Synchronization: Patterns

Condition Variables & Semaphores

Topics

- Can we do something more powerful than just locking?
  - Condition variables to “signal” other threads.
  - Semaphores to count how many things are available.
- Can we allow multiple readers but only one writer?
- What can we solve with synchronization?
  - How do dining philosophers help us with sychronization?
  - What’s a circular buffer?

Condition Variables

Producer-Consumer pattern

- Producer-Consumer

  A common programming pattern.

  - Producer(s): one set of threads creating data.
  - Consumer(s): one set of threads using the data.
  - Store data: shared resource (e.g., variable or buffer) to hold the values that have been produced but not yet consumed.

  ..

ABCD: Data race

```
static int avail = 0;

int main() {
  pthread_t t1;
  pthread_create(&t1, NULL, thread_func, NULL);

  for (;;) {
    while (avail > 0) {
      printf("I just consumed %d\n", avail);
      avail--;
    }
  }
  pthread_join(t1, NULL);
}
```

```
static void *thread_func(void *arg) {
  for (;;) {
    avail++;
    sleep(1);
  }

  return 0;
}
```

- Is there a data race in this code?
  - a) Yes, two threads change a shared variable.
  - b) No, one increments, the other decrements.
  - c) No, avail is static.
  - d) No, main()'s while loop prevents concurrent edits to a shared variable.

Producer-Consumer

```
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static int avail = 0;

int main() {
  pthread_t t1;
  pthread_create(&t1, NULL, thread_func, NULL);

  for (;;) {
    pthread_mutex_lock(&mtx);
    {
      while (avail > 0) {
        // Simulate "consume everything available"
        printf("I just consumed %d\n", avail);
        avail--;

      }
    }
    pthread_mutex_unlock(&mtx);
  }
  pthread_join(t1, NULL);
}
```

Simulate consuming something: decrement to 0

```
static void *thread_func(void *arg) {
  for (;;) {
    pthread_mutex_lock(&mtx);
    {

      avail++;

    }
    pthread_mutex_unlock(&mtx);
    sleep(1);
  }

  return 0;
}
```

Simulate making something one at a time.

ABCD: Efficiency

```
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static int avail = 0;

int main() {
  pthread_t t1;
  pthread_create(&t1, NULL, thread_func, NULL);

  for (;;) {
    pthread_mutex_lock(&mtx);
    {
      while (avail > 0) {
        // Simulate "consume everything available"
        printf("I just consumed %d\n", avail);
        avail--;

      }
    }
    pthread_mutex_unlock(&mtx);
  }
  pthread_join(t1, NULL);
}
```

```
static void *thread_func(void *arg) {
  for (;;) {
    pthread_mutex_lock(&mtx);
    {
      avail++;
    }
    pthread_mutex_unlock(&mtx);
    sleep(1);
  }

  return 0;
}
```

- What is the major source of inefficiency in this program?

a) Wasted space: Use of an int when a bool would be better for `avail`.

b) Wasted CPU: main keeps looping even when nothing to consume.

c) Wasted CPU: main locking & unlocking mutex when there are multiple values to consume.

d) Wasted CPU: Program will never end.

Producer-Consumer (with Error Checking)

```
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static int avail = 0;

int main() {
    pthread_t t1;
    int s = pthread_create(&t1, NULL, thread_func, NULL);
    if (s != 0) {
        perror("pthread_create");
        exit(1);
    }

    for (;;) {
        s = pthread_mutex_lock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_lock");
            exit(1);
        }

        while (avail > 0) {
            printf("I just consumed %d\n", avail);
            avail--;
        }

        s = pthread_mutex_unlock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_unlock");
            exit(1);
        }
    }

    s = pthread_join(t1, NULL);
    if (s != 0) {
        perror("pthread_create");
        exit(1);
    }
}
```

```
static void *thread_func(void *arg) {
    for (;;) {
        int s = pthread_mutex_lock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_lock");
            pthread_exit((void *)1);
        }
        avail++;

        s = pthread_mutex_unlock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_unlock");
            pthread_exit((void *)1);
        }
        sleep(1);
    }

    return 0;
}
```

Condition Variable

- Condition variable purpose:

  ..

