

Synchronization

When multithreading gets interesting

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Synchronization are a series of mechanisms to control what threads are allowed to perform what operation at a time. Most of the time, the threads can progress without having to communicate, but every so often two or more threads may want to access a critical section. A critical section is a section of code that can only be executed by one thread at a time, if the program is to function correctly. If two threads (or processes) were to execute code inside the critical section at the same time, it is possible that program may no longer have correct behavior.

As we said in the previous chapter, race conditions happen when an operation touches a piece of memory at the same time as another thread. If the memory location is only accessible by one thread, for example the automatic variable `i` below, then there is no possibility of a race condition and no Critical Section associated with `i`. However the `sum` variable is a global variable and accessed by two threads. It is possible that two threads may attempt to increment the variable at the same time.

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

int sum = 0; //shared

void *countgold(void *param) {
    int i; //local to each thread
    for (i = 0; i < 10000000; i++) {
        sum += 1;
    }
    return NULL;
}

int main() {
    pthread_t tid1, tid2;
    pthread_create(&tid1, NULL, countgold, NULL);
    pthread_create(&tid2, NULL, countgold, NULL);

    //Wait for both threads to finish:
    pthread_join(tid1, NULL);
    pthread_join(tid2, NULL);

    printf("ARRRRRG sum is %d\n", sum);
    return 0;
}
```

```
}
```

Typical output of the above code is ARGGGH sum is <some number less than expected> because there is a race condition. The code does not stop two threads from reading-writing sum at the same time. For example, both threads copy the current value of sum into CPU that runs each thread (let's pick 123). Both threads increment one to their own copy. Both threads write back the value (124). If the threads had accessed the sum at different times then the count would have been 125. A few of the possible different orderings are below.

Permissible Pattern	
Thread 1	Thread 2
Load Addr, Add 1 (i=1 locally)	...
Store (i=1 globally)	...
...	Load Addr, Add 1 (i=2 locally)
...	Store (i=2 globally)
Partial Overlap	
Thread 1	Thread 2
Load Addr, Add 1 (i=1 locally)	...
Store (i=1 globally)	Load Addr, Add 1 (i=1 locally)
...	Store (i=1 globally)
Full Overlap	
Thread 1	Thread 2
Load Addr, Add 1 (i=1 locally)	Load Addr, Add 1 (i=1 locally)
Store (i=1 globally)	Store (i=1 globally)

We would like the first pattern of the code being mutually exclusive. Which leads us to our first synchronization primitive, a Mutex.

Mutex

To ensure only one thread at a time can access a global variable, use a mutex – short for Mutual Exclusion. If one thread is currently inside a critical section we would like another thread to wait until the first thread is complete. A mutex isn't a primitive in the truest sense, though it is one of the smallest pieces of data structures that has some threading API sense. A mutex also isn't really a data structure. It is an abstract data type, much like you learned in your data structures class. There are many ways to implement a mutex, and we'll give a few in this chapter. For right now let's use the black box that the pthread library gives us. Here is how we declare a mutex.

```
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER; // global variable
pthread_mutex_lock(&m); // start of Critical Section
// Critical section
pthread_mutex_unlock(&m); //end of Critical Section
```

Mutex Lifetime

There are a few ways of initializing a mutex. You can use the macro PTHREAD_MUTEX_INITIALIZER only for global ('static') variables. `m = PTHREAD_MUTEX_INITIALIZER` is exactly equivalent to the more general purpose `pthread_mutex_init(m, NULL)` but for our purposes it is the same. The init version includes options to trade performance for additional error-checking and advanced sharing options. The init version also makes sure that the mutex is correctly initialized after the call, global mutexes are initialized on first lock. You can also call the init function inside of a program for a mutex located on the heap.

```
pthread_mutex_t *lock = malloc(sizeof(pthread_mutex_t));
pthread_mutex_init(lock, NULL);
//later
pthread_mutex_destroy(lock);
free(lock);
```

Once we are finished with the mutex we should also call `pthread_mutex_destroy(m)` too. Note, you can only destroy an unlocked mutex, destroy on a locked mutex is undefined behavior. Things to keep in mind about init and destroy You don't need to destroy a mutex created with the global initializer.

1. Multiple threads init/destroy has undefined behavior
2. Destroying a locked mutex has undefined behavior
3. Keep to the pattern of one and only one thread initializing a mutex.
4. Copying the bytes of the mutex to a new memory location and then using the copy is *not* supported. To reference a mutex, you have to have a pointer to that memory address.

Mutex Usages

How would I use a mutex? Here is a complete example in the spirit of the earlier piece.

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

// Create a mutex this ready to be locked!
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

int sum = 0;

void *countgold(void *param) {
    int i;

    //Same thread that locks the mutex must unlock it
    //Critical section is just 'sum += 1'
    //However locking and unlocking a million times
    //has significant overhead

    pthread_mutex_lock(&m);

    // Other threads that call lock will have to wait until we call unlock

    for (i = 0; i < 10000000; i++) {
        sum += 1;
    }
    pthread_mutex_unlock(&m);
    return NULL;
}

int main() {
    pthread_t tid1, tid2;
    pthread_create(&tid1, NULL, countgold, NULL);
    pthread_create(&tid2, NULL, countgold, NULL);

    pthread_join(tid1, NULL);
    pthread_join(tid2, NULL);

    printf("ARRRRRG sum is %d\n", sum);
    return 0;
}
```

In the code above, the thread gets the lock to the counting house before entering. The critical section is only the `sum+=1` so the following version is also correct.

```
for (i = 0; i < 10000000; i++) {
    pthread_mutex_lock(&m);
    sum += 1;
    pthread_mutex_unlock(&m);
}
return NULL;
}
```

This process runs slower because we lock and unlock the mutex a million times, which is expensive - at least compared with incrementing a variable. In this simple example, we didn't really need threads - we could have added up twice! A faster multi-thread example would be to add one million using an automatic (local) variable and only then adding it to a shared total after the calculation loop has finished:

```
int local = 0;
for (i = 0; i < 10000000; i++) {
    local += 1;
}

pthread_mutex_lock(&m);
sum += local;
pthread_mutex_unlock(&m);

return NULL;
}
```

Obviously if you know the gaussian sum, you can avoid race conditions altogether, but this is just for illustration.

Starting with the gotchas. Firstly, C Mutexes do not lock variables. A mutex is not that smart. It works with code, not data. If I lock a mutex, the other threads will continue. It's only when a thread attempts to lock a mutex that is already locked, will the thread have to wait. As soon as the original thread unlocks the mutex, the second (waiting) thread will acquire the lock and be able to continue. The following code creates a mutex that does effectively nothing.

```
int a;
pthread_mutex_t m1 = PTHREAD_MUTEX_INITIALIZER,
                m2 = PTHREAD_MUTEX_INITIALIZER;

// later
// Thread 1
pthread_mutex_lock(&m1);
a++;
pthread_mutex_unlock(&m1);

// Thread 2
pthread_mutex_lock(&m2);
a++;
pthread_mutex_unlock(&m2);
```

Here are some other gotchas in no particular order

1. Don't cross the streams! If you are using threads, don't fork in the middle of your program. This means any time after your mutexes have been initialized.
2. The thread that locks a mutex is the only thread that can unlock it.
3. Each program can have multiple mutex locks. You can design your program to have one lock per data structure, one lock per heap, or one lock per set of data structures. If you only have one lock, then there may be significant contention for the lock between two threads that was unnecessary. For example if two threads were updating two different counters, it might not be necessary to use the same lock.
4. Locks are only tools. They don't spot critical sections for you!
5. There will always be a small amount of overhead of calling `pthread_mutex_lock` and `pthread_mutex_unlock`. However, this is the price you pay for correctly functioning programs!
6. Not unlocking a mutex due to an early return during an error condition
7. Resource leak (not calling `pthread_mutex_destroy`)
8. Using an uninitialized mutex or using a mutex that has already been destroyed
9. Locking a mutex twice on a thread without unlocking first
10. Deadlock

Mutex Implementation

So we have this cool data structure. How do we implement it? First a naive, incorrect implementation is shown below. The `unlock` function simply unlocks the mutex and returns. The `lock` function first checks to see if the lock is already locked. If it is currently locked, it will keep checking again until another thread has unlocked the mutex.

```
// Version 1 (Incorrect!)

void lock(mutex_t *m) {
    while(m->locked) { /*Locked? Nevermind - just loop and check again!*/ }

    m->locked = 1;
}

void unlock(mutex_t *m) {
    m->locked = 0;
}
```

Version 1 uses 'busy-waiting' unnecessarily wasting CPU resources. However, there is a more serious problem. We have a race-condition! If two threads both called `lock` concurrently, it is possible that both threads would read `m_locked` as zero. Thus both threads would believe they have exclusive access to the lock and both threads will continue.

We might attempt to reduce the CPU overhead a little by calling `pthread_yield()` inside the loop - `pthread_yield` suggests to the operating system that the thread does not use the CPU for a short while, so the CPU may be assigned to threads that are waiting to run. But does not fix the race-condition. We need a better implementation.

Extra: Implementing a Mutex with hardware

We can use C11 Atomics to do that perfectly! A complete solution is detailed [here](#). This is a spinlock mutex, `futex` implementations can be found online.

