Condition Variables

CMPU 224 – Computer Organization
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Condition Variables

- There are many cases where we wish to have **coordination** between threads
- 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*
  - As we have seen, this is a `join()`

Condition Variables Example

A Parent Waiting For Its Child

```
1        void *child(void *arg) {
2            printf("child\n");
3            // TODO: how to indicate we are done?
4            return NULL;
5        }
6
7        int main(int argc, char *argv[]) {
8            printf("parent: begin\n");
9            pthread_t c;
10           Pthread_create(&c, NULL, child, NULL); // create child
11           // TODO: how to wait for child?
12           printf("parent: end\n");
13           return 0;
14       }
```

What we would like to see here is:

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

Parent waiting for child: Spin-based Approach

```
1     volatile int done = 0;
2
3     void *child(void *arg) {
4         printf("child\n");
5         done = 1;
6         return NULL;
7     }
8
9     int main(int argc, char *argv[]) {
10        printf("parent: begin\n");
11        pthread_t c;
12        Pthread_create(&c, NULL, child, NULL); // create child
13        while (done == 0)
14            ; // spin
15        printf("parent: end\n");
16        return 0;
17    }
```

- This is hugely <u>inefficient</u> as the parent spins and **wastes CPU time**
- How should a thread wait for a condition?

How to wait for a condition

- **Condition variable** – an object used to wait for some condition to be true
  - **Waiting** on the condition variable
    - An explicit queue that threads can put themselves on when some state of execution is not as desired
    - The thread is no longer running, freeing up the CPU to run another thread
  - **Signaling** on the condition variable
    - Some other thread, *when it changes said state*, can wake one of those waiting threads and allow them to continue

Pthread Condition Variables

- Declare condition variable

```
pthread_cond_t c;
```

  - Proper initialization is required

```
pthread_cond_t c = PTHREAD_COND_INITIALIZER; // Declaration and initialization
or
pthread_cond_init(pthread_cond_t *c, pthread_attr_t *attr) // Initialization with attributes
```

- Operation

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

  - The `wait()` call takes a `mutex` as a parameter
    - The thread that calls `wait()` is assumed to be **holding the mutex lock**
    - The `wait()` call releases the lock and puts the calling thread to sleep
    - When the thread wakes up, it must re-acquire the lock before `wait()` returns
  - `signal()` will wake up a thread that is waiting on the condition variable

Parent waiting for Child: Use a condition variable

```
1 volatile int done = 0;
2 pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3 pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4
5 void thr_exit() {
6     Pthread_mutex_lock(&m);
7     done = 1;
8     Pthread_cond_signal(&c);
9     Pthread_mutex_unlock(&m);
10 }
11
12 void *child(void *arg) {
13     printf("child\n");
14     thr_exit();
15     return NULL;
16 }
17
18 void thr_join() {
19     Pthread_mutex_lock(&m);
20     while (done == 0)
21         Pthread_cond_wait(&c, &m);
22     Pthread_mutex_unlock(&m);
23 }
```

```
25 int main(int argc, char *argv[]) {
26     printf("parent: begin\n");
27     pthread_t p;
28     Pthread_create(&p, NULL, child, NULL);
29     thr_join();
30     printf("parent: end\n");
31     return 0;
32 }
```

Parent waiting for child using 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

The Importance of the state variable `done`

```
1 void thr_exit() {
2       Pthread_mutex_lock(&m);
3       Pthread_cond_signal(&c);
4       Pthread_mutex_unlock(&m);
5 }
6
7 void thr_join() {
8       Pthread_mutex_lock(&m);
9       Pthread_cond_wait(&c, &m);
10      Pthread_mutex_unlock(&m);
11}
```

```
25 int main(int argc, char *argv[]) {
26      printf("parent: begin\n");
27      pthread_t p;
28      Pthread_create(&p, NULL, child, NULL);
29      thr_join();
30      printf("parent: end\n");
31      return 0;
32 }
```

`thr_exit()` and `thr_join()` without variable `done`

- Can you think of a scenario where we could run into problems?
- Imagine the case where the **child runs immediately**
  - The child will signal, but there is no thread sleeping on the condition
  - When the parent runs, it will call wait and be stuck
  - No thread will ever wake it, **sad panda!**