- Using a condition variable:

  (i) one thread sends a notification to the condition variable,

  (ii) another thread waits until
  a notification is sent to the condition variable.

  – While waiting,..

Integrates with Mutex

- We want to ensure that consumer(s) are thread safe.
  - ..
- A condition variable works closely with a mutex:

We need to hold the mutex
while processing data..

We'll wait until there is data available,..

That way the producer
(or other consumers)
can do work while we sleep.

pthread Condition Variables

- Define the variable
  pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
- Wait on a condition variable
  pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_t *mutex);
  - Internally, it will:
    - ..
    - Once signalled,..
  - Why release mutex when waiting?
    ..
- Lock-safe Sleep

  cond is paired with a mutex so consumer can be sure that:
  - No items added between unlocking mutex and waiting for cond. (important because a signal with no thread waiting is lost).
  - Once woken up, it again holds the mutex.

pthread Condition Variables (cont)

- Wake up ***one*** thread waiting on cond
  pthread_cond_signal(pthread_cond_t *cond);
  - How many threads are waiting on cond?
    1: It wakes it up one thread.
    2+: One wakes up, no control over which one.
    0: ..

- Wake up all threads waiting on cond
  pthread_cond_broadcast(pthread_cond_t *cond);
  - All threads wake up and try to grab mutex;
    ..

pthread Condition Variables (cont)

- Guideline on Signalling
  signal() and broadcast() are similar; how to choose?
  - If *any* of the waiting threads is sufficient to process the event:
    ..
    - It’s likely that all the threads do the same thing.
  - If *all* of the waiting threads need to respond to an event:
    ..
    - It’s likely *each thread does something different* in response to the event; all need to happen

Usage Pattern

Producer:

```
pthread_mutex_lock(&mutex);

<do some work producing an item>

pthread_mutex_unlock(&mutex);

pthread_cond_signal(&cond);
```

Consumer:

```
pthread_mutex_lock(&mutex);

while ( <no work to do> ) {
    pthread_cond_wait(&cond, &mutex);
}

<do some work>

pthread_mutex_unlock(&mutex);
```

- Details
  - ..
  - Producer should signal after releasing mutex to avoid waking up a consumer with cond only to wait for mutex (extra context switch)
  - Some systems optimize with "wait morphing" to just move process from one wait queue to another in the OS

Producer-Consumer with Condition Variable

```c
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

static int avail = 0;

int main() {
    pthread_t t1;
    pthread_create(&t1, NULL, thread_func, NULL);

    for (;;) {
        pthread_mutex_lock(&mtx);

        // This while loop is new.
        while (avail == 0) {
            pthread_cond_wait(&cond, &mtx);
        }

        while (avail > 0) {
            // Simulate "consume everything"
            printf("--> Consumer:%d.\n", avail);
            avail--;
        }

        pthread_mutex_unlock(&mtx);
    }

    pthread_join(t1, NULL);
}
```

```c
static void *thread_func(void *arg) {
    for (;;) {
        pthread_mutex_lock(&mtx);

        avail++;
        printf("Producer: %d.\n", avail);

        pthread_mutex_unlock(&mtx);

        // This signal is new.
        pthread_cond_signal(&cond);
        sleep(1);
    }
}
```

Discussion of Code

- Use of Condition Variables Discussion
  - mutex still protects the shared variable avail.
  - After producing an item, producer sends a signal to cond to wake up a waiting thread, if any: pthread_cond_signal(&cond)
    - This notifies other thread there is something to consume.
  - At each iteration, consumer checks if there is any available item to consume (the new while loop).
    - If nothing's available (avail == 0), it sleeps: pthread_cond_wait()
    - This releases the mutex before sleeping
  - Consumer wakes up when signalled by the producer:
    - pthread_cond_wait() grabs mutex before returning.

pthread_cond_wait() in loop?

