

CSE4509 Operating Systems

Condition Variables

Salman Shamil



United International University (UIU)
Summer 2025

Original slides by Mathias Payer and Sanidhya Kashyap [EPFL]

- Condition Variables
- Producer-Consumer Problem

This slide deck covers chapters 30 in OSTEP.

Condition Variables (CV)

In concurrent programming, a common scenario is one thread waiting for another thread to complete an action.

```
1  bool done = false;
2
3  /* called in the child to signal termination */
4  void thr_exit() {
5      done = true;
6  }
7  /* called in the parent to wait for a child thread */
8  void thr_join() {
9      while (!done);
10 }
```

Condition Variables (CV)

- Locks enable mutual exclusion of a shared region.
 - Unfortunately they are oblivious to ordering
- Waiting and signaling (i.e., T2 waits until T1 completes a given task) could be implemented by spinning until the value changes

Condition Variables (CV)

- Locks enable mutual exclusion of a shared region.
 - Unfortunately they are oblivious to ordering
- Waiting and signaling (i.e., T2 waits until T1 completes a given task) could be implemented by spinning until the value changes
- But spinning is incredibly *inefficient*

Condition Variables (CV)

- Locks enable mutual exclusion of a shared region.
 - Unfortunately they are oblivious to ordering
- Waiting and signaling (i.e., T2 waits until T1 completes a given task) could be implemented by spinning until the value changes
- But spinning is incredibly *inefficient*
- New synchronization primitive: ***condition variables***

Condition Variables (CV)

- A CV allows:
 - A thread to wait for a condition
 - Another thread signals the waiting thread
- Implement CV using queues

Condition Variables (CV)

- A CV allows:
 - A thread to wait for a condition
 - Another thread signals the waiting thread
- Implement CV using queues
- API: wait, signal or broadcast
 - wait: wait until a condition is satisfied
 - signal: wake up one waiting thread
 - broadcast: wake up all waiting threads
- On Linux, pthreads provides CV implementation

Signal parent that child has exited

```
1  bool done = false;
2  pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;
3  pthread_cond_t c = PTHREAD_COND_INITIALIZER;
4  /* called in the child to signal termination */
5  void thr_exit() {
6      pthread_mutex_lock(&m);
7      done = true;
8      pthread_cond_signal(&c);
9      pthread_mutex_unlock(&m);
10 }
11 /* called in the parent to wait for a child thread */
12 void thr_join() {
13     pthread_mutex_lock(&m);
14     while (!done)
15         pthread_cond_wait(&c, &m);
16     pthread_mutex_unlock(&m);
17 }
```

Signal parent that child has exited (2)

- `pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m)`
 - Assume mutex `m` is held; *atomically* unlock mutex when waiting, retake it when waking up
- Question: Why do we need to check a condition before sleeping?

Signal parent that child has exited (2)

- `pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m)`
 - Assume mutex `m` is held; *atomically* unlock mutex when waiting, retake it when waking up
- Question: Why do we need to check a condition before sleeping?
- Thread may have already exited, i.e., no need to wait
 - Principle: Check the condition before sleeping

Signal parent that child has exited (2)

- `pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m)`
 - Assume mutex `m` is held; *atomically* unlock mutex when waiting, retake it when waking up
- Question: Why do we need to check a condition before sleeping?
- Thread may have already exited, i.e., no need to wait
 - Principle: Check the condition before sleeping
- Question: Why can't we use `if` when waiting?

Signal parent that child has exited (2)

- `pthread_cond_wait(pthread_cond_t *c, pthread_mutex_t *m)`
 - Assume mutex `m` is held; *atomically* unlock mutex when waiting, retake it when waking up
- Question: Why do we need to check a condition before sleeping?
- Thread may have already exited, i.e., no need to wait
 - Principle: Check the condition before sleeping
- Question: Why can't we use `if` when waiting?
- Multiple threads could be woken up, racing for done flag
 - Principle: `while` instead of `if` when waiting

Signal parent that child has exited (3)

- Question: Why do we need to protect done with mutex m ?

Signal parent that child has exited (3)

- Question: Why do we need to protect done with mutex m ?
- Mutex m allows one thread to access done for protecting against missed updates
 - Parent reads `done == false` but is interrupted
 - Child sets `done = true` and signals but no one is waiting
 - Parent continues and goes to sleep (forever)
- Lock is therefore required for wait/signal synchronization

Producer/consumer synchronization

- Producer/consumer is a common programming pattern
- For example: map (producers) / reduce (consumer)
- For example: a concurrent database (consumers) handling parallel requests from clients (producers)
 - Clients produce new requests (encoded in a queue)
 - Handlers consume these requests (popping from the queue)

Producer/consumer synchronization

- Producer/consumer is a common programming pattern
- For example: map (producers) / reduce (consumer)
- For example: a concurrent database (consumers) handling parallel requests from clients (producers)
 - Clients produce new requests (encoded in a queue)
 - Handlers consume these requests (popping from the queue)
- Strategy: use CV to synchronize
 - Make producers wait if buffer is full
 - Make consumers wait if buffer is empty (nothing to consume)