First the data structure and initialization code.

```
typedef struct mutex_{
    // We need some variable to see if the lock is locked
```

```

    atomic_int_least8_t lock;
    // A mutex needs to keep track of its owner so
    // Another thread can't unlock it
    pthread_t owner;
} mutex;

#define UNLOCKED 0
#define LOCKED 1
#define UNASSIGNED_OWNER 0

int mutex_init(mutex* mtx){
    // Some simple error checking
    if(!mtx){
        return 0;
    }
    // Not thread safe the user has to take care of this
    atomic_init(&mtx->lock, UNLOCKED);
    mtx->owner = UNASSIGNED_OWNER;
    return 1;
}

```

This is the initialization code, nothing fancy here. We set the state of the mutex to unlocked and set the owner to locked.

```

int mutex_lock(mutex* mtx){
    int_least8_t zero = UNLOCKED;
    while(!atomic_compare_exchange_weak_explicit
        (&mtx->lock,
         &zero,
         LOCKED,
         memory_order_seq_cst,
         memory_order_seq_cst)){
        zero = UNLOCKED;
        sched_yield(); // Use system calls for scheduling speed
    }
    // We have the lock now
    mtx->owner = pthread_self();
    return 1;
}

```

What does this code do? Well to start it it initializes a variable that we will keep as the unlocked state. Atomic Compare and Exchange is an instruction supported by most modern architectures (on x86 it's `lock cmpxchg`). The pseudocode for this operation looks like this

```

int atomic_compare_exchange_pseudo(int* addr1, int* addr2, int val){
    if(*addr1 == *addr2){
        *addr1 = val;
        return 1;
    }else{
        *addr2 = *addr1;
        return 0;
    }
}

```

Except it is all done *atomically* meaning in one uninterruptible operation. What does the *weak* part mean? Well atomic instructions are prone to **spurious failures** meaning that there are two versions to these atomic functions a *strong* and a *weak* part, strong guarantees the success or failure while weak may fail even when the operation succeeds. These are the same spurious failures that you'll see in condition variables below. We are using weak because weak is faster, and we are in a loop! That means we are okay if it fails a little bit more often because we will just keep spinning around anyway.

Inside the while loop, we have failed to grab the lock! We reset zero to unlocked and sleep for a little while. When we wake up we try to grab the lock again. Once we successfully swap, we are in the critical section! We set the mutex's owner to the current thread for the unlock method and return successful.

How does this guarantee mutual exclusion, when working with atomics we are not entirely sure! But in this simple example, we can because the thread that is able to successfully expect the lock to be UNLOCKED (0) and swap it to a LOCKED (1) state is considered the winner. How do we implement unlock?

```
int mutex_unlock(mutex* mtx){
    if(unlikely(pthread_self() != mtx->owner)){
        return 0; //You can't unlock a mutex if you aren't the owner
    }
    int_least8_t one = 1;
    //Critical section ends after this atomic
    mtx->owner = UNASSIGNED_OWNER;
    if(!atomic_compare_exchange_strong_explicit(
        &mtx->lock,
        &one,
        UNLOCKED,
        memory_order_seq_cst,
        memory_order_seq_cst)){
        //The mutex was never locked in the first place
        return 0;
    }
    return 1;
}
```

To satisfy the api, you can't unlock the mutex unless you are the one who owns it. Then we unassign the mutex owner, because critical section is over after the atomic. We want a strong exchange because we don't want to block (pthread_mutex_unlock doesn't block). We expect the mutex to be locked, and we swap it to unlock. If the swap was successful, we unlocked the mutex. If the swap wasn't, that means that the mutex was UNLOCKED and we tried to switch it from UNLOCKED to UNLOCKED, preserving the non blocking of unlock.

What is this memory order business? We were talking about memory fences earlier, here it is! We won't go into detail because it is outside the scope of this course but not the scope of this article. Basically we need consistency to make sure no loads or stores are ordered before or after. You need to create dependency chains for more efficient ordering.

Semaphore

A semaphore is another synchronization primitive. It is initialized to some value. Threads can either `sem_wait` or `sem_post` which lowers or increases the value. If the value reaches zero and a wait is called, the thread will be blocked until a post is called.

Using a semaphore is as easy as creating a mutex. First decide if the initial value should be zero or some other value, for example the number of remaining spaces in an array. Unlike pthread mutex there are not shortcuts to creating a semaphore - use `sem_init`.

```
#include <semaphore.h>

sem_t s;
```

```
int main() {
    sem_init(&s, 0, 10); // returns -1 (=FAILED) on OS X
    sem_wait(&s); // Could do this 10 times without blocking
    sem_post(&s); // Announce that we've finished (and one more resource
                  // item is available; increment count)
    sem_destroy(&s); // release resources of the semaphore
}
```

When using a semaphore, wait and post can be called from different threads! Unlike a mutex, the increment and decrement can be from different threads.

This becomes especially useful if you want to use a semaphore to implement a mutex. A mutex is a semaphore that always waits before it posts. Some textbooks will refer to a mutex as a binary semaphore. You do have to be careful to never add more than one to a semaphore or otherwise your mutex abstraction breaks. That is usually why a mutex is used to implement a semaphore and vice versa.

- Initialize the semaphore with a count of one.
- Replace `pthread_mutex_lock` with `sem_wait`
- Replace `pthread_mutex_unlock` with `sem_post`

```
sem_t s;
sem_init(&s, 0, 1);

sem_wait(&s);
// Critical Section
sem_post(&s);
```

But be warned, it isn't the same! A mutex can handle what we call lock inversion well. Meaning the following code breaks with a traditional mutex, but produces a race condition with threads.

```
// Thread 1
sem_wait(&s);
// Critical Section
sem_post(&s);

// Thread 2
// Some threads just want to see the world burn
sem_post(&s);

// Thread 3
sem_wait(&s);
// Not thread safe!
sem_post(&s);
```

If we replace it with mutex lock it won't work now.

```
// Thread 1
mutex_lock(&s);
// Critical Section
```



```
mutex_unlock(&s);

// Thread 2
// Foiled!
mutex_unlock(&s);

// Thread 3
mutex_lock(&s);
// Now it's thread safe
mutex_unlock(&s);
```

Signal Safety

Also, keyword `sem_post` is one of a handful of functions that can be correctly used inside a signal handler `pthread_mutex_unlock` is not. This means we can release a waiting thread which can now make all of the calls that we were not allowed to call inside the signal handler itself e.g. `printf`. Here is some code that utilizes this;

```
#include <stdio.h>
#include <pthread.h>
#include <signal.h>
#include <semaphore.h>
#include <unistd.h>

sem_t s;

void handler(int signal) {
    sem_post(&s); /* Release the Kraken! */
}

void *singsong(void *param) {
    sem_wait(&s);
    printf("I had to wait until your signal released me!\n");
}

int main() {
    int ok = sem_init(&s, 0, 0 /* Initial value of zero*/);
    if (ok == -1) {
        perror("Could not create unnamed semaphore");
        return 1;
    }
    signal(SIGINT, handler); // Too simple! See Signals chapter

    pthread_t tid;
    pthread_create(&tid, NULL, singsong, NULL);
    pthread_exit(NULL); /* Process will exit when there are no more
        threads */
}
```

Other uses for semaphores are keeping track of empty spaces in arrays. We will discuss these in the thread-safe data structures section.

Condition Variables

Condition variables allow a set of threads to sleep until woken up. You can wake up one thread or all threads that are sleeping. If you only wake one thread then the operating system will decide which thread to wake up. You don't wake threads directly instead you 'signal' the condition variable, which then will wake up one (or all) threads that are sleeping inside the condition variable.

Condition variables are also used with a mutex and with a loop, so when woken up they have to check a condition in a critical section. If you just need to be woken up not in a critical section, there are other ways to do this in POSIX. Threads sleeping inside a condition variable are woken up by calling `pthread_cond_broadcast` (wake up all) or `pthread_cond_signal` (wake up one). Note despite the function name, this has nothing to do with POSIX signals!

Occasionally a waiting thread may appear to wake up for no reason. This is called a *spurious wake*. If you read the hardware implementation of a mutex section, this is similar. This is not an issue because you always use `wait` inside a loop that tests a condition that must be true to continue.

Why do spurious wakeups happen? For performance. On multi-CPU systems, it is possible that a race-condition could cause a wake-up (signal) request to be unnoticed. The kernel may not detect this lost wake-up call but can detect when it might occur. To avoid the potential lost signal, the thread is woken up so that the program code can test the condition again.

Condition wait Wait Example

The call `pthread_cond_wait` performs three actions:

1. Unlock the mutex; it must be locked.
2. Sleeps until `pthread_cond_signal` is called on the same condition variable)
3. Before returning, locks the mutex

Condition variables are *always* used with a mutex lock. Before calling `wait`, the mutex lock must be locked and `wait` must be wrapped with a loop.

```
pthread_cond_t cv;
pthread_mutex_t m;
int count;

// Initialize
pthread_cond_init(&cv, NULL);
pthread_mutex_init(&m, NULL);
count = 0;

// Thread 1
pthread_mutex_lock(&m);
while (count < 10) {
    pthread_cond_wait(&cv, &m);
    /* Remember that cond_wait unlocks the mutex before blocking (waiting)!
     */
    /* After unlocking, other threads can claim the mutex. */
    /* When this thread is later woken it will */
    /* re-lock the mutex before returning */
}
pthread_mutex_unlock(&m);

//later clean up with pthread_cond_destroy(&cv); and mutex_destroy

// Thread 2:
while (1) {
    pthread_mutex_lock(&m);
    count++;
```

```
pthread_cond_signal(&cv);
/* Even though the other thread is woken up it cannot not return */
/* from pthread_cond_wait until we have unlocked the mutex. This is */
/* a good thing! In fact, it is usually the best practice to call */
/* cond_signal or cond_broadcast before unlocking the mutex */
pthread_mutex_unlock(&m);
}
```

This is a pretty naive example, but it shows that we can tell threads to wake up in a standardized manner. In the next section, we will use these to implement efficient blocking data structures.

