

Synchronization: Patterns

Condition Variables & Semaphores



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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 synchronization?
 - 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.

- .. **This is the shared resource needs protection.**

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;
```

Use same mutex in both to serialize
access to shared data.
Avoids data race problems.

```
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.

```
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);
    }
}
```

Producer-Consumer (with Error Checking)

```
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:
 - .. to signal a change in state
- 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,.. **the thread sleeps (no CPU use).**

Integrates with Mutex

- We want to ensure that consumer(s) are thread safe.
 - .. Expect the processing of a value to occur inside a mutex.
- A condition variable works closely with a mutex:

We need to hold the mutex while processing data.. so we don't corrupt the shared resource.

We'll wait until there is data available,.. but not hold the mutex while waiting!

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:

- .. Atomically release the mutex and wait for cond
- Once signalled,.. wakes up and grabs the mutex

–Why release mutex when waiting?

- .. Don't sleep while holding a lock.

- 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: .. **Signal is lost:**
doesn't count of how many signals are pending.
- Wake up **all** threads waiting on cond
`pthread_cond_broadcast(pthread_cond_t *cond);`
 - All threads wake up and try to grab mutex;
.. **they compete for the lock**

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:

.. use `pthread_cond_signal()`

- It's likely that all the threads do the same thing.

– If *all* of the waiting threads need to respond to an event:

.. use `pthread_cond_broadcast()`

- 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:

```
while(true) {  
    pthread_mutex_lock(&mutex);  
  
    while ( <no work to do> ) {  
        pthread_cond_wait(&cond, &mutex);  
    }  
  
    <do some work>  
  
    pthread_mutex_unlock(&mutex);  
}
```

- Details

- .. A condition variable must always use the same mutex.
- 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

```
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);
```

```
}
```

```
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.. condition variable's predicate.
 - Consumer only waits if there is no data to process.
For this, just if (avail == 0) seems fine.
 - But, we must recheck the predicate after we are signalled:
 - We were waiting on the mutex as well as cond,
.. so another thread may have consumed the data first.
 - 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);  
    }  
}
```

```
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);
        }
    }
}
```

Producer-Consumer with Condition Variable with Error Checking

```
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 semaphore is a lock with a count
 - A lock (mutex) is either available or not available, i.e., binary.
 - A semaphore is more flexible:
 - .. it indicates the availability as a count, 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.. unavailable.
 - If the availability count is greater than 0, it means the semaphore is.. available.
 - Must initialize the semaphore with an initial max availability count.

pthread Semaphore Functions

- Create & Initialize the semaphore

```
#include <semaphore.h>
```

```
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**:
 - .. **it counts the availability of a resource.**
- Signal to count-up the semaphore:
`sem_post(sem_t *sem);`
 - If synchronizing access a.. **limited resources** then posting can be like.. **releasing a resource.**
 - **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.. single section of code wait and then post to acquire and release the resources.
 - Can have different parts of the code use them, such as:
 - Produce: .. post when an item is ready
 - Consumer: .. wait until an item is ready
 - May still need a mutex to protect shared data.

Read-Write Lock

Read-Write Lock

- **Read-write lock**
 - Another synchronization primitive.
 - .. **Allows either unlimited readers, xor a single writer:**
 - Multiple readers can all read at the same time!
 - Nobody else can access data while anyone writes.
- **Initialize:** `pthread_rwlock_t rwlock = PTHREAD_RWLOCK_INITIALIZER;`
- **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.

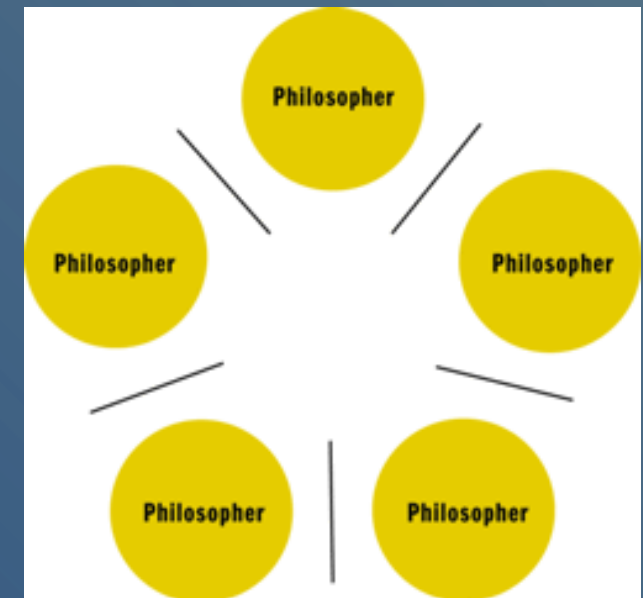
Dining Philosophers

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.

- .. Each fork is a resource shared by two adjacent philosophers.
- We can model this as a synchronization problem:
 - .. Each thread is a philosopher.
 - 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:

- .. Use one mutex to guard all forks and control access.

- Correctly avoids deadlocks but

- .. allows only one philosopher to eat.

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



Try 2: 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.. no philosophers can grab their left fork.
 - The result:.. deadlock due to hold-and-wait and circular-wait.
- 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:

- .. Have a philosopher grab forks in a different order.
 - E.g., Most philosophers grab right fork then left fork. Have one philosopher grab left fork then right fork.
- .. This breaks circular-wait condition from occurring.

- Solution 2:

- .. Try grabbing both locks at once.
 - Grab the left lock. Try the right lock. If you can't grab it,
- .. give up the left lock, and try again.
 - .. This breaks hold-and-wait condition since no philosopher can hold a fork and wait.
- This does not prevent starvation and could also lead to livelock.

Dining Philosophers Implementation

```
#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);  
    }  
}
```

```
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.. if the buffer is full.
- Consumers threads take items from the buffer.
 - They must wait.. if buffer is empty.

- 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,.. wrap-around to index 0.

Solution

- Possible solution:
 - ..Mutex + Condition Variable
 - Mutex protects the data structure for all threads
 - Condition variable signals consumer (and producer?)
 - Inefficient because..
 - all threads need to compete and check for availability.

```
#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);
```

Semaphores: Elegant Solution

```
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**

- `pthread_cond_signal(&cond); pthread_cond_broadcast(&cond); pthread_cond_wait(&cond, &mutex);`
- One thread **signals** another for an event.
- **Paired with a mutex for mutual exclusion.**

- **Produce-Consumer Pattern:** Shared data structure storing waiting items.

- **Semaphore**

- `Sem_init(&sem, 0, 0); sem_wait(&sem); sem_post(&sem);`
- Synchronization with a **count**

- **Read-Write Lock**

- `Pthread_rwlock_rdlock(&rwlock); pthread_rwlock_wrlock(&rwlock);`
- **Multiple readers allowed**; only one writer.

- **Classing problems**

- **Dining Philosophers:** worry about deadlock / livelock
- **Bounded buffer:** elegant semaphore solution.