Importance of locks

```
1   volitile int done = 0;
2
3   void thr_exit() {
4         done = 1;
5         Pthread_cond_signal(&c);
6   }
7
8   void thr_join() {
9         if (done == 0)
10              Pthread_cond_wait(&c);
11  }
```

```
25 int main(int argc, char *argv[]) {
26       printf("parent: begin\n");
27       pthread_t p;
28       Pthread_create(&p, NULL, child, NULL);
29       thr_join();
30       printf("parent: end\n");
31       return 0;
32 }
```

- Can you find the bug? (assume you don't need a lock to use signal and wait)
- The issue here is a **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 `pthread_cond_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, **sad!**

The Producer / Consumer (Bounded Buffer) Problem

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

Producer/Consumer (non-working)

```
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  }
```

```
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  }
```

- Put -- Only put data into the buffer when `count` is zero (i.e., when the buffer is *empty*)
- Get -- Only get data from the buffer when `count` is one (i.e., when the buffer is *full*)
- **Producer** -- puts an integer into the shared buffer loops number of times
- **Consumer** -- gets the data out of that shared buffer
- Need synchronization between the producer and consumer

Producer/Consumer: Single CV and If Statement

```
1   cond_t cond;
2   mutex_t mutex;
3
4   void *producer(void *arg) {
5       int i;
6       int loops = (int) arg;
7       for (i = 0; i < loops; i++) {
8           Pthread_mutex_lock(&mutex);
9           if (count == 1) // buffer is full
10              Pthread_cond_wait(&cond, &mutex);
11          put(i);
12          Pthread_cond_signal(&cond);
13          Pthread_mutex_unlock(&mutex);
14      }
15  }
```

```
16 void *consumer(void *arg) {
17      int i;
18      for (i = 0; i < loops; i++) {
19          Pthread_mutex_lock(&mutex);
20          if (count == 0)
21              Pthread_cond_wait(&cond, &mutex);
22          int tmp = get();
23          Pthread_cond_signal(&cond);
24          Pthread_mutex_unlock(&mutex);
25          printf("%d\n", tmp);
26      }
27 }
```

- A single condition variable `cond` and associated lock `mutex`
  - Works if there is one producer and one consumer
- What happens if that is not the case (e.g., 2 consumers, 1 producer)?
  - C1 runs and waits, P1 puts an item in and signals C1
  - Before C1 gets to run, C2 sneaks in and consumes the item, setting count to 0
  - When C1 runs, no more items left, **sad!**
- **Fix**: Recheck state (in a `while` loop) upon returning from wait!

Thread Trace: Broken Solution

- The problem arises for a simple reason:
  - After the producer woke T_{c1}, but before T_{c1} ever ran, the state of the bounded buffer *changed by* T_{c2}
- There is no guarantee that when the woken up thread runs, the state will still be as desired → **Mesa semantics**
  - Virtually every system ever built employs *Mesa semantics*
- **Hoare semantics** provides a stronger guarantee that the woken up thread will run immediately upon being woken

Producer/Consumer: Single CV and While

```
1  cond_t cond;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      int loops = (int) arg;
7      for (i = 0; i < loops; i++) {
8          Pthread_mutex_lock(&mutex);
9          while (count == 1)
10             Pthread_cond_wait(&cond, &mutex);
11         put(i);
12         Pthread_cond_signal(&cond);
13         Pthread_mutex_unlock(&mutex);
14     }
15 }
```

```
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);
20         while (count == 0)
21             Pthread_cond_wait(&cond, &mutex);
22         int tmp = get();
23         Pthread_cond_signal(&cond);
24         Pthread_mutex_unlock(&mutex);
25         printf("%d\n", tmp);
26     }
27 }
```

- This fixes our previous problem; however, this code still has a bug
  - Assume two consumers and one producer:
    - C1 runs, finds the buffer empty and waits, C2 runs, finds the buffer empty and waits
    - P1 runs, produces an item, signals, and waits because buffer is full
    - C1 wakes (from P1 signal) and acquires the lock, consumes the buffer, and signals
      - Who gets the signal, P1 or C2? Assume C2
    - C2 wakes, finds the buffer empty and waits – everyone is sleeping, **sad!**