Thread Safe Data Structures

Naturally, we want our data structures to be thread safe as well! We can use mutexes and synchronization primitives to make that happen. First a few definitions. Atomicity is when an operation is thread safe. We have atomic instructions in hardware by providing the lock prefix

```
lock ...
```

But atomicity also applies to higher orders of operations. We say a data structure operation is an atomic if it happens all at once and successfully or not at all.

As such, we can use synchronization primitives in order to make our data structures thread safe. For the most part, we will be using mutexes because they carry more semantic meaning than a binary semaphore. Note, this is just an introduction - writing high-performance thread-safe data structures requires its own book! Take for example the following non thread-safe stack.

```
// A simple fixed-sized stack (version 1)
#define STACK_SIZE 20
int count;
double values[STACK_SIZE];

void push(double v) {
    values[count++] = v;
}

double pop() {
    return values[--count];
}

int is_empty() {
    return count == 0;
}
```

Version 1 of the stack is not thread-safe because if two threads call push or pop at the same time then the results or the stack can be inconsistent. For example, imagine if two threads call pop at the same time then both threads may read the same value, both may read the original count value.

To turn this into a thread-safe data structure we need to identify the *critical sections* of our code, meaning we need to ask which section(s) of the code must only have one thread at a time. In the above example the push, pop and is_empty functions access the same memory and all critical sections for the stack. While push (and pop) is executing, the data structure is in an inconsistent state, for example the count may not have been written to, so may still contain the original value. By wrapping these methods with a mutex we can ensure that only one thread at a time can update (or read) the

stack. A candidate ‘solution’ is shown below. Is it correct? If not, how will it fail?

```
// An attempt at a thread-safe stack (version 2)
#define STACK_SIZE 20
int count;
double values[STACK_SIZE];

pthread_mutex_t m1 = PTHREAD_MUTEX_INITIALIZER;
pthread_mutex_t m2 = PTHREAD_MUTEX_INITIALIZER;

void push(double v) {
    pthread_mutex_lock(&m1);
    values[count++] = v;
    pthread_mutex_unlock(&m1);
}

double pop() {
    pthread_mutex_lock(&m2);
    double v = values[--count];
    pthread_mutex_unlock(&m2);

    return v;
}

int is_empty() {
    pthread_mutex_lock(&m1);
    return count == 0;
    pthread_mutex_unlock(&m1);
}
```

Version 2 contains at least one error. Take a moment to see if you can find the error(s) and work out the consequence(s).

If three threads called `push()` at the same time, the lock `m1` ensures that only one thread at a time manipulates the stack on `push` or `is_empty` – Two threads will need to wait until the first thread completes. A similar argument applies to concurrent calls to `pop`. However, version 2 does not prevent `push` and `pop` from running at the same time because `push` and `pop` use two different mutex locks. The fix is simple in this case – use the same mutex lock for both the `push` and `pop` functions.

The code has a second error. `is_empty` returns after the comparison and will not unlock the mutex. However, the error would not be spotted immediately. For example, suppose one thread calls `is_empty` and a second thread later calls `push`. This thread would mysteriously stop. Using a debugger you can discover that the thread is stuck at the `lock()` method inside the `push` method because the lock was never unlocked by the earlier `is_empty` call. Thus an oversight in one thread led to problems much later in time in an arbitrary other thread. Let’s try to rectify these problems

```
// An attempt at a thread-safe stack (version 3)
int count;
double values[count];
pthread_mutex_t m = PTHREAD_MUTEX_INITIALIZER;

void push(double v) {
    pthread_mutex_lock(&m);
    values[count++] = v;
    pthread_mutex_unlock(&m);
}

double pop() {
```

```

pthread_mutex_lock(&m);
double v = values[--count];
pthread_mutex_unlock(&m);
return v;
}
int is_empty() {
pthread_mutex_lock(&m);
int result = count == 0;
pthread_mutex_unlock(&m);
return result;
}

```

Version 3 is thread-safe. We have ensured mutual exclusion for all of the critical sections. There are a few things to note.

- `is_empty` is thread-safe but its result may already be out-of-date. The stack may no longer be empty by the time the thread gets the result! This is usually why in thread safe data structures, functions that return sizes are removed or deprecated.
- There is no protection against underflow (popping on an empty stack) or overflow (pushing onto an already-full stack)

The last point can be fixed using counting semaphores. The implementation assumes a single stack. A more general purpose version might include the mutex as part of the memory struct and use `pthread_mutex_init` to initialize the mutex. For example,

```

// Support for multiple stacks (each one has a mutex)
typedef struct stack {
    int count;
    pthread_mutex_t m;
    double *values;
} stack_t;

stack_t* stack_create(int capacity) {
    stack_t *result = malloc(sizeof(stack_t));
    result->count = 0;
    result->values = malloc(sizeof(double) * capacity);
    pthread_mutex_init(&result->m, NULL);
    return result;
}

void stack_destroy(stack_t *s) {
    free(s->values);
    pthread_mutex_destroy(&s->m);
    free(s);
}

// Warning no underflow or overflow checks!

void push(stack_t *s, double v) {
    pthread_mutex_lock(&s->m);
    s->values[(s->count)++] = v;
    pthread_mutex_unlock(&s->m);
}

double pop(stack_t *s) {
    pthread_mutex_lock(&s->m);

```

```

    double v = s->values[--(s->count)];
    pthread_mutex_unlock(&s->m);
    return v;
}

int is_empty(stack_t *s) {
    pthread_mutex_lock(&s->m);
    int result = s->count == 0;
    pthread_mutex_unlock(&s->m);
    return result;
}

int main() {
    stack_t *s1 = stack_create(10 /* Max capacity*/);
    stack_t *s2 = stack_create(10);
    push(s1, 3.141);
    push(s2, pop(s1));
    stack_destroy(s2);
    stack_destroy(s1);
}

```

Before we fix the problems with semaphores. How would we fix the problems with condition variables? Try it out before you look at the code in the previous section. Basically, we need to wait in push and pop if our stack is full or empty respectively. Attempted solution:

```

// Assume cv is a condition variable
// correctly initialized

void push(stack_t *s, double v) {
    pthread_mutex_lock(&s->m);
    if(s->count == 0) pthread_cond_wait(&s->cv, &s->m);
    s->values[(s->count)++] = v;
    pthread_mutex_unlock(&s->m);
}

double pop(stack_t *s) {
    pthread_mutex_lock(&s->m);
    if(s->count == 0) pthread_cond_wait(&s->cv, &s->m);
    double v = s->values[--(s->count)];
    pthread_mutex_unlock(&s->m);
    return v;
}

```

Does the following solution work? Take a second before looking at the answer to spot the errors. So did you catch all of them?

1. The first one is a simple one. In push, our check should be against the total capacity, not zero.
2. We only have if statement checks. wait() could spuriously wake up
3. We never signal any of the threads! Threads could get stuck waiting indefinitely.

Let's fix those errors Does this solution work?

```

void push(stack_t *s, double v) {
    pthread_mutex_lock(&s->m);
    while(s->count == capacity) pthread_cond_wait(&s->cv, &s->m);
    s->values[(s->count)++] = v;
    pthread_cond_signal(&s->cv);
    pthread_mutex_unlock(&s->m);
}

double pop(stack_t *s) {
    pthread_mutex_lock(&s->m);
    while(s->count == 0) pthread_cond_wait(&s->cv, &s->m);
    double v = s->values[--(s->count)];
    pthread_cond_broadcast(&s->cv);
    pthread_mutex_unlock(&s->m);
    return v;
}

```

This solution doesn't work either! The problem is with the signal. Can you see why? What would you do to fix it? Now, how would we use counting semaphores to prevent over and underflow? Let's discuss it in the next section.

Using semaphores

Let's use a counting semaphore to keep track of how many spaces remain and another semaphore to keep to track the number of items in the stack. We will call these two semaphores `sremain` and `sitems`. Remember `sem_wait` will wait if the semaphore's count has been decremented to zero (by another thread calling `sem_post`).

```

// Sketch #1

sem_t sitems;
sem_t sremain;
void stack_init(){
    sem_init(&sitems, 0, 0);
    sem_init(&sremain, 0, 10);
}

double pop() {
    // Wait until there's at least one item
    sem_wait(&sitems);
    ...

void push(double v) {
    // Wait until there's at least one space
    sem_wait(&sremain);
    ...
}

```

Sketch #2 has implemented the post too early. Another thread waiting in `push` can erroneously attempt to write into a full stack and similarly a thread waiting in the `pop()` is allowed to continue too early.

```

// Sketch #2 (Error!)
double pop() {

```

```

// Wait until there's at least one item
sem_wait(&sitems);
sem_post(&sremain); // error! wakes up pushing() thread too early
return values[--count];
}

void push(double v) {
// Wait until there's at least one space
sem_wait(&sremain);
sem_post(&sitems); // error! wakes up a popping() thread too early
values[count++] = v;
}

```

Sketch 3 implements the correct semaphore logic, but can you spot the error?

```

// Sketch #3 (Error!)
double pop() {
// Wait until there's at least one item
sem_wait(&sitems);
double v= values[--count];
sem_post(&sremain);
return v;
}

void push(double v) {
// Wait until there's at least one space
sem_wait(&sremain);
values[count++] = v;
sem_post(&sitems);
}