- Why put pthread_cond_wait() in a loop?
  - Consumer only has work to do when: `(avail != 0)`
    `(avail != 0)` is called the..
  - Consumer only waits if there is no data to process.
    For this, just `if (avial == 0)` *seems* fine.
  - But, we must recheck the predicate after we are signalled:
    - We were waiting on the mutex as well as cond,
      ..
    - Therefore, no guarantee after a wake-up that data is available.

```
int main() {
  for (;;) {
    pthread_mutex_lock(&mtx);

    // This while loop is new.
    while (avail == 0) {
      pthread_cond_wait(&cond, &mtx);
    }

    while (avail > 0) {
      // Simulate "consume everything"
      avail--;
    }

    pthread_mutex_unlock(&mtx);
  }
}
```

Producer-Consumer with Condition Variable with Error Checking

```c
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
static int avail = 0;

int main() {
    pthread_t t1;
    void *res;
    int s;

    s = pthread_create(&t1, NULL, thread_func, NULL);
    if (s != 0) {
        perror("pthread_create");
        exit(1);
    }

    for (;;) {
        s = pthread_mutex_lock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_lock");
            exit(1);
        }

        // This while loop is new.
        while (avail == 0) {
            s = pthread_cond_wait(&cond, &mtx);
            if (s != 0) {
                perror("pthread_mutex_lock");
                exit(1);
            }
        }

        while (avail > 0) {
            /* This is simulating "consume everything available" */
            printf("--> Consumer: avail at %d.\n", avail);
            avail--;
        }

        s = pthread_mutex_unlock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_unlock");
            exit(1);
        }
    }
}
```

```c
static void *thread_func(void *arg) {
    for (;;) {
        int s = pthread_mutex_lock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_lock");
            pthread_exit((void *)1);
        }
        avail++;
        printf("Producer: avail up to %d.\n", avail);

        s = pthread_mutex_unlock(&mtx);
        if (s != 0) {
            perror("pthread_mutex_unlock");
            pthread_exit((void *)1);
        }

        // This signal is new.
        s = pthread_cond_signal(&cond);
        if (s != 0) {
            perror("pthread_cond_signal");
            pthread_exit((void *)1);
        }
        sleep(1);
    }

    return 0;
}
```

Condition Variable Template for Consumer

```
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>

static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;
static pthread_cond_t cond = PTHREAD_COND_INITIALIZER;

int main() {
    int s = pthread_mutex_lock(&mtx);

    if (s != 0) {
        perror("pthread_mutex_lock");
        exit(1);
    }

    while (/* Check if there is nothing to consume */) {
        /* Use while, not if, other threads might have woken
           up first and changed the shared variable. */
        pthread_cond_wait(&cond, &mtx);
    }

    // Do the necessary work with the shared variable, e.g., consume.

    s = pthread_mutex_unlock(&mtx);
    if (s != 0) {
        perror("pthread_mutex_lock");
        exit(1);
    }
}
```

Semaphores

Semaphores

- ..
  - A lock (mutex) is either available or not available, i.e., binary.
  - A semaphore is more flexible:
    ..
    i.e., *how many* are available.
- Useful when availability is not binary but a count
  e.g., *how many items are available to consume?*
  - If the availability count is 0,
    it means the semaphore is..
  - If the availability count is greater than 0,
    it means the semaphore is..
  - Must initialize the semaphore with
    an initial max availability count.

pthread Semaphore Functions

- Create & Initialize the semaphore

  sem_t sem;

  sem_init(sem_t *sem, int pshared, unsigned int value);

  - Sets current # available to value for sem.
  - pshared indicates if sem is for threads (0) or processes (1).

pthread Semaphore Functions

- Wait to "acquire" one of the semaphore's count
  sem_wait(sem_t *sem);
  - If count is 0, it blocks until count > 0.
  - When count is > 0 it decrements count and returns.
  - Does not guarantee mutual exclusion to a critical section:
    ..
- Signal to count-up the semaphore:
  sem_post(sem_t *sem);
  - If synchronizing access a..
    then posting can be like..
    - E.g., allow at most 50 students registered in a course.
  - If synchronizing between different sections of code,
    then it might indicate a new resource produced.

