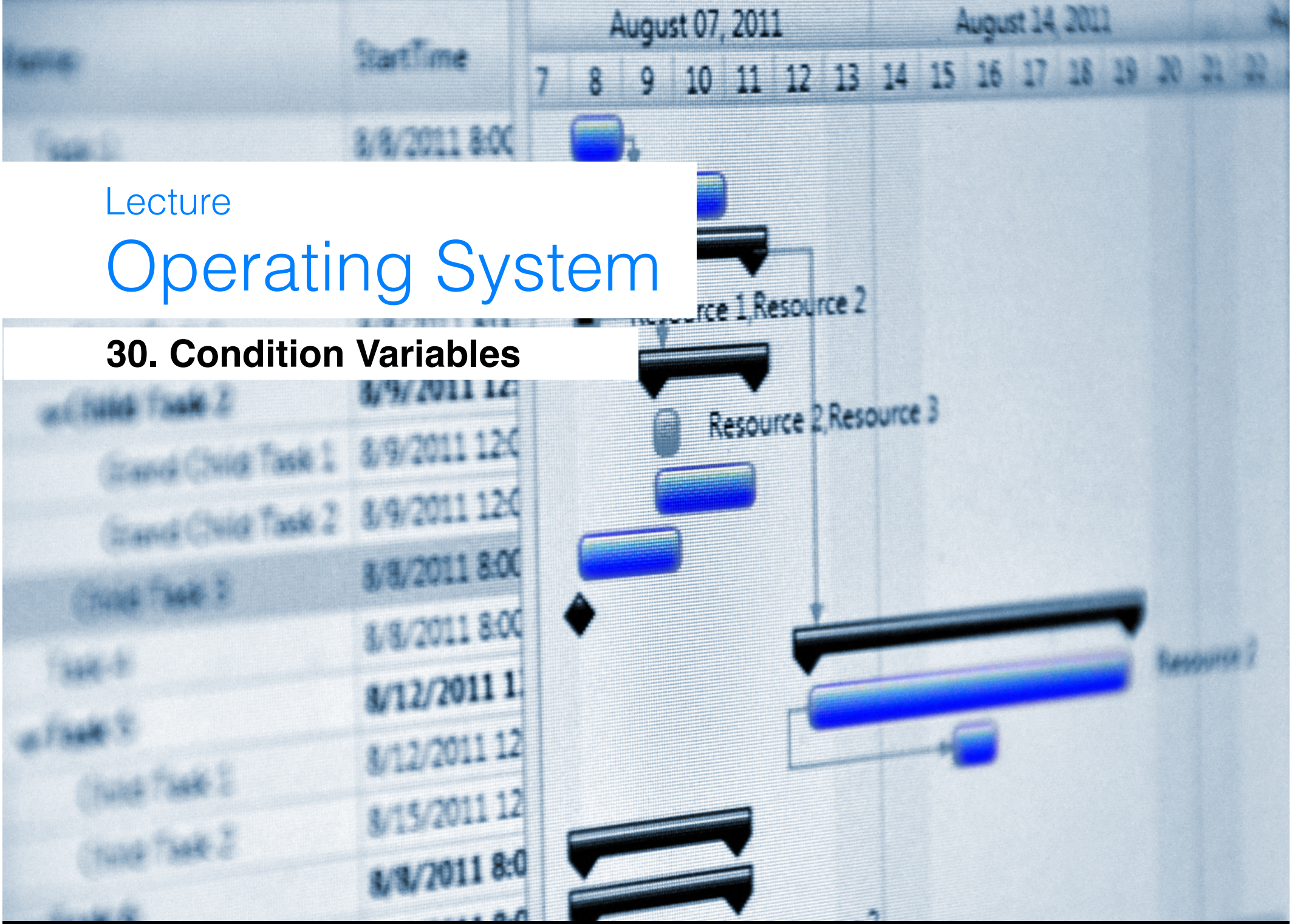
Lecture

Operating System

30. Condition Variables



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Concurrency Objectives

- **Mutual exclusion** (e.g., A and B don't run at same time)
  - solved with locks
- **Ordering** (e.g., B runs after A does something)
  - solved with **condition variables** and semaphores

30. Condition Variables

1. **Join**
2. **Bounded Buffer**
3. **Broadcast**

30. Condition Variables

1. **Join**
2. **Bounded Buffer**
3. **Broadcast**

Condition Variables

- There are many cases where a thread wishes to **check** whether a **condition** is true before continuing its execution.
- Example:
  - A parent thread might wish to check whether a child thread has **completed**.
  - This is often called a `join()`.
- The crux: How to wait for a condition?