```

Sketch 3 correctly enforces buffer full and buffer empty conditions using semaphores. However there is no *mutual exclusion*. Two threads can be in the *critical section* at the same time, which would corrupt the data structure or least lead to data loss. The fix is to wrap a mutex around the critical section:

```

// Simple single stack - see above example on how to convert this into a
// multiple stacks.
// Also a robust POSIX implementation would check for EINTR and error
// codes of sem_wait.

// PTHREAD_MUTEX_INITIALIZER for statics (use pthread_mutex_init() for
// stack/heap memory)
#define SPACES 10
pthread_mutex_t m= PTHREAD_MUTEX_INITIALIZER;
int count = 0;
double values[SPACES];
sem_t sitems, sremain;

void init() {
sem_init(&sitems, 0, 0);
sem_init(&sremain, 0, SPACES); // 10 spaces
}

```



```

double pop() {
    // Wait until there's at least one item
    sem_wait(&sitems);

    pthread_mutex_lock(&m); // CRITICAL SECTION
    double v= values[--count];
    pthread_mutex_unlock(&m);

    sem_post(&sremain); // Hey world, there's at least one space
    return v;
}

void push(double v) {
    // Wait until there's at least one space
    sem_wait(&sremain);

    pthread_mutex_lock(&m); // CRITICAL SECTION
    values[count++] = v;
    pthread_mutex_unlock(&m);

    sem_post(&sitems); // Hey world, there's at least one item
}
// Note a robust solution will need to check sem_wait's result for EINTR
// (more about this later)

```

Now let's start doing some crazy things. What happens when we start inverting the lock and wait orders?

```

double pop() {
    pthread_mutex_lock(&m);
    sem_wait(&sitems);

    double v= values[--count];
    pthread_mutex_unlock(&m);

    sem_post(&sremain);
    return v;
}

void push(double v) {
    sem_wait(&sremain);

    pthread_mutex_lock(&m);
    values[count++] = v;
    pthread_mutex_unlock(&m);

    sem_post(&sitems);
}

```

Rather than just giving you the answer, we'll let you think about this. Is this a permissible way to lock and unlock? Is there a series of pattern that could cause a race condition? How about deadlock? If there is, provide it. If there isn't, provide a short english proof of why that won't happen.

Software Solutions to the Critical Section

As already discussed, there are critical parts of our code that can only be executed by one thread at a time. We describe this requirement as ‘mutual exclusion’. Only one thread (or process) may have access to the shared resource. In multi-threaded programs, we can wrap a critical section with mutex lock and unlock calls:

```
pthread_mutex_lock() // one thread allowed at a time! (others will have
                    to wait here)
// ... Do Critical Section stuff here!
pthread_mutex_unlock() // let other waiting threads continue
```

How would we implement these lock and unlock calls? Can we create a pure software algorithm that assures mutual exclusion?

```
pthread_mutex_lock(p_mutex_t *m) {
    while(m->lock) ;
    m->lock = 1;
}
pthread_mutex_unlock(p_mutex_t *m) {
    m->lock = 0;
}
```

At first glance, the code appears to work. if one thread attempts to locks the mutex, a later thread must wait until the lock is cleared. However this implementation *does not satisfy Mutual Exclusion*. We’ll ignore the part about other threads being able to unlock another thread’s lock. Let’s take a close look at this ‘implementation’ from the point of view of two threads running around the same time.

To simplify the discussion we consider only two threads. Note, these arguments work for threads and processes and the classic CS literature discusses these problem in terms of two processes that need exclusive access to a critical section or shared resource. Raising a flag represents a thread/process’s intention to enter the critical section.

Remember that the psuedo-code outlined below is part of a larger program. The thread or process will typically need to enter the critical section many times during the lifetime of the process. So imagine each example as wrapped inside a loop where for a random amount of time the thread or process is working on something else.

Is there anything wrong with candidate solution described below?

```
// Candidate #1
wait until your flag is lowered
raise my flag
// Do Critical Section stuff
lower my flag
```

Answer: Candidate solution #1 also suffers a race condition because both threads/processes could read each other’s flag value as lowered and continue.

This suggests we should raise the flag *before* checking the other thread’s flag, which is candidate solution #2 below.

```
// Candidate #2
raise my flag
wait until your flag is lowered
// Do Critical Section stuff
lower my flag
```

Candidate #2 satisfies mutual exclusion - it is impossible for two threads to be inside the critical section at the same time. However this code suffers from deadlock! Suppose two threads wish to enter the critical section at the same time.

Time	Thread 1	Thread 2
1	Raise Flag	
2		Raise Flag
3	Wait	Wait

Both threads / processes are now waiting for the other one to lower their flags. Neither one will enter the critical section as both are now stuck forever! This suggests we should use a turn-based variable to try to resolve who should proceed.

Turn-based solutions

The following candidate solution #3 uses a turn-based variable to politely allow one thread and then the other to continue

```
// Candidate #3
wait until my turn is myid
// Do Critical Section stuff
turn = yourid
```

Candidate #3 satisfies mutual exclusion – each thread or process gets exclusive access to the Critical Section. However, both threads/processes must take a strict turn-based approach to using the critical section. They are forced into an alternating critical section access pattern. For example if thread 1 wishes to read a hashtable every millisecond, but another thread writes to a hashtable every second, then the reading thread would have to wait another 999ms before being able to read from the hashtable again. This ‘solution’ is not effective because our threads should be able to make progress and enter the critical section if no other thread is currently in the critical section.

Desired Properties for Solutions

There are three main desirable properties that we desire in a solution the critical section problem

1. Mutual Exclusion. The thread/process gets exclusive access. Others must wait until it exits the critical section.
2. Bounded Wait. A thread/process cannot get superceded by another thread infinite amounts of time.
3. Progress. If no thread/process is inside the critical section, the thread/process should be able to proceed without having to wait.

With these ideas in mind let’s examine another candidate solution that uses a turn-based flag only if two threads both required access at the same time.

Turn and Flag solutions

Is the following a correct solution to CSP?

```
\ Candidate #4
raise my flag
if your flag is raised, wait until my turn
// Do Critical Section stuff
turn = yourid
lower my flag
```

One instructor and another CS faculty member initially thought so **TODO: citation needed!** However, analyzing these solutions is tricky. Even peer-reviewed papers on this specific subject contain incorrect solutions! At first glance it appears to satisfy Mutual Exclusion, Bounded Wait and Progress The turn-based flag is only used in the event of a tie, so Progress and Bounded Wait is allowed and mutual exclusion appears to be satisfied. Perhaps you can find a counter-example?

Candidate #4 fails because a thread does not wait until the other thread lowers their flag. After some thought or inspiration the following scenario can be created to demonstrate how Mutual Exclusion is not satisfied.

Imagine the first thread runs this code twice. The turn flag now points to the second thread. While the first thread is still inside the Critical Section, the second thread arrives. The second thread can immediately continue into the Critical Section!

Time	Turn	Thread # 1	Thread # 2
1	2	Raise my flag	
2	2	If your flag is raise, wait until my turn	Raise my flag
3	2	// Do Critical Section Stuff	If your flag is raised, wait until my turn (TRUE!)
4	2	// Do Critical Section Stuff	Do Critical Section Stuff - OOPS

Working Solutions

The first solution to the problem was Dekker's Solution. Dekker's Algorithm (1962) was the first provably correct solution. Though, it was in an unpublished paper so it was not discovered until later [1] – this is an english transcribed version released in 1965. A version of the algorithm is below.

```
raise my flag
while (your flag is raised) :
    if it's your turn to win :
        lower my flag
        wait while your turn
        raise my flag
// Do Critical Section stuff
set your turn to win
lower my flag
```

Notice how the process's flag is always raised during the critical section no matter if the loop is iterated zero, once or more times. Further the flag can be interpreted as an immediate intent to enter the critical section. Only if the other process has also raised the flag will one process defer, lower their intent flag and wait.

Let's check the conditions.

1. Mutual Exclusion. Let's try to sketch a simple proof. The loop invariant is that at the start of checking the condition, your flag has to be raised – this is by exhaustion. Since the only way that a thread can leave the loop is by having the condition be false, the flag must be raised for the entirety of the critical section. Since the loop prevents a thread from exiting while the other thread's flag is raised and a thread has its flag raised in the critical section, the other thread can't enter the critical section at the same time.
2. Bounded Wait. Assuming that the critical section ends in finite time, a thread once it has left the critical section cannot then get the critical section back. The reason being is the turn variable is set to the other thread, meaning that that thread now has priority. That means a thread cannot be superseded infinitely by another thread.
3. Progress. If the other thread isn't in the critical section, it will simply continue with a simple check. We didn't make any statement about if threads are randomly stopped by the system scheduler. This is an idealized scenario where threads will keep executing instructions.

Peterson's Solution

Peterson published his novel and surprisingly simple solution in 1981 [2]. A version of his algorithm is shown below that uses a shared variable turn.

```
\\ Candidate #5
raise my flag
turn = other_thread_id
while (your flag is up and turn is other_thread_id)
```

```

loop
// Do Critical Section stuff
lower my flag

```

This solution satisfies Mutual Exclusion, Bounded Wait and Progress. If thread #2 has set turn to 2 and is currently inside the critical section. Thread #1 arrives, *sets the turn back to 1* and now waits until thread 2 lowers the flag.