Condition variables

- Programmer must keep state, orthogonal to locks
- CV enables access to critical section with a thread wait queue
- Always wait/signal while holding lock
- Whenever thread wakes, recheck state

Semaphore

- A semaphore extends a CV with an integer as internal state
- `int sem_init(sem_t *sem, unsigned int value):`
creates a new semaphore with value slots
- `int sem_wait(sem_t *sem):` waits until the semaphore has at least one slot, decrements the number of slots
- `int sem_post(sem_t *sem):` increments the semaphore (and wakes one waiting thread)
- `int sem_destroy(sem_t *sem):` destroys the semaphore and releases any waiting threads

Concurrent programming: producer consumer

- One or more producers create items, store them in buffer
- One or more consumers process items from buffer

Concurrent programming: producer consumer

- One or more producers create items, store them in buffer
- One or more consumers process items from buffer
- Need synchronization for buffer
 - Want concurrent production and consumption
 - Use as many cores as available
 - Minimize access time to shared data structure

Concurrent programming: producer consumer

```
1 void *producer(void *arg) {
2     unsigned int max = (unsigned int)arg;
3     for (unsigned int i = 0; i < max; i++) {
4         put(i); // store in shared buffer
5     }
6     return NULL;
7 }
8 void *consumer(void *arg) {
9     unsigned int max = (unsigned int)arg;
10    for (unsigned int i = 0; i < max; i++) {
11        printf("%d\n", get(i)); // recv from buffer
12    }
13    return NULL;
14 }
pthread_t p, c;
pthread_create(&p, NULL, &producer, (void*)NUMITEMS);
pthread_create(&c, NULL, &consumer, (void*)NUMITEMS);
```

Concurrent programming: producer consumer

```
1  unsigned int buffer[BUFSIZE] = { 0 };
2  unsigned int cpos = 0, ppos = 0;
3
4  void put(unsigned int val) {
5      buffer[ppos] = val;
6      ppos = (ppos + 1) % BUFSIZE;
7  }
8
9  unsigned int get() {
10     unsigned long val = buffer[cpos];
11     cpos = (cpos + 1) % BUFSIZE;
12     return val;
13 }
```

What are the issues in this code?

Concurrent programming: producer consumer

```
1  unsigned int buffer[BUFSIZE] = { 0 };
2  unsigned int cpos = 0, ppos = 0;
3
4  void put(unsigned int val) {
5      buffer[ppos] = val;
6      ppos = (ppos + 1) % BUFSIZE;
7  }
8
9  unsigned int get() {
10     unsigned long val = buffer[cpos];
11     cpos = (cpos + 1) % BUFSIZE;
12     return val;
13 }
```

What are the issues in this code?

- Producers may overwrite unconsumed entries
- Consumers may consume uninitialized or stale entries

Producer/consumer: use semaphores!

```
sem_t csem, psem;
```

```
/* BUFSIZE items are available for producer to create */  
sem_init(&psem, 0, BUFSIZE);
```

```
/* 0 items are available for consumer */  
sem_init(&csem, 0, 0);
```

Producer: semaphores

```
1 void put(unsigned int val) {  
2     /* we wait until there is buffer space available */  
3     sem_wait(&psem);  
4  
5     /* store element in buffer */  
6     buffer[ppos] = val;  
7     ppos = (ppos + 1) % BUFSIZE;  
8  
9     /* notify consumer that data is available */  
10    sem_post(&csem);  
11 }
```

Consumer: semaphores

```
1  unsigned int get() {
2      /* wait until data is produced */
3      sem_wait(&csem);
4
5      /* consumer entry */
6      unsigned long val = buffer[cpos];
7      cpos = (cpos + 1) % BUFSIZE;
8
9      /* notify producer that a space has freed up */
10     sem_post(&psem);
11     return val;
12 }
```

Producer/consumer: remaining issues?

- We now synchronize between consumers and producers
 - Producer waits until buffer space is available
 - Consumer waits until data is ready

Producer/consumer: remaining issues?

- We now synchronize between consumers and producers
 - Producer waits until buffer space is available
 - Consumer waits until data is ready
- How would you handle multiple producers/consumers?
 - Currently no synchronization between producers (or consumers)

Multiple producers: use locking!

```
/* mutex handling mutual exclusive access to ppos */
1  pthread_mutex_t pmutex = PTHREAD_MUTEX_INITIALIZER;
2
3  void put(unsigned int val) {
4      unsigned int mypos;
5      /* we wait until there is buffer space available */
6      sem_wait(&psem);
7      /* ppos is shared between all producers */
8      pthread_mutex_lock(&pmutex);
9      mypos = ppos;
10     ppos = (ppos + 1) % BUFSIZE;
11     /* store information in buffer */
12     buffer[mypos] = val;
13     pthread_mutex_unlock(&pmutex);
14     sem_post(&csem);
15 }
```

Semaphores/spin locks/CVs are interchangeable

- Each is implementable through a combination of the others
- Depending on the use-case one is faster than the other
 - How often is the critical section executed?
 - How many threads compete for a critical section?
 - How long is the lock taken?