ABCD: Semaphore

- Which of these creates a semaphore which behaves the same as a mutex?
  a) `sem_init(&sem, 0, 0);`
  b) `sem_init(&sem, 0, 1);`
  c) `sem_init(&sem, 0, 2);`
  d) `sem_init(&mutex, 0, 10);`

```
sem_init(sem_t *sem, int pshared, unsigned int value);
```

Semaphore Use Ideas

- Places to use a Semaphore
  - Can have a..
    to acquire and release the mutex.
  - Can have different parts of the code use them, such as:
    - Produce: ..
    - Consumer: ..
    - May still need a mutex to protect shared data.

Read-Write Lock

Read-Write Lock

- Read-write lock
  - Another synchronization primitive.
  - ..
    - Multiple readers can all read at the same time!
    - Nobody else can access data while anyone writes.
- Acquire lock for reading

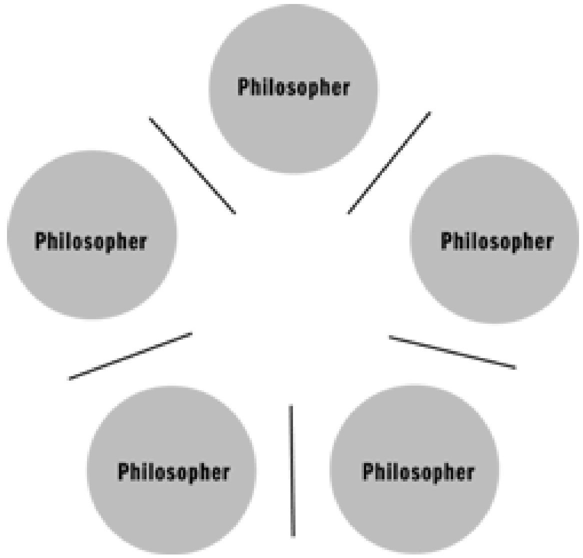
  pthread_rwlock_rdlock(pthread_rwlock_t *rwlock);
  - Allows any thread(s) to grab rwlock for reading as long as there is no thread that hold it for writing.
- Acquire lock for writing

  pthread_rwlock_wrlock(pthread_rwlock_t *rwlock);
  - This allows only one thread to grab rwlock for writing.

Dining Philosophers

Dining Philosophers

- Problem Description
  - Philosophers sit at a round table.
  - Philosophers alternate between eating and thinking.
  - To eat, a philosopher needs two forks (at their left and right). To think, no forks are needed.
  - One fork between adjacent philosophers.
    - ..



- We can model this as a synchronization problem:
  - ..
  - A fork is a shared resource that only one should access at a time

Try 1: Big lock!

- Challenge
  - come up with a solution that protects shared resources correctly and does not deadlock.
- Try 1: One big lock (not efficient)
  - Idea:

    ..
  - Correctly avoids deadlocks but

    ..
  - Linux used to use this approach to protect kernel resource during a syscall: “the big kernel lock”

Try 1: Lock each fork

- Try 2: One lock per fork.
- Let’s create a bad “solution”:
  - Have all threads grab their right fork and then their left fork.
  - But if every philosopher grabs their right fork at the same time, then..
  - The result:..
- Recall: deadlock conditions discussed previously
  - We can break any of these conditions to avoid a deadlock.