1. Mutual Exclusion. Let's try to sketch a simple proof again. You don't get into the critical section until the turn variable is yours or the other thread's flag isn't up. If the other thread's flag isn't up, it isn't trying to enter the critical section. That is the first action the thread does and the last action the thread undoes. If the turn variable is set to this thread, that means that the other thread has given the control to this thread. Since my flag is raised and the turn variable is set, the other thread has to wait in the loop until the current thread is done.
2. Bounded Wait. After one thread lowers, a thread waiting in the while loop will leave because the first condition is broken. This means that threads cannot win all the time.
3. Progress. If no other thread is contesting, other thread's flags are not up. That means that a thread can go past the while loop and do critical section items.

Extra: Can I just implement Software Exclusion in C?

Yes - and with a bit searching it is possible even today to find it in production for specific simple mobile processors. Peterson's algorithm is used to implement low-level Linux Kernel locks for the Tegra mobile processor (a system-on-chip ARM process and GPU core by Nvidia) <https://android.googlesource.com/kernel/tegra.git/+android-tegra-3.10/arch/arm/mach-tegra/sleep.S#58>

However in general, CPUs and C compilers can re-order CPU instructions or use CPU-core-specific local cache values that are stale if another core updates the shared variables. Thus a simple pseudo-code to C implementation is too naive for most platforms. You can stop reading now.

So, you decided to keep reading. Well, here be dragons! Don't say we didn't warn you. Consider this advanced and gnarly topic but (spoiler alert) a happy ending.

Consider the following code,

```

while(flag2) { /* busy loop - go around again */

```

An efficient compiler would infer that `flag2` variable is never changed inside the loop, so that test can be optimized to `while(true)` Using `volatile` goes some way to prevent compiler optimizations of this kind.

Independent instructions can be re-ordered by an optimizing compiler or at runtime by an out-of-order execution optimization by the CPU. These sophisticated optimizations if the code requires variables to be modified and checked and a precise order.

A related challenge is that CPU cores include a data cache to store recently read or modified main memory values. Modified values may not be written back to main memory or re-read from memory immediately. Thus data changes, such as the state of a flag and turn variable in the above examples, may not be shared between two CPU codes.

But there is happy ending. Modern hardware addresses these issues using 'memory fences' also known as memory barrier. This prevents instructions from getting ordered before or after the barrier. There is a performance loss, but it is needed for correct programs!

In addition, there are CPU instructions to ensure that main memory and the CPUs' cache is in a reasonable and coherent state. Higher level synchronization primitives, such as `pthread_mutex_lock` are will call these CPU instructions as part of their implementation. Thus, in practice, surrounding critical section with a mutex lock and unlock calls is sufficient to ignore these lower-level problems.

For further reading, we suggest the following web post that discusses implementing Peterson's algorithm on an x86 process and the linux documentation on memory barriers.

1. <http://bartoszmilewski.com/2008/11/05/who-ordered-memory-fences-on-an-x86/>
2. <http://lxr.free-electrons.com/source/Documentation/memory-barriers.txt>

Implementing Counting Semaphore

Now that we have a solution to the critical section problem. We can reasonably implement a mutex. How would we implement other synchronization primitives? Let's start with a semaphore. To implement a semaphore with efficient CPU usage, we will say that we have implemented a condition variable. Implementing an $O(1)$ space condition variable using only a mutex is not trivial, or at least a $O(1)$ heap condition variable is not trivial. We don't want to call malloc while implementing a primitive, or we may deadlock! Check the end of the section for an example.

- We can implement a counting semaphore using condition variables.
- Each semaphore needs a count, a condition variable and a mutex

```
typedef struct sem_t {
    ssize_t count;
    pthread_mutex_t m;
    pthread_condition_t cv;
} sem_t;
```

Implement `sem_init` to initialize the mutex and condition variable

```
int sem_init(sem_t *s, int pshared, int value) {
    if (pshared) {
        errno = ENOSYS /* 'Not implemented' */;
        return -1;
    }

    s->count = value;
    pthread_mutex_init(&s->m, NULL);
    pthread_cond_init(&s->cv, NULL);
    return 0;
}
```

Our implementation of `sem_post` needs to increment the count. We will also wake up any threads sleeping inside the condition variable. Notice we lock and unlock the mutex so only one thread can be inside the critical section at a time.

```
sem_post(sem_t *s) {
    pthread_mutex_lock(&s->m);
    s->count++;
    pthread_cond_signal(&s->cv);
    /* A woken thread must acquire the lock, so it will also have to wait
       until we call unlock */

    pthread_mutex_unlock(&s->m);
}
```

Our implementation of `sem_wait` may need to sleep if the semaphore's count is zero. Just like `sem_post` we wrap the critical section using the lock, so only one thread can be executing our code at a time. Notice if the thread does need to wait then the mutex will be unlocked, allowing another thread to enter `sem_post` and waken us from our sleep!

Notice that even if a thread is woken up, before it returns from `pthread_cond_wait`, it must re-acquire the lock, so it will have to wait until `sem_post` finishes.

```
sem_wait(sem_t *s) {
    pthread_mutex_lock(&s->m);
    while (s->count == 0) {
        pthread_cond_wait(&s->cv, &s->m); /*unlock mutex, wait, relock
        mutex*/
    }
    s->count--;
    pthread_mutex_unlock(&s->m);
}
```

Notice that we are calling `sem_post` every single time. In practice, this means `sem_post` would unnecessary call `pthread_cond_signal` even if there are no waiting threads. A more efficient implementation would only call `pthread_cond_signal` when necessary i.e.

```
/* Did we increment from zero to one- time to signal a thread sleeping
   inside sem_post */
if (s->count == 1) /* Wake up one waiting thread!*/
    pthread_cond_signal(&s->cv);
```

Other semaphore considerations

- Real semaphores implementation may include a queue and scheduling concerns to ensure fairness and priority. Meaning, we wake up the highest-priority longest sleeping thread.
- Also, an advanced use of `sem_init` allows semaphores to be shared across processes. Our implementation only works for threads inside the same process. We could fix this by setting the condition variable and mutex attributes.

Extra: Implementing CVs with Mutexes Alone

Implementing a condition variable using only a mutex isn't trivial. Here is a sketch of how we could do it.

```
typedef struct cv_node_ {
    pthread_mutex_t *dynamic;
    int is_awoken;
    struct cv_node_ *next;
} cv_node;

typedef struct {
    cv_node_ *head
} cond_t

void cond_init(cond_t *cv) {
    cv->head = NULL;
    cv->dynamic = NULL;
}

void cond_destroy(cond_t *cv) {
    // Nothing to see here
    // Though may be useful for the future to put pieces
}

static int remove_from_list(cond_t *cv, cv_node *ptr) {
```

```

// Function assumes mutex is locked
// Some sanity checking
if (ptr == NULL) {
    return
}

// Special case head
if (ptr == cv->head) {
    cv->head = cv->head->next;
    return;
}

// Otherwise find the node previous
for (cv_node *prev = cv->head; prev->next; prev = prev->next) {
    // If we've found it, patch it through
    if (prev->next == ptr) {
        prev->next = prev->next->next;
        return;
    }
    // Otherwise keep walking
    prev = prev->next;
}

// We couldn't find the node, invalid call
}

```

This is all the boring definitional stuff. The interesting stuff is below.

```

void cond_wait(cond_t *cv, pthread_mutex_t *m) {
    // See note (dynamic) below
    if (cv->dynamic == NULL) {
        cv->dynamic = m
    } else if (cv->dynamic != m) {
        // Error can't wait with a different mutex!

        abort();
    }
    // mutex is locked so we have the critical section right now
    // Create linked list node _on the stack_
    cv_node my_node;
    my_node.is_awoken = 0;
    my_node.next = cv->head;
    cv->head = my_node.next;
    pthread_mutex_unlock(m);

    // May do some cache busting here
    while(my_node == 0) {
        pthread_yield();
    }

    pthread_mutex_lock(m);
    remove_from_list(cv, &my_node);
}

```



```

// The dynamic binding is over
if (cv->head == NULL) {
    cv->dynamic = NULL;
}
}

void cond_signal(cond_t *cv) {
    for (cv_node *iter = cv->head; iter; iter = iter->next) {
        // Signal makes sure one thread that has not woken up
        // is woken up
        if (iter->is_awoken == 0) {
            // DON'T remove from the linked list here
            // There is no mutual exclusion, so we could
            // have a race condition
            iter->is_awoken = 1;
            return;
        }
    }

    // No more threads to free! No-op
}

void cond_broadcast(cond_t *cv) {
    for (cv_node *iter = cv->head; iter; iter = iter->next) {
        // Wake everyone up!
        iter->is_awoken = 1;
    }
}

```

So how does this work? Instead of malloc'ing space which could lead to deadlock. We keep the datastructures or the linked list nodes on each thread's stack. The linked list in the wait function is created **While the thread has the mutex lock** this is important because otherwise we may have a race condition on the insert and removal. A more robust implementation would have a mutex per condition variable.

What is the note about (dynamic)? In the pthread man pages, wait creates a runtime binding to a mutex. This means that after the first call is called, a mutex is associated with a condition variable while there is still a thread waiting on that condition variable. Each new thread coming in must have the same mutex, and it must be locked. Hence, the beginning and end of wait (everything besides the while loop) is mutually exclusive. After the last thread leaves, meaning when head is NULL, then the binding is lost.

The signal and broadcast functions merely tell either one thread or all threads respectively that they should be woken up. **It doesn't modify the linked lists because there is no mutex to prevent a corruption if two threads call signal or broadcast**

Now an advanced point. Do you see how a broadcast could cause a spurious wakeup in this case? Consider this series of events.