Implementing a mutex with a semaphore

```
1 sem_t sem;  
2 sem_init(&sem, 1);  
3  
4 sem_wait(&sem);  
5 ... // critical section  
6 sem_post(&sem);
```


Implementing a semaphore with CV/locks

```
1  typedef struct {
2      int value;           // sem value
3      pthread_mutex_t lock; // access to sem
4      pthread_cond_t cond;  // wait queue
5  } sem_t;
6
7  void sem_init(sem_t *s, int val) {
8      s->value = val;
9      pthread_mutex_init(&(s->lock), NULL);
10     pthread_cond_init(&(s->cond), NULL);
11 }
```

Implementing a semaphore with CV/locks

```
1 void sem_wait(sem_t *s) {
2     pthread_mutex_lock(&(s->lock));
3     while (s->value <= 0)
4         pthread_cond_wait(&(s->cond), &(s->lock));
5     s->value--;
6     pthread_mutex_unlock(&(s->lock));
7 }
8
9 void sem_post(sem_t *s) {
10    pthread_mutex_lock(&(s->lock));
11    s->value++;
12    pthread_cond_signal(&(s->cond));
13    pthread_mutex_unlock(&(s->lock));
14 }
```

- A single (exclusive) writer, multiple (N) concurrent readers
- Implement using two semaphores: `lock` for the data structure, `wlock` for the writer
 - Both semaphores initialized with (1)
 - Writer only waits/posts on `wlock` when acquiring/releasing
 - Reader waits on `lock`, increments/decrements reader count
 - If number of readers==0, must wait/post on `wlock`

Reader/writer locks

```
1 void rwlock_acquire_readlock(rwlock_t *rw) {
2     sem_wait(&rw->lock);
3     rw->readers++;
4     if (rw->readers == 1)
5         sem_wait(&rw->wlock); // first r, also grab wlock
6     sem_post(&rw->lock);
7 }
8
9 void rwlock_release_readlock(rwlock_t *rw) {
10    sem_wait(&rw->lock);
11    rw->readers--;
12
13    if (rw->readers == 0)
14        sem_post(&rw->wlock); // last r, also release wlock
15    sem_post(&rw->lock);
16 }
```

Bugs in concurrent programs

- Writing concurrent programs is hard!
- **Atomicity bug:** concurrent, unsynchronized modification (lock!)
- **Order-violating bug:** data is accessed in wrong order (use CV!)
- **Deadlock:** program no longer makes progress (locking order)

Atomicity bugs

One thread checks value and prints it while another thread concurrently modifies it.

```
1  int shared = 24;
2
3  void T1() {
4      if (shared > 23) {
5          printf("Shared is >23: %d\n", shared);
6      }
7  }
8  void T2() {
9      shared = 12;
10 }
```

Atomicity bugs

One thread checks value and prints it while another thread concurrently modifies it.

```
1  int shared = 24;
2
3  void T1() {
4      if (shared > 23) {
5          printf("Shared is >23: %d\n", shared);
6      }
7  }
8  void T2() {
9      shared = 12;
10 }
```

- T2 may modify shared between if check and printf in T1.
- Fix: use a common mutex between both threads when accessing the shared resource.

Order-violating bug

One thread assumes the other has already updated a value.

Thread 1::

```
void init() {  
    mThread = PR_CreateThread(mMain, ...);  
    mThread->State = ...;  
}
```

Thread 2::

```
void mMain(...) {  
    mState = mThread->State;  
}
```


Order-violating bug

One thread assumes the other has already updated a value.

Thread 1::

```
void init() {  
    mThread = PR_CreateThread(mMain, ...);  
    mThread->State = ...;  
}
```

Thread 2::

```
void mMain(...) {  
    mState = mThread->State;  
}
```

- Thread 2 may run before mThread is assigned in T1.
- Fix: use a CV to signal that mThread has been initialized.

Deadlock

Locks are taken in conflicting order.

```
void T1() {  
    lock(L1);  
    lock(L2);  
}
```

```
void T2() {  
    lock(L2);  
    lock(L1);  
}
```

Deadlock

Locks are taken in conflicting order.

```
void T1() {  
    lock(L1);  
    lock(L2);  
}
```

```
void T2() {  
    lock(L2);  
    lock(L1);  
}
```

- Threads 1/2 may be stuck after taking the first lock, program makes no more progress
- Fix: acquire locks in increasing (global) order.

Summary

- Spin lock, CV, and semaphore synchronize multiple threads
 - Spin lock: atomic access, no ordering, spinning
 - Condition variable: atomic access, queue, OS primitive
 - Semaphore: shared access to critical section with (int) state
- All three primitives are equally powerful
 - Each primitive can be used to implement both other primitives
 - Performance may differ!
- Synchronization is challenging and may introduce different types of bugs such as atomicity violation, order violation, or deadlocks.

Don't forget to get your learning feedback through the Moodle quiz!