CMSC 125: Operating Systems

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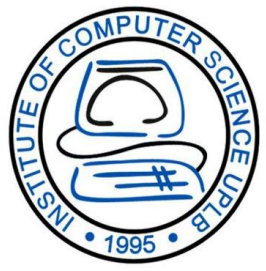
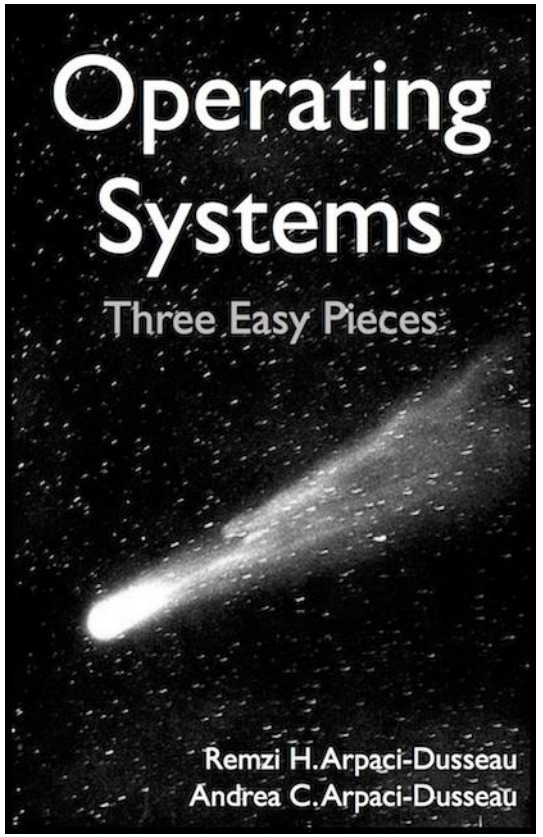


Resources

Book: https://pages.cs.wisc.edu/~remzi/OSTEP/

Slides Template:
https://pages.cs.wisc.edu/~remzi/OSTEP/Educators-Slides/Youjip/



Acknowledgement

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30. Condition Variables

Operating System: Three Easy Pieces

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()`

Condition Variables (Cont.)

A Parent Waiting For Its Child

```
1       void *child(void *arg) {
2           printf("child\n");
3           // XXX 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          // XXX 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 fore 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 inefficient as the parent spins and **wastes CPU time.**

How to wait for a condition

- **What is a Condition Variable?**
  - An **explicit queue** that threads can put themselves on when some state of execution(the **condition**) is not as desired (by waiting on the condition)
    - **Waiting** on the condition
      - A threads put itself in the queue until another thread signals, ensures that thread does not spin
    - **Signaling** on the condition
      - Some other thread, *when it changes said state(condition)*, 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);    // wait()
pthread_cond_signal(pthread_cond_t *c);                      // signal()
```

  - The wait() call takes a mutex as a parameter(assumed to be locked) because
    - The wait() call releases the lock and puts the calling thread to sleep
    - When the thread wakes up, it must re-acquire the lock

Parent waiting for Child: Use a condition variable

```
1       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      }
24
```

Parent waiting for Child: Use a condition variable

```
(cont.)
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: 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

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      }
```

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

- 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

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

- 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

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 into 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 (a pipe)
  - Bounded buffer is shared resource → **Synchronized access** is required

The Put and Get Routines (Version 1)

```
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      }
```

- 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*

Producer/Consumer Threads (Version 1)

```
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      }
```

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

Producer/Consumer: Single CV and If Statement

- A single condition variable `cond` and associated lock `mutex`

```
1       int loops; cond_t cond;
2       mutex_t mutex;
3
4       void *producer(void *arg) {
5           int i;
6           for (i = 0; i < loops; i++) {
7               Pthread_mutex_lock(&mutex);             // p1
8               if (count == 1)                         // p2
9                   Pthread_cond_wait(&cond, &mutex);   // p3
10              put(i);                                 // p4
11              Pthread_cond_signal(&cond);             // p5
12              Pthread_mutex_unlock(&mutex);           // p6
13          }
14      }
15
16      void *consumer(void *arg) {
17          int i;
18          for (i = 0; i < loops; i++) {
19              Pthread_mutex_lock(&mutex);             // c1
```