1. Some number more than 2 threads start waiting
2. Another thread calls broadcast.
3. That thread calling broadcast is SIGSTOP'ed before it flip any threads to awake.
4. Another thread calls wait on the condition variable and adds itself to the queue.
5. Broadcast iterates through and frees all of the threads.

There is no assurance as to *when* broadcast was called and when threads were added in a high performance mutex. The ways to prevent this behavior are to include lamport time stamps or require that broadcast be called with the mutex in question. That way something that *happens-before* the broadcast call doesn't get signaled after. The same argument is put forward for signal too.

Did you also notice something else? **This is why we ask you to signal or broadcast before you unlock.** If you broadcast after you unlock, the time that broadcast takes could be infinite!

1. Broadcast is called on a waiting queue of threads
2. First thread is freed, broadcast thread is frozen. Since the mutex is unlocked, it locks and continues.
3. It continues for such a long time that it calls broadcast again.
4. With our implementation of a condition variable, this would be terminated. If you had an implementation that appended to the tail of the list and iterated from the head to the tail, this could go on infinitely many times.

In high performance systems, we want to make sure that each thread that calls wait isn't passed by another thread that calls wait. With the current API that we have, we can't assure that. We'd have to ask users to pass in a mutex or use a global mutex. Instead, we tell programmers to always signal or broadcast before unlocking.

Barriers

Suppose we wanted to perform a multi-threaded calculation that has two stages, but we don't want to advance to the second stage until the first stage is completed. We could use a synchronization method called a **barrier**. When a thread reaches a barrier, it will wait at the barrier until all the threads reach the barrier, and then they'll all proceed together.

Think of it like being out for a hike with some friends. You make a mental note of how many friends you have and agree to wait for each other at the top of each hill. Say you're the first one to reach the top of the first hill. You'll wait there at the top for your friends. One by one, they'll arrive at the top, but nobody will continue until the last person in your group arrives. Once they do, you'll all proceed.

Pthreads has a function `pthread_barrier_wait()` that implements this. You'll need to declare a `pthread_barrier_t` variable and initialize it with `pthread_barrier_init()`. `pthread_barrier_init()` takes the number of threads that will be participating in the barrier as an argument. Here is a sample program using barriers.

```
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include <pthread.h>
#include <time.h>

#define THREAD_COUNT 4

pthread_barrier_t mybarrier;

void* threadFn(void *id_ptr) {
    int thread_id = *(int*)id_ptr;
    int wait_sec = 1 + rand() % 5;
    printf("thread %d: Wait for %d seconds.\n", thread_id, wait_sec);
    sleep(wait_sec);
    printf("thread %d: I'm ready...\n", thread_id);

    pthread_barrier_wait(&mybarrier);

    printf("thread %d: going!\n", thread_id);
    return NULL;
}

int main() {
    int i;
    pthread_t ids[THREAD_COUNT];
    int short_ids[THREAD_COUNT];
```

```

srand(time(NULL));
pthread_barrier_init(&mybarrier, NULL, THREAD_COUNT + 1);

for (i=0; i < THREAD_COUNT; i++) {
    short_ids[i] = i;
    pthread_create(&ids[i], NULL, threadFn, &short_ids[i]);
}

printf("main() is ready.\n");

pthread_barrier_wait(&mybarrier);

printf("main() is going!\n");

for (i=0; i < THREAD_COUNT; i++) {
    pthread_join(ids[i], NULL);
}

pthread_barrier_destroy(&mybarrier);

return 0;
}

```

Now let's implement our own barrier and use it to keep all the threads in sync in a large calculation.

```
double data[256][8192]
```

1 Threads do first calculation (use and change values in data)

2 Barrier! Wait for all threads to finish first calculation before continuing

3 Threads do second calculation (use and change values in data)

The thread function has four main parts-

```

void *calc(void *arg) {
    /* Do my part of the first calculation */
    /* Am I the last thread to finish? If so wake up all the other threads!
       */
    /* Otherwise wait until the other threads has finished part one */
    /* Do my part of the second calculation */
}

```

Our main thread will create the 16 threads, and we will divide each calculation into 16 separate pieces. Each thread will be given a unique value (0,1,2,..15), so it can work on its own block. Since a (void*) type can hold small integers, we will pass the value of i by casting it to a void pointer.

```

#define N (16)
double data[256][8192] ;
int main() {
    pthread_t ids[N];
    for(int i = 0; i < N; i++)
        pthread_create(&ids[i], NULL, calc, (void *) i);
}

```

Note, we will never dereference this pointer value as an actual memory location. We will just cast it straight back to an integer.

```
void *calc(void *ptr) {
// Thread 0 will work on rows 0..15, thread 1 on rows 16..31
    int x, y, start = N * (int) ptr;
    int end = start + N;
    for(x = start; x < end; x++) for (y = 0; y < 8192; y++) { /* do calc #1
        */ }
}
```

After calculation 1 completes, we need to wait for the slower threads unless we are the last thread!. So, keep track of the number of threads that have arrived at our barrier aka ‘checkpoint’:

```
// Global:
int remain = N;

// After calc #1 code:
remain--; // We finished
if (remain == 0) { /*I'm last! - Time for everyone to wake up! */ }
else {
    while (remain != 0) { /* spin spin spin*/ }
}
```

However the code has a few flaws. One is two threads might try to decrement `remain`. The other is the loop is a busy loop. We can do better! Let's use a condition variable and then we will use a broadcast/signal functions to wake up the sleeping threads.

A reminder, that a condition variable is similar to a house! Threads go there to sleep (`pthread_cond_wait`). You can choose to wake up one thread (`pthread_cond_signal`) or all of them (`pthread_cond_broadcast`). If there are no threads currently waiting then these two calls have no effect.

A condition variable version is usually very similar to a busy loop incorrect solution - as we will show next. First, let's add a mutex and condition global variables and don't forget to initialize them in `main`.

```
//global variables
pthread_mutex_t m;
pthread_cond_t cv;

main() {
    pthread_mutex_init(&m, NULL);
    pthread_cond_init(&cv, NULL);
}
```

We will use the mutex to ensure that only one thread modifies `remain` at a time. The last arriving thread needs to wake up *all* sleeping threads - so we will use `pthread_cond_broadcast(cv)` not `pthread_cond_signal`

```
pthread_mutex_lock(&m);
remain--;
```

```

if (remain == 0) {
    pthread_cond_broadcast(&cv);
}
else {
    while(remain != 0) {
        pthread_cond_wait(&cv, &m);
    }
}
pthread_mutex_unlock(&m);

```

When a thread enters `pthread_cond_wait`, it releases the mutex and sleeps. At some point in the future, it will be awoken. Once we bring a thread back from its sleep, before returning it must wait until it can lock the mutex. Notice that even if a sleeping thread wakes up early, it will check the while loop condition and re-enter wait if necessary.

The above barrier is not reusable. Meaning that if we stick it into any old calculation loop there is a good chance that the code will encounter a condition where the barrier either deadlocks or a thread races ahead one iteration faster. Why is that? I'm glad you asked.

The concept here is what we call the ambitious thread. We will assume that one thread is much faster than all the other threads. With the barrier API, this thread should be waiting, but it may not be. To make it concrete let's look at this code

```

barrier_wait(barrier *b) {
    pthread_mutex_lock(&b->m);
    // If it is 0 before decrement, we should be on
    // another iteration right?
    if (b->remain == 0) b->remain = NUM_THREADS;
    b->remain--;
    if (b->remain == 0) {
        pthread_cond_broadcast(&cv);
    }
    else {
        while(b->remain != 0) {
            pthread_cond_wait(&cv, &m);
        }
    }
    pthread_mutex_unlock(&b->m);
}

for () {
    // Some calc
    barrier_wait(b);
}

```

What happens if you have what we call **The ambitious thread**? Well

1. Many other threads wait on the condition variable
2. The last thread broadcasts.
3. A single thread leaves the while loop.
4. This single thread performs its calculation before any other threads *even wake up*
5. Reset the number of remaining threads and goes back to sleep.

Now the problem becomes all the other threads who should've woken up never do and our implementation deadlocks. How would you go about solving this? Hint: If multiple threads call `barrier_wait` in a loop then one can guarantee that they are on the same iteration.

Reader Writer Problem

Imagine you had a key-value map data structure which is used by many threads. Multiple threads should be able to look up (read) values at the same time provided the data structure is not being written to. The writers are not so gregarious. To avoid data corruption, only one thread at a time may modify (write) the data structure and no readers may be reading at that time.

This is an example of the *Reader Writer Problem*. Namely how can we efficiently synchronize multiple readers and writers such that multiple readers can read together, but a writer gets exclusive access?

An incorrect attempt is shown below (“lock” is a shorthand for `pthread_mutex_lock`):

Attempt #1

```
void read() {
    lock(&m)
    // do read stuff
    unlock(&m)
}

void write() {
    lock(&m)
    // do write stuff
    unlock(&m)
}
```

At least our first attempt does not suffer from data corruption. Readers must wait while a writer is writing and vice versa! However, readers must also wait for other readers. Let’s try another implementation.

Attempt #2:

```
void read() {
    while(writing) { /*spin*/ }
    reading = 1
    // do read stuff
    reading = 0
}

void write() {
    while(reading || writing) { /*spin*/ }
    writing = 1
    // do write stuff
    writing = 0
}
```

Our second attempt suffers from a race condition. Imagine if two threads both called `read` and `write` or both called `write` at the same time. Both threads would be able to proceed! Secondly, we can have multiple readers and multiple writers, so let’s keep track of the total number of readers or writers Which brings us to attempt #3.

