Synchronization: Another Perspective

Yajin Zhou (http://yajin.org)

Zhejiang University

Credit: https://cs61.seas.harvard.edu/site/2018/

Last time

- We looked at **locks**
  - Two operations: acquire and release
  - At most one thread can hold a lock at a time
  - Can use to enforce mutual exclusion and critical sections
  - Considered how to efficiently implement

Higher-level synchronization primitives

- We have looked at one synchronization primitive: **locks**
- Locks are useful for many things, but sometimes programs have different requirements.
- Examples?
  - Say we had a shared variable where we wanted any number of threads to read the variable, but only one thread to write it.
  - How would you do this with locks?

```
Reader() {
  acquire(lock);
  mycopy = shared_var;
  release(lock);
  return mycopy;
}
```

```
Writer() {
  acquire(lock);
  shared_var = NEW_VALUE;
  release(lock);
}
```

What's wrong with this code?

Today

- Semaphores
- Condition variables
- Monitors

Semaphores

- Higher-level synchronization construct
  - Designed by Edsger Dijkstra in the 1960's
- Semaphore is a **shared counter**
- Two operations on semaphores:
  - P() or wait() or down()
    - From Dutch *proeberen*, meaning “test”
    - **Atomic action**: Wait for semaphore value to become > 0, then **decrement** it
  - V() or signal() or up()
    - From Dutch *verhogen*, meaning “increment”
    - **Atomic** action: **Increment** semaphore value by 1.

Semaphore Example

- Semaphores can be used to implement locks:

```
Semaphore my_semaphore = 1; // Initialize to nonzero
int withdraw(account, amount) {
  wait(my_semaphore);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  signal(my_semaphore);
  return balance;
}
```

critical section

- A semaphore where the counter value is only 0 or 1 is called a **binary semaphore**.
  - Essentially the same as a lock.

Simple Semaphore Implementation

```
struct semaphore {
     int val;
     thread_list waiting;  // List of threads waiting for semaphore
}
```

```
wait(semaphore Sem):    // Wait until > 0 then decrement
  while (Sem.val <= 0) {
    add this thread to Sem.waiting;
    block(this thread);
  }
  Sem.val = Sem.val - 1;
return;
```

wait() and signal() must be atomic actions!

```
signal(semaphore Sem):// Increment value and wake up next thread
     Sem.val = Sem.val + 1;
     if (Sem.waiting is nonempty) {
          remove a thread T from Sem.waiting;
          wakeup(T);
     }
```

Simple Semaphore Implementation

```
struct semaphore {
     int val;
     thread_list waiting;  // List of threads waiting for semaphore
}
```

```
wait(semaphore Sem):     // Wait until > 0 then decrement
  while (Sem.val <= 0) {
    add this thread to Sem.waiting;
    block(this thread);
  }
  Sem.val = Sem.val - 1;
return;
```

Why is this a while loop, and not an if?

wait could be called by another thread while this thread is waiting

```
signal(semaphore Sem):// Increment value and wake up next thread
     Sem.val = Sem.val + 1;
     if (Sem.waiting is nonempty) {
          remove a thread T from Sem.waiting;
          wakeup(T);
     }
```

Semaphore Implementation

- How do we ensure that the semaphore implementation is atomic?
- One option: use a lock for wait() and signal()
  - Make sure that only one wait() or signal() can be executed by any process at a time
  - Need to be careful to release lock before sleeping, acquire lock on waking up
- Another option: hardware support

Why are semaphores useful?

- A binary semaphore (counter is always 0 or 1) is basically a lock.
  - Start with semaphore value = 1
  - acquire( ) = wait( )
  - release( ) = signal( )
- The real value of semaphores becomes apparent when the counter can be initialized to a value other than 0 or 1.

The Producer/Consumer Problem

- Also called the Bounded Buffer problem.