Parent waiting for Child

```
void *child(void *arg) {
    printf("child\n");
    // XXX how to indicate we are done?
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    // XXX how to wait for child?
    printf("parent: end\n");
    return 0;
}
```

What we would like to see here is:

```
parent: begin
child
parent: end
```

join: Spin-based Approach

```
volatile int done = 0;

void *child(void *arg) {
    printf("child\n");
    done = 1;
    return NULL;
}

int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t c;
    Pthread_create(&c, NULL, child, NULL); // create child
    while (done == 0)
        ; // spin
    printf("parent: end\n");
    return 0;
}
```

This is hugely inefficient as the parent spins and wastes CPU time.

How to wait for a condition

- Condition variable
  - **Waiting** on the condition
    - *An explicit queue* that threads can put themselves on when some state of execution is not as desired.
  - **Signaling** on the condition
    - Some other thread, *when it changes said state*, can wake one of those waiting threads and allow them to continue.

Definition and Routines

- Declare condition variable
  - **`pthread cond t c;`**
    - Proper initialization is required.
- Operation (the POSIX calls)
  - **`pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m);`**
  - **`pthread_cond_signal(pthread_cond_t *c);`**
  - The wait() call takes a mutex as a parameter.
    - The wait() call release the lock and put the calling thread to sleep.
    - When the thread wakes up, it must re-acquire the lock.

Parent waiting for Child:

Use a condition variable

```c
int done = 0;
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
pthread_cond_t c = PTHREAD_COND_INITIALIZER;

void thr_exit() {
    Pthread_mutex_lock(&m);
    done = 1;
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void *child(void *arg) {
    printf("child\n");
    thr_exit();
    return NULL;
}

void thr_join() {
    Pthread_mutex_lock(&m);
    while (done == 0)
        Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}
```

```c
int main(int argc, char *argv[]) {
    printf("parent: begin\n");
    pthread_t p;
    Pthread_create(&p, NULL, child, NULL);
    thr_join();
    printf("parent: end\n");
    return 0;
}
```

Parent waiting for Child:

Use a condition variable

- Parent:
  - Create the child thread and continues running itself.
  - Call into `thr_join()` to wait for the child thread to complete.
    - Acquire the lock
    - Check *if* the child is *done*
    - Put itself to sleep by calling `wait()`
    - Release the lock
- Child:
  - Print the message “child”
  - Call `thr_exit()` to wake the parent thread
    - Grab the lock
    - *Set* the state variable *done*
    - `Signal()` the parent thus waking it.

Importance of state variable `done`

```
void thr_exit() {
    Pthread_mutex_lock(&m);
    Pthread_cond_signal(&c);
    Pthread_mutex_unlock(&m);
}

void thr_join() {
    Pthread_mutex_lock(&m);
    Pthread_cond_wait(&c, &m);
    Pthread_mutex_unlock(&m);
}
```

- Imagine the case where the child runs immediately.
  - The child will `signal()`, but there is no **thread asleep** on the condition.
  - When the parent runs, it will call `wait()` and be stuck.
  - **No thread will ever wake it.**

Another poor implementation

- The issue here is a subtle race condition.
  - The parent calls `thr_join()`.
    - The parent checks the value of `done`.
    - It will see that it is 0 and try to go to sleep.
    - **Just before** it calls wait to go to sleep, the parent is **interrupted** and the child runs.
  - The child changes the state variable `done` to 1 and signals.
    - But no thread is waiting and thus no thread is woken.
    - When the parent runs again, it sleeps forever.

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

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

30. Condition Variables

1. Join
2. **Bounded Buffer**
3. Broadcast

The Producer / Consumer
(Bounded Buffer) Problem

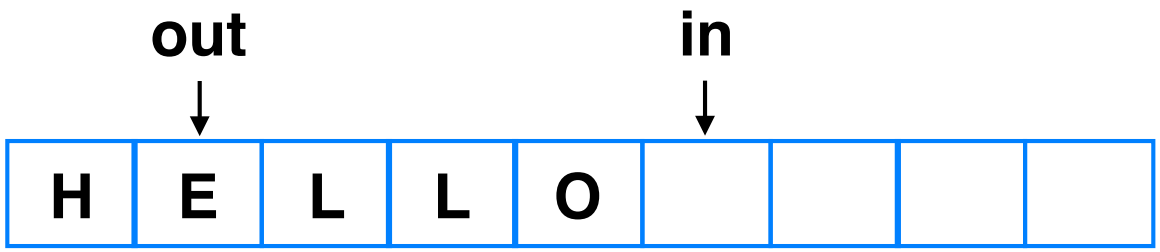
- Producer
  - **Produce** data items
  - Wish to place data items in a buffer
- Consumer
  - Grab data items out of the buffer **consume** them in some way
- Example: Multi-threaded web server
  - A producer puts HTTP requests in to a work queue
  - Consumer threads take requests out of this queue and process them

Bounded buffer

- A bounded buffer is used when you *pipe the output* of one program into another.
  - Example: **`grep foo file.txt | wc -l`**
    - The **`grep`** process is the producer.
    - The **`wc`** process is the consumer.
    - Between them is an in-kernel **bounded buffer**.
- Bounded buffer is Shared resource
  - **Synchronized access** is required.