Attempt #3

Remember that `pthread_cond_wait` performs *Three* actions. Firstly it atomically unlocks the mutex and then sleeps (until it is woken by `pthread_cond_signal` or `pthread_cond_broadcast`). Thirdly the awoken thread must re-acquire the mutex lock before returning. Thus only one thread can actually be running inside the critical section defined by the lock and `unlock()` methods.

Implementation #3 below ensures that a reader will enter the `cond_wait` if there are any writers writing.

```

read() {
    lock(&m)
    while (writing)
        cond_wait(&cv, &m)
    reading++;

    /* Read here! */

    reading--
    cond_signal(&cv)
    unlock(&m)
}

```

However only one reader a time can read because candidate #3 did not unlock the mutex. A better version unlocks before reading.

```

read() {
    lock(&m);
    while (writing)
        cond_wait(&cv, &m)
    reading++;
    unlock(&m)
    /* Read here! */
    lock(&m)
    reading--
    cond_signal(&cv)
    unlock(&m)
}

```

Does this mean that a writer and read could read and write at the same time? No! First of all, remember `cond_wait` requires the thread re-acquire the mutex lock before returning. Thus only one thread can be executing code inside the critical section (marked with `**`) at a time!

```

read() {
    lock(&m);
    ** while (writing)
    **     cond_wait(&cv, &m)
    ** reading++;
    **     unlock(&m)
    /* Read here! */
    lock(&m)
    ** reading--
    **     cond_signal(&cv)
    **     unlock(&m)
}

```

Writers must wait for everyone. Mutual exclusion is assured by the lock.

```

write() {
    lock(&m);
    ** while (reading || writing)
    **     cond_wait(&cv, &m);
    ** writing++;
    **
    ** /* Write here! */
    ** writing--;
    ** cond_signal(&cv);
    unlock(&m);
}

```

Candidate #3 above also uses `pthread_cond_signal`. This will only wake up one thread. For example if many readers are waiting for the writer to complete, only one sleeping reader will be awoken from their slumber. The reader and writer should use `cond_broadcast` so that all threads should wake up and check their while-loop condition.

Starving writers

Candidate #3 above suffers from starvation. If readers are constantly arriving then a writer will never be able to proceed (the ‘reading’ count never reduces to zero). This is known as *starvation* and would be discovered under heavy loads. Our fix is to implement a bounded-wait for the writer. If a writer arrives they will still need to wait for existing readers however future readers must be placed in a “holding pen” and wait for the writer to finish. The “holding pen” can be implemented using a variable and a condition variable so that we can wake up the threads once the writer has finished.

Our plan is that when a writer arrives, and before waiting for current readers to finish, register our intent to write by incrementing a counter ‘writer’

```

write() {
    lock()
    writer++

    while (reading || writing)
        cond_wait
    unlock()
    ...
}

```

And incoming readers will not be allowed to continue while writer is nonzero. Notice ‘writer’ indicates a writer has arrived, while ‘reading’ and ‘writing’ counters indicate there is an *active* reader or writer.

```

read() {
    lock()
    // readers that arrive *after* the writer arrived will have to wait
    // here!
    while(writer)
        cond_wait(&cv,&m)

    // readers that arrive while there is an active writer
    // will also wait.
    while (writing)
        cond_wait(&cv,&m)
    reading++
    unlock
    ...
}

```



```
}
```

Attempt #4

Below is our first working solution to the Reader-Writer problem. Note if you continue to read about the “Reader Writer problem” then you will discover that we solved the “Second Reader Writer problem” by giving writers preferential access to the lock. This solution is not optimal. However, it satisfies our original problem of N active readers, single active writer, and avoiding starvation of the writer if there is a constant stream of readers.

Can you identify any improvements? For example, how would you improve the code so that we only woke up readers or one writer?

```
int writers; // Number writer threads that want to enter the critical
              section (some or all of these may be blocked)
int writing;  // Number of threads that are actually writing inside the
              C.S. (can only be zero or one)
int reading; // Number of threads that are actually reading inside the
              C.S.
// if writing !=0 then reading must be zero (and vice versa)

reader() {
    lock(&m)
    while (writers)
        cond_wait(&turn, &m)
    // No need to wait while(writing here) because we can only exit the
    // above loop
    // when writing is zero
    reading++
    unlock(&m)

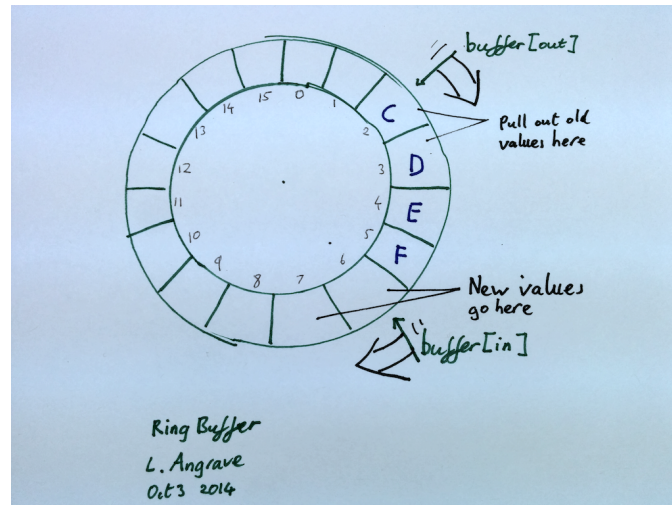
    // perform reading here

    lock(&m)
    reading--
    cond_broadcast(&turn)
    unlock(&m)
}

writer() {
    lock(&m)
    writers++
    while (reading || writing)
        cond_wait(&turn, &m)
    writing++
    unlock(&m)
    // perform writing here
    lock(&m)
    writing--
    writers--
    cond_broadcast(&turn)
    unlock(&m)
}
```

Ring Buffer

A ring buffer is a simple, usually fixed-sized, storage mechanism where contiguous memory is treated as if it is circular, and two index counters keep track of the current beginning and end of the queue. As array indexing is not circular, the index counters must wrap around to zero when moved past the end of the array. As data is added (enqueued) to the front of the queue or removed (dequeued) from tail of the queue, the current items in the buffer form a train that appears to circle the track



A simple (single-threaded) implementation is shown below. Note, enqueue and dequeue do not guard against underflow or overflow. It's possible to add an item when the queue is full and possible to remove an item when the queue is empty. For example if we added 20 integers (1,2,3...) to the queue and did not dequeue any items then values 17, 18, 19, 20 would overwrite the 1, 2, 3, 4. We won't fix this problem right now, instead when we create the multi-threaded version we will ensure enqueue-ing and dequeue-ing threads are blocked while the ring buffer is full or empty respectively.

```
void *buffer[16];
int in = 0, out = 0;

void enqueue(void *value) { /* Add one item to the front of the queue */
    buffer[in] = value;
    in++; /* Advance the index for next time */
    if (in == 16) in = 0; /* Wrap around! */
}

void *dequeue() { /* Remove one item to the end of the queue. */
    void *result = buffer[out];
    out++;
    if (out == 16) out = 0;
    return result;
}
```

Ring Buffer Gotchas

It's very tempting to write the enqueue or dequeue method in the following compact form.

```
// N is the capacity of the buffer
void enqueue(void *value)
    b[ (in++) % N ] = value;
}
```

This method would appear to work (pass simple tests etc) but contains a subtle bug. With enough enqueue operations (a bit more than two billion) the int value of `in` will overflow and become negative! The modulo (or ‘remainder’) operator `%` preserves the sign. Thus you might end up writing into `b[-14]` for example!

A compact form is correct uses bit masking provided N is 2^x (16,32,64,...)

```
b[ (in++) & (N-1) ] = value;
```

This buffer does not yet prevent buffer underflow or overflow. For that, we’ll turn to our multi-threaded attempt that will block a thread until there is space or there is at least one item to remove.

Multithreaded Correctness

The following code is an incorrect implementation. What will happen? Will enqueue and/or dequeue block? Is mutual exclusion satisfied? Can the buffer underflow? Can the buffer overflow? For clarity `pthread_mutex` is shortened to `p_m` and we assume `sem_wait` cannot be interrupted.

```
#define N 16
void *b[N]
int in = 0, out = 0
p_m_t lock
sem_t s1,s2
void init() {
    p_m_init(&lock, NULL)
    sem_init(&s1, 0, 16)
    sem_init(&s2, 0, 0)
}

enqueue(void *value) {
    p_m_lock(&lock)

    // Hint: Wait while zero. Decrement and return
    sem_wait( &s1 )

    b[ (in++) & (N-1) ] = value

    // Hint: Increment. Will wake up a waiting thread
    sem_post(&s1)
    p_m_unlock(&lock)
}

void *dequeue(){
    p_m_lock(&lock)
    sem_wait(&s2)
    void *result = b[(out++) & (N-1) ]
    sem_post(&s2)
    p_m_unlock(&lock)
    return result
}
```

Analysis

Before reading on, see how many mistakes you can find. Then determine what would happen if threads called the enqueue and dequeue methods.

- The enqueue method waits and posts on the same semaphore (s1) and similarly with enqueue and (s2) i.e. we decrement the value and then immediately increment the value, so by the end of the function the semaphore value is unchanged!
- The initial value of s1 is 16, so the semaphore will never be reduced to zero - enqueue will not block if the ring buffer is full - so overflow is possible.
- The initial value of s2 is zero, so calls to dequeue will always block and never return!
- The order of mutex lock and sem_wait will need to be swapped, however this example is so broken that this bug has no effect!