Mmmm... donuts

Producer

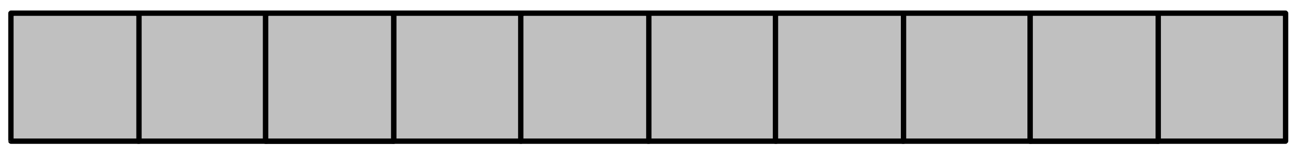
Consumer

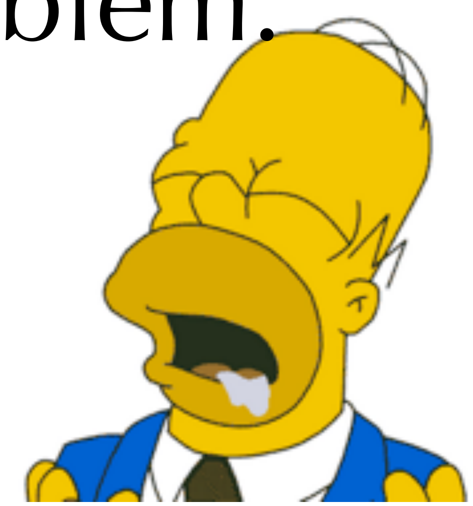
- Producer pushes items into the buffer.
- Consumer pulls items from the buffer.
- Producer needs to wait when buffer is full.
- Consumer needs to wait when the buffer is empty.

The Producer/Consumer Problem

- Also called the Bounded Buffer problem.

Producer





Consumer

- Producer pushes items into the buffer.
- Consumer pulls items from the buffer.
- Producer needs to wait when buffer is full.
- Consumer needs to wait when the buffer is empty.

An implementation

Mmmm... donuts

Proc

```
int count = 0;

Producer() {
  int item;
  while (TRUE) {
    item = bake();
    if (count == N) sleep();
    insert_item(item);
    count = count + 1;
    if (count == 1)
      wakeup(consumer);
  }
}
```

```
Consumer() {
  int item;
  while (TRUE) {
    if (count == 0) sleep();
    item = remove_item();
    count = count - 1;
    if (count == N-1)
        wakeup(producer);
    eat(item);
  }
}
```

- What's wrong with this code?

An implementation

Mmmm... donuts

Proc

```
int count = 0;

Producer() {
  int item;
  while (TRUE) {
    item = bake();
    if (count == N) sleep();
    insert_item(item);
    count = count + 1;
    if (count == 1)
      wakeup(consumer);
  }
}
```

Access to `count` not synchronized

What if we context switch between the test and sleep?

```
Consumer() {
  int item;
  while (TRUE) {
    if (count == 0) sleep();
    item = remove_item();
    count = count - 1;
    if (count == N-1)
        wakeup(producer);
    eat(item);
  }
}
```

- What's wrong with this code?

An implementation with semaphores

Mmmm... donuts

Proc

```
Semaphore mutex = 1;
Semaphore empty = N;
Semaphore full = 0;

Producer() {
    int item;
    while (TRUE) {
        item = bake();
        wait(empty);
        wait(mutex);
        insert_item(item);
        signal(mutex);
        signal(full);
    }
}
```

```
Consumer() {
    int item;
    while (TRUE) {
        wait(full);
        wait(mutex);
        item = remove_item();
        signal(mutex);
        signal(empty);
        eat(item);
    }
}
```

Why is it important that `wait(empty)` is before `wait(mutex)`?

Otherwise a thread could acquire mutex and wait for empty; prevent another thread acquiring mutex. DEADLOCK! (more on this next week)

Semaphore library

- There are POSIX semaphores, but they are not part of the pthreads library
- All semaphore functions are declared in `semaphore.h`
- The semaphore type is a `sem_t`.
- Intialize: `sem_init(&theSem, 0, initialVal);`
- Wait: `sem_wait(&theSem);`
- Signal: `sem_post(&theSem);`
- Get the current value of the semaphore:

```
sem_getvalue(&theSem, &result);
```