UNIX pipe

- A pipe may have many writers and readers
- Internally, there is a finite-sized buffer
- Writers add data to the buffer
  - Writers have to wait if buffer is full
- Readers remove data from the buffer
  - Readers have to wait if buffer is empty



The Put and Get Routines

- Only put data into the buffer when `count` is zero.
  - i.e., when the buffer is ***empty***.
- Only get data from the buffer when `count` is one.
  - i.e., when the buffer is ***full***.

```
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 Threads

- **Producer**
  - puts an integer into the shared buffer loops number of times.
- **Consumer**
  - gets the data out of that shared buffer.

```
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:

Single CV and If Statement

```
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
    }
}
```

p1-p3: A producer waits for the buffer to be empty

Producer/Consumer:

Single CV and If Statement

```
cond_t cond;
mutex_t mutex;

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

c1-c3: A consumer waits for the buffer to be full.

Producer/Consumer:

Single CV and If Statement

- With just a single producer and a single consumer, the code works.
- If we have more than one of producer and consumer?

```
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
    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);
}
```

Thread Trace

Single CV and If Statement

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:

Single CV and While Statement

- Try to fix with **`while`** instead of **`if`**
- Better, but still broken
  - but it solves the problem before. Why?
  - Still a problem, because of only one CV ...

```
cond_t cond;
mutex_t mutex;

void *producer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);            // p1
        while (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
        while (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);
    }
```

Thread Trace

Single CV and While Statement

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}**

Thread Trace (Cont.)

Single CV and While Statement

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**

- Solution:
  - Use **two** condition variables and **while**
    - Producer threads wait on the condition **empty**, and signals **fill**.
    - Consumer threads wait on **fill** and signal **empty**.

The single Buffer Producer/Consumer

Solution

```
cond_t empty, fill;
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(&fill);
        Pthread_mutex_unlock(&mutex);
    }
}
```

```
void *consumer(void *arg) {
    int i;
    for (i = 0; i < loops; i++) {
        Pthread_mutex_lock(&mutex);
        while (count == 0)
            Pthread_cond_wait(&fill, &mutex);
        int tmp = get();
        Pthread_cond_signal(&empty);
        Pthread_mutex_unlock(&mutex);
        printf("%d\n", tmp);
    }
}
```

The Final Producer/Consumer Solution

- More **concurrency** and **efficiency**
  - Add more buffer slots.
    - Allow concurrent production or consuming to take place.
    - Reduce context switches.

```
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;
}
```

The Final Producer/Consumer Solution

```
cond_t empty, fill;
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(&fill);            // 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(&fill, &mutex);  // c3
        int tmp = get();                       // c4
} }
```

- **p2**: A **producer** only sleeps if all buffers are currently filled.
- **c2**: A **consumer** only sleeps if all buffers are currently empty.

30. Condition Variables

1. Join
2. Bounded Buffer
3. **Broadcast**

Covering Conditions

- Multithreaded Memory Allocation Library
- Assume there are zero bytes press
  - Thread T_a calls `allocate(100)`.
  - Thread T_b calls `allocate(10)`.
  - Both, T_a and T_b wait on the condition and go to sleep.
  - Thread T_c calls `free(50)`.
- **Which waiting thread should be woken up?**

Example: Code

```
// 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);    // whom to signal??
    Pthread_mutex_unlock(&m);
}
```

Solution for Covering Conditions

- Replace `pthread_cond_signal()` with `pthread_cond_broadcast()`
- `pthread_cond_broadcast()`
  - Wake up **all waiting threads**.
  - **Cost**: too many threads might be woken.
    - Threads that shouldn't be awake will simply wake up, re-check the condition, and then go back to sleep.

Solution: Code

```
// 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_broadcast(&c);    // send all!
    Pthread_mutex_unlock(&m);
}
```

Summary

- Keep state in addition to CV's
- Always do wait/signal with lock held
- Whenever thread wakes from waiting, recheck state
  - Possible for another thread to grab lock in between signal and wakeup from wait

Thanks

Questions?