Producer/Consumer: Single CV and If Statement

```
20              if (count == 0)                          // c2
21                  Pthread_cond_wait(&cond, &mutex);    // c3
22              int tmp = get();                         // c4
23              Pthread_cond_signal(&cond);              // c5
24              Pthread_mutex_unlock(&mutex);            // c6
25              printf("%d\n", tmp);
26          }
27      }
```

- p1-p3: A producer waits for the buffer to be empty
- c1-c3: A consumer waits for the buffer to be full
- With just *a single producer* and *a single consumer*, the code works

If we have more than one of producer and consumer?

Thread Trace: Broken Solution (Version 1)

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**

c3 is skipped since count is 1

Thread Trace: Broken Solution (Version 1)

- 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 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 thread will run immediately upon being woken

Producer/Consumer: Single CV and While

- Consumer T_{c1} wakes up and re-checks the state of the shared variable
  - If the buffer is empty, the consumer simply goes back to sleep

```
1       cond_t cond;
2       mutex_t mutex;
3
4       void *producer(void *arg) {
5           int i;
6           for (i = 0; i < loops; i++) {
7               Pthread_mutex_lock(&mutex);             // p1
8               while (count == 1)                      // p2
9                   Pthread_cond_wait(&cond, &mutex);   // p3
10              put(i);                                 // p4
11              Pthread_cond_signal(&cond);             // p5
12              Pthread_mutex_unlock(&mutex);           // p6
13          }
14      }
15
```

Producer/Consumer: Single CV and While

```
(Cont.)
16      void *consumer(void *arg) {
17          int i;
18          for (i = 0; i < loops; i++) {
19              Pthread_mutex_lock(&mutex);              // c1
20              while (count == 0)                       // c2
21                  Pthread_cond_wait(&cond, &mutex);    // c3
22              int tmp = get();                         // c4
23              Pthread_cond_signal(&cond);              // c5
24              Pthread_mutex_unlock(&mutex);            // c6
25              printf("%d\n", tmp);
26          }
27      }
```

- A simple rule to remember with condition variables is to **always use while loops**
- However, this code still has a bug (*next page*)

Thread Trace: Broken Solution (Version 2)

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: Broken Solution (Version 2) (Cont.)

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 …**

- A consumer should not wake other consumers, only producers, and vice-versa

The single Buffer Producer/Consumer 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`

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

The single Buffer Producer/Consumer Solution

```
(Cont.)
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      }
```

The Final Put and Get Routines

The Final Producer/Consumer Solution (Cont.)

```
1       cond_t empty, fill;
2       mutex_t mutex;
3
4       void *producer(void *arg) {
5           int i;
6           for (i = 0; i < loops; i++) {
7               Pthread_mutex_lock(&mutex);             // p1
8               while (count == MAX)                    // p2
9                   Pthread_cond_wait(&empty, &mutex);  // p3
10              put(i);                                 // p4
11              Pthread_cond_signal(&fill);             // p5
12              Pthread_mutex_unlock(&mutex);           // p6
13          }
14      }
15
16      void *consumer(void *arg) {
17          int i;
18          for (i = 0; i < loops; i++) {
19              Pthread_mutex_lock(&mutex);             // c1
20              while (count == 0)                      // c2
21                  Pthread_cond_wait(&fill, &mutex);   // c3
22              int tmp = get();                        // c4
```

The Final Producer/Consumer Solution (Cont.)

```
(Cont.)
23              Pthread_cond_signal(&empty);                    // c5
24              Pthread_mutex_unlock(&mutex);                   // c6
25              printf("%d\n", tmp);
26          }
27      }
```

The Final Working Solution (Cont.)

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

Covering Conditions

- Assume there are zero bytes 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 (Cont.)

```
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);        // whom to signal??
23          Pthread_mutex_unlock(&m);
24      }
```

Covering Conditions (Cont.)

- Solution (Suggested by Lampson and Redell)
  - 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