Issues with Semaphores

- Much of the power of semaphores derives from calls to wait() and signal() that are unmatched
  - See previous example!
  - Unlike locks, where acquire() and release() are always paired.
- This means it is a lot easier to get into trouble with semaphores.
  - Semaphores are a lot of rope to tie yourself in knots with…

Condition Variables

- A **condition variable** represents some condition that a thread can:
  - **Wait on**, until the condition occurs; or
  - **Notify** other waiting threads that the condition has occurred
  - Very useful primitive for signaling between threads.
- Condition variable indicates an event; cannot store or retrieve a value from a CV
- Three operations on condition variables:
  - `wait()` — Block until another thread calls `signal()` or `broadcast()` on the CV
  - `signal()` — Wake up one thread waiting on the CV
  - `broadcast()` — Wake up all threads waiting on the CV
- In Pthreads, the CV type is a `pthread_cond_t`.
  - Use `pthread_cond_init()` to initialize
  - `pthread_cond_wait(&theCV, &someLock);`
  - `pthread_cond_signal(&theCV);`
  - `pthread_cond_broadcast(&theCV);`

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- In pthreads, all condition variable operations **must** be performed while a mutex is locked!!!
  - Why is the lock necessary?

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- If no lock on Thread A:
  - Might wait after another thread sets counter to 10
- If no lock on Thread B:
  - No guarantee that increment and test is atomic

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- What happens to the lock when you call wait on the CV?

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- `wait()` released the lock while Thread A is sleeping
  - That is why pthreads requires that the `myLock` is passed in

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- `signal()` wakes up Thread A, but Thread A cannot proceed. Why?
    - Thread A requires lock to continue. Lock is still held by Thread B

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- `signal()` wakes up Thread A, but Thread A cannot proceed. Why?
  - Thread A requires lock to continue. Lock is still held by Thread B

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- Once Thread B releases lock, Thread A can acquire it and continue running

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

Using Condition Variables

```
pthread_mutex_t myLock;
pthread_cond_t myCV;
int counter = 0;

/* Thread A */
pthread_mutex_lock(&myLock);

while (counter < 10) {
    pthread_cond_wait(&myCV,
                      &myLock);
  }

pthread_mutex_unlock(&myLock);
```

```
/* Thread B */
pthread_mutex_lock(&myLock);

counter++;
if (counter == 10) {
    pthread_cond_signal(&myCV);
}

pthread_mutex_unlock(&myLock);
```

- Key ideas
  - `wait()` on a CV releases the lock
  - `signal()` on a CV wakes up a thread waiting on the CV
  - The thread that wakes up has to re-acquire the lock before `wait()` returns

Bounded buffer using CVs

Mmmm... donuts

Pro

```
int theArray[ARRAY_SIZE], size;
pthread_mutex_t theLock;
pthread_cond_t theCV;

/* Initialize */
pthread_mutex_init(&theLock, NULL);
pthread_condvar_init(&theCV, NULL);

void put(int val) {
    pthread_mutex_lock(&theLock);
    while (size == ARRAY_SIZE) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    addItemToArray(val);
    size++;
    if (size == 1) {
        pthread_cond_signal(&theCV);
    }
    pthread_mutex_unlock(&theLock);
}
```

What's wrong with this code?

```
int get() {
    int item;
    pthread_mutex_lock(&theLock);
    while (size == 0) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    item = getItemFromArray();
    size--;
    if (size == ARRAY_SIZE-1) {
        pthread_cond_signal(&theCV);
    }
    pthread_mutex_unlock(&theLock);
    return item;
}
```

Bounded buffer using CVs

Pro

onuts

Assumes only a single thread calling put() or get() at a time!
If two threads call get(), then two threads call put(), only one will be woken up!!

```
int theArray[ARRAY_SIZE], size;
pthread_mutex_t theLock;
pthread_cond_t theCV;

/* Initialize */
pthread_mutex_init(&theLock, NULL);
pthread_condvar_init(&theCV, NULL);

void put(int val) {
    pthread_mutex_lock(&theLock);
    while (size == ARRAY_SIZE) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    addItemToArray(val);
    size++;
    if (size == 1) {
        pthread_cond_signal(&theCV);
    }
    pthread_mutex_unlock(&theLock);
}
```

size = 0
T0 GET AND WAIT
T1 GET AND WATI

T2 put, size =1, wakeup T0
T3 put, size =2

T0 hold lock, get item,
size =1, release lock

```
int get() {
    int item;
    pthread_mutex_lock(&theLock);
    while (size == 0) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    item = getItemFromArray();
    size--;
    if (size == ARRAY_SIZE-1) {
        pthread_cond_signal(&theCV);
    }
    pthread_mutex_unlock(&theLock);
    return item;
}
```