The single Buffer Producer/Consumer Solution

- Use two condition variables and while loops
  - **Producer** threads wait on the condition `empty`, and signals `fill`
  - **Consumer** threads wait on `fill` and signal `empty`

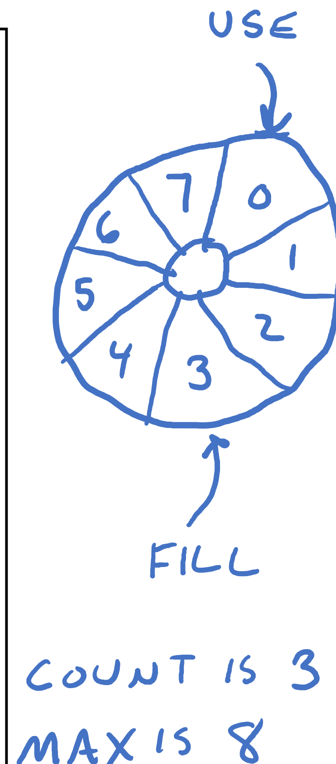
```
1  cond_t empty, fill;
2  mutex_t mutex;
3
4  void *producer(void *arg) {
5      int i;
6      int loops = (int) arg;
7      for (i = 0; i < loops; i++) {
8          Pthread_mutex_lock(&mutex);
9          while (count == 1)
10             Pthread_cond_wait(&empty, &mutex);
11         put(i);
12         Pthread_cond_signal(&fill);
13         Pthread_mutex_unlock(&mutex);
14     }
15 }
```

```
16 void *consumer(void *arg) {
17     int i;
18     for (i = 0; i < loops; i++) {
19         Pthread_mutex_lock(&mutex);
20         while (count == 0)
21             Pthread_cond_wait(&fill, &mutex);
22         int tmp = get();
23         Pthread_cond_signal(&empty);
24         Pthread_mutex_unlock(&mutex);
25         printf("%d\n", tmp);
26     }
27 }
```

The Final Producer/Consumer Solution

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

```
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  }
```




```
1   cond_t empty, fill;
2   mutex_t mutex;
3
4   void *producer(void *arg) {
6     for (int i = 0; i < loops; i++) {
7        int loops = (int) arg;
8        Pthread_mutex_lock(&mutex);
9        while (count == MAX)
10          Pthread_cond_wait(&empty, &mutex);
11       put(i);
12       Pthread_cond_signal(&fill);
13       Pthread_mutex_unlock(&mutex);
14    }
15  }
16
17  void *consumer(void *arg) {
18     for (int i = 0; i < loops; i++) {
19        Pthread_mutex_lock(&mutex);
20        while (count == 0)
21           Pthread_cond_wait(&fill, &mutex);
22        int tmp = get();
23        Pthread_cond_signal(&empty);
24        Pthread_mutex_unlock(&mutex);
25        printf("%d\n", tmp);
26     }
27  }
```

Covering Conditions

- Assume we have implemented a multi-threaded memory allocator
- Also, assume there are zero bytes are currently free
  - 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?**

Covering Conditions Example Code

```
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); // who do we signal??
23     Pthread_mutex_unlock(&m);
24 }
```

Covering Conditions Solution

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

Covering Conditions Solution Code

```
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_broadcast(&c); // wake up all the threads waiting
23     Pthread_mutex_unlock(&m);
24 }
```

Condition Variable Summary

- We have a new **synchronization** primitive beyond locks
  - Condition variables
- Allows for a thread to sleep when some program state is not as desired
  - Once sleeping, another thread must wake up the thread by signal/broadcast
- Condition variables are used in conjunction with a lock
  - When waiting on the CV, the lock is (temporarily) given up
  - While returning from the wait, the thread re-acquires the lock
- When a thread is signaled, it may not wake up right away
  - The state of the world may have changed
  - Recheck your state (in a while loop) upon returning from wait if there is any chance the state may have changed