1) Hold-and-wait
2) Circular wait
3) Mutual exclusion
4) No preemption

Possible Solutions

- Solution 1:

  ..

  - E.g., Most philosophers grab right fork then left fork. Have have one philosopher grab left fork then right fork.
  - ..
- Solution 2:

  ..

  - Grab the left lock. Try the right lock. If you can't grab it,

    ..
  - ..

    since no philosopher can hold a fork and wait.
  - This does not prevent starvation

    and could also lead to livelock.

Dining Philosophers Implementation

```c
#define NUMBER 5

static pthread_mutex_t mtx[NUMBER] = {PTHREAD_MUTEX_INITIALIZER};



int main() {
  pthread_t t[NUMBER];

  for (int i = 0; i < NUMBER; ++i) {
    pthread_create(&t[i], NULL,
         thread_func, i);
  }

  for (int i = 0; i < NUMBER; ++i) {
    pthread_join(t[i], NULL);
  }
}
```

```c
static void *thread_func(void *arg) {
  int left = (int)arg;
  int right = ((int)arg + 1) % NUMBER;
  for (;;) {
    printf("Thread %d: thinking\n", (int)arg);
    sleep(5);

    pthread_mutex_lock(&mtx[left]);

    if (pthread_mutex_trylock(&mtx[right]) != 0) {
      pthread_mutex_unlock(&mtx[left]);
      continue;
    }

    printf("Thread %d: eating\n", (int)arg);

    pthread_mutex_unlock(&mtx[left]);

    pthread_mutex_unlock(&mtx[right]);
  }

  return 0;
}
```

Bounded Buffer
(Circular Buffer)

Bounded Buffer

- Problem Description
  - Multiple threads share a buffer.
  - Producer threads place items into the buffer.
    - They must wait..
  - Consumers threads take items from the buffer.
    - They must wait..
- Details
  - Producers:
    place items from index 0 to higher indices, one at a time.
  - Consumers:
    remove items from index 0 to higher indices, one at a time.
  - When get to last element,..

Solution

- Possible solution:
  ..
  - Mutex protects the data structure for all threads
  - Condition variable signals consumer (and producer?)
  - Inefficient because..

Semaphores: Elegant Solution

```c
#define SIZE 10

static char buf[SIZE] = {0};
static int in = 0, out = 0;
static sem_t filled_cnt;
static sem_t avail_cnt;
static pthread_mutex_t mtx = PTHREAD_MUTEX_INITIALIZER;


int main() {
  pthread_t t1;
  sem_init(&filled_cnt, 0, 0);
  sem_init(&avail_cnt, 0, SIZE);

  pthread_create(&t1, NULL, thread_func, NULL);

  // Producer Code
  for (int i = 0;; i++) {
    sem_wait(&avail_cnt);
    pthread_mutex_lock(&mtx);

    // Produce
    buf[in] = i;
    printf("Produced: %d in %d\n", buf[in], in);
    in = (in + 1) % SIZE;

    pthread_mutex_unlock(&mtx);

    sem_post(&filled_cnt);
  }

  pthread_join(t1, NULL);
}
```

```c
static void *thread_func(void *arg) {
  for (;;) {
    sleep(1);
    sem_wait(&filled_cnt);
    pthread_mutex_lock(&mtx);

    // Consume
    printf("Consumed: %d\n", buf[out]);
    out = (out + 1) % SIZE;

    pthread_mutex_unlock(&mtx);

    sem_post(&avail_cnt);
  }

  return 0;
}
```

Summary

- Condition Variable
  - One thread signals another for an event.
  - Paired with a mutex for mutual exclusion.
- Produce-Consumer Pattern
  - Shared data structure storing waiting items.
- Semaphore
  - Synchronization with a count
- Read-Write Lock
  - Multiple readers allowed; only one writer.
- Classing problems
  - Dining Philosophers: worry about deadlock / livelock
  - Bounded buffer: elegant semaphore solution.