Bounded buffer using CVs

lonuts

Prc

```
int theArray[ARRAY_SIZE], size;
pthread_mutex_t theLock;
pthread_cond_t theCV;

/* Initialize */
pthread_mutex_init(&theLock, NULL);
pthread_condvar_init(&theCV, NULL);

void put(int val) {
    pthread_mutex_lock(&theLock);
    while (size == ARRAY_SIZE) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    addItemToArray(val);
    size++;

    pthread_cond_signal(&theCV);

    pthread_mutex_unlock(&theLock);
}
```

One fix: **always signal**

Less efficient but OK.

```
int get() {
    int item;
    pthread_mutex_lock(&theLock);
    while (size == 0) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    item = getItemFromArray();
    size--;

    pthread_cond_signal(&theCV);

    pthread_mutex_unlock(&theLock);
    return item;
}
```

Bounded buffer using CVs

Another fix: **use broadcast()**

Wakes up all threads when the condition changes. Note: Only one thread will grab the lock when it wakes up. The others wake up and immediately wait to acquire the lock again.

Pr

```
int theArray[ARRAY_SIZE], size;
pthread_mutex_t theLock;
pthread_cond_t theCV;

/* Initialize */
pthread_mutex_init(&theLock, NULL);
pthread_condvar_init(&theCV, NULL);

void put(int val) {
    pthread_mutex_lock(&theLock);
    while (size == ARRAY_SIZE) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    addItemToArray(val);
    size++;
    if (size == 1) {
      pthread_cond_broadcast(&theCV);
    }
    pthread_mutex_unlock(&theLock);
}
```

```
int get() {
    int item;
    pthread_mutex_lock(&theLock);
    while (size == 0) {
        pthread_cond_wait(&theCV,
                          &theLock);
    }
    item = getItemFromArray();
    size--;
    if (size == ARRAY_SIZE-1) {
      pthread_cond_broadcast(&theCV);
    }
    pthread_mutex_unlock(&theLock);
    return item;
}
```

Monitors

- A monitor uses this style of locks and condition variables to protect resources and coordinate threads
- A **monitor** is an object containing variables, condition variables, and methods
- At most one thread can be active in a monitor at a time

```
monitor M {
    int size, theArray[ARRAY_SIZE];
    ConditionVariable emptyFull;
    void put(int x) {
      if (size == ARRAY_SIZE) wait(emptyFull);
      theArray[size] = x;
      size++;
      if (size == 1) broadcast(emptyFull);
    }
    int get() {
      if (size == 0) wait(emptyFull);
      size--;
      if (size == ARRAY_SIZE-1) broadcast(emptyFull);
      return theArray[size];
    }
}
```

The Big Picture

- Getting synchronization right is hard!
  - Even your TFs and faculty have been known to get it wrong.
  - Testing isn’t enough.
  - Need to assume worst case: all interleavings are possible
- We need to synchronize for correctness
  - Unsynchronized code can cause incorrect behavior
  - But too much synchronization means threads spend a lot of time waiting, not performing productive work.

The Big Picture

- How to choose between locks, semaphores, condition variables, monitors?
- Locks are very simple and suitable for many cases.
  - Issues: Maybe not the most efficient solution
  - For example, can't allow multiple readers but one writer inside a standard lock.
- Condition variables allow threads to sleep while holding a lock
  - Just be sure you understand whether they use Mesa or Hoare semantics!
- Semaphores provide pretty general functionality
  - But also make it really easy to botch things up.
- Monitors are a “pattern” for using locks and condition variables that is often very useful.