Another Analysis

The following code is an incorrect implementation. What will happen? Will enqueue and/or dequeue block? Is mutual exclusion satisfied? Can the buffer underflow? Can the buffer overflow? For clarity pthread_mutex is shortened to p_m and we assume sem_wait cannot be interrupted.

```
void *b[16]
int in = 0, out = 0
p_m_t lock
sem_t s1, s2
void init() {
    sem_init(&s1,0,16)
    sem_init(&s2,0,0)
}

enqueue(void *value){
    sem_wait(&s2)
    p_m_lock(&lock)

    b[ (in++) & (N-1) ] = value

    p_m_unlock(&lock)
    sem_post(&s1)
}

void *dequeue(){
    sem_wait(&s1)
    p_m_lock(&lock)
    void *result = b[(out++) & (N-1)]
    p_m_unlock(&lock)
    sem_post(&s2)

    return result;
}
```

Here are a few problems that we hope you've found.

- The initial value of s2 is 0. Thus enqueue will block on the first call to sem_wait even though the buffer is empty!
- The initial value of s1 is 16. Thus dequeue will not block on the first call to sem_wait even though the buffer is empty - Underflow! The dequeue method will return invalid data.

- The code does not satisfy Mutual Exclusion. Two threads can modify `in` or `out` at the same time! The code appears to use mutex lock. Unfortunately the lock was never initialized with `pthread_mutex_init()` or `PTHREAD_MUTEX_INITIALIZER` - so the lock may not work (`pthread_mutex_lock` may simply do nothing)

Correct implementation of a ring buffer

As the mutex lock is stored in global (static) memory it can be initialized with `PTHREAD_MUTEX_INITIALIZER`. If we had allocated space for the mutex on the heap, then we would have used `pthread_mutex_init(ptr, NULL)`

```
#include <pthread.h>
#include <semaphore.h>
// N must be 2^i
#define N (16)

void *b[N]
int in = 0, out = 0
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER
sem_t countsem, spacesem

void init() {
    sem_init(&countsem, 0, 0)
    sem_init(&spacesem, 0, 16)
}
```

The enqueue method is shown below. Make sure to note.

1. The lock is only held during the critical section (access to the data structure).
2. A complete implementation would need to guard against early returns from `sem_wait` due to POSIX signals.

```
enqueue(void *value){
    // wait if there is no space left:
    sem_wait( &spacesem )

    pthread_mutex_lock(&lock)
    b[ (in++) & (N-1) ] = value
    pthread_mutex_unlock(&lock)

    // increment the count of the number of items
    sem_post(&countsem)
}
```

The dequeue implementation is shown below. Notice the symmetry of the synchronization calls to `enqueue`. In both cases, the functions first wait if the count of spaces or count of items is zero.

```
void *dequeue(){
    // Wait if there are no items in the buffer
    sem_wait(&countsem)

    pthread_mutex_lock(&lock)
    void *result = b[(out++) & (N-1)]
```

```

p_m_unlock(&lock)

// Increment the count of the number of spaces
sem_post(&spacesem)

return result
}

```

Food for thought:

- What would happen if the order of `pthread_mutex_unlock` and `sem_post` calls were swapped?
- What would happen if the order of `sem_wait` and `pthread_mutex_lock` calls were swapped?

Extra: Process Synchronization

You thought that you were using different processes, so you don't have to synchronize? Think again! You may not have race conditions within a process but what if your process needs to interact with the system around it? Let's consider a motivating example

```

void write_string(const char *data) {
    int fd = open("my_file.txt", O_WRONLY);
    write(fd, data, strlen(data));
    close(fd);
}

int main() {
    if(!fork()) {
        write_string("key1: value1");
        wait(NULL);
    } else {
        write_string("key2: value2");
    }
    return 0;
}

```

If none of the system calls fail then we should get something that looks like this given the file was empty to begin with.

```

key1: value1
key2: value2

```

```

key2: value2
key1: value1

```

Interruption

But, there is a hidden nuance. Most system calls can be interrupted meaning that the operating system can stop an ongoing system call because it needs to stop the process. So barring `fork` `wait` `open` and `close` from failing – they

typically go to completion – what happens if `write` fails? If `write` fails and no bytes are written, we can get something like `key1: value1` or `key2: value2`. This is data loss which is incorrect but won't corrupt the file. What happens if `write` gets interrupted after a partial write? We get all sorts of madness. For example,

```
key2: key1: value1
```

Solution

You can create mutex before fork-ing - however the child and parent process will not share virtual memory and each one will have a mutex independent of the other. Advanced note: There are advanced options using shared memory that allow a child and parent to share a mutex if it's created with the correct options and uses a shared memory segment. See [stackoverflow example](#)

So what should we do? We should use a shared mutex! Consider the following code.

```
pthread_mutex_t * mutex = NULL;
pthread_mutexattr_t attr;

void write_string(const char *data) {
    pthread_mutex_lock(mutex);
    int fd = open("my_file.txt", O_WRONLY);
    int bytes_to_write = strlen(data), written = 0;
    while(written < bytes_to_write) {
        written += write(fd, data + written, bytes_to_write - written);
    }
    close(fd);
    pthread_mutex_unlock(mutex);
}

int main() {
    pthread_mutexattr_init(&attr);
    pthread_mutexattr_setpshared(&attr, PTHREAD_PROCESS_SHARED);
    pmutex = mmap (NULL, sizeof(pthread_mutex_t),
                  PROT_READ|PROT_WRITE, MAP_SHARED|MAP_ANON, -1, 0);
    pthread_mutex_init(pmutex, &attrmutex);
    if(!fork()) {
        write_string("key1: value1");
        wait(NULL);
        pthread_mutex_destroy(pmutex);
        pthread_mutexattr_destroy(&attrmutex);
        munmap((void *)pmutex, sizeof(*pmutex));
    } else {
        write_string("key2: value2");
    }
    return 0;
}
```

What the code does in `main` is initialize a process shared mutex using a piece of shared memory. You will find out what this call to `mmap` does later – just assume for the time being that it create memory that is shared between processes. We can initialize a `pthread_mutex_t` in that special piece of memory and use it as normal. To counter `write` failing, we have put the `write` call inside a while loop that keeps writing so long as there are bytes left to write. Now if all the other system calls function, there should be more more race conditions.

Most programs try to avoid this problem entirely by writing to separate files, but it is good to know that there are

mutexes across processes, and they are useful. You can use all of the primitives that you were taught previously! Barriers, semaphores, and condition variables can all be initialized on a shared piece of memory and used in similar ways to their multithreading counterparts. You don't need to know the implementation, just need to know that mutexes and other synchronization primitives can be shared across processes and some of the benefits.

- You don't have to worry about arbitrary memory addresses becoming race condition candidates. This means that only areas that you specifically `mmap` or outside system resources like files are ever in danger.
- You get the nice isolation of a processes so if one process fails the system can maintain intact
- When you have a lot of threads, creating a process might ease the system load

Extra: Higher Order Models of Synchronization

When using atomics, you need to specify the right model of synchronization in order to make sure you have the correct behavior for your program. You can read more about them On the gcc wiki These examples are adapted from those.

Sequentially Consistent

Sequentially consistent is the simplest, least error prone and most expensive model. This model says that any change that happens, all changes before it will be synchronized between all threads.

Thread 1	Thread 2
1.0 <code>atomic_store(x, 1)</code>	
1.1 <code>y = 10</code>	2.1 <code>if (atomic_load(x) == 0)</code>
1.2 <code>atomic_store(x, 0);</code>	2.2 <code>y != 10 && abort();</code>

Will never quit. This is because either the store happens before the if statement in thread 2 and `y == 1` or the store happens after and `x` does not equal 2.

Relaxed

Relaxed is a simple memory order providing for more optimizations. This means that only a particular operation needs to be atomic. One can have stale reads and writes, but after reading the new value, it won't become old.

-Thread 1-	-Thread 2-
<code>atomic_store(x, 1);</code>	<code>printf("%d\n", x) // 1</code>
<code>atomic_store(x, 0);</code>	<code>printf("%d\n", x) // could be 1 or 0</code>
	<code>printf("%d\n", x) // could be 1 or 0</code>

But that means that previous loads and stores don't need to effect other threads. In the previous example, the code can now fail.

Acquire/Release

The simplest way I can explain it is the order of atomic variables don't need to be consistent – meaning if I assign atomic var `y` to be 10 then atomic var `x` to be 0 those don't need to propagate and you could get stale reads. Non-atomic variables have to get updated in all threads though.

Consume

Imagine the same as above except non-atomic variables don't need to get updated in all threads. This model was introduced so that there can be an Acquire/Release/Consume model without mixing in Relaxed because Consume is similar to relax.

External Resources

- `pthread_mutex_lock` man page
- `pthread_mutex_unlock` man page
- `pthread_mutex_init` man page
- `pthread_mutex_destroy` man page
- `sem_init`

- sem_wait
- sem_post
- sem_destroy

Topics

- Atomic operations
- Critical Section
- Producer Consumer Problem
- Using Condition Variables
- Using Counting Semaphore
- Implementing a barrier
- Implementing a ring buffer
- Using pthread_mutex
- Implementing producer consumer
- Analyzing multi-threaded coded

Questions

- What is atomic operation?
- Why will the following not work in parallel code

```
//In the global section
size_t a;
//In pthread function
for(int i = 0; i < 100000000; i++) a++;
```

And this will?

```
//In the global section
atomic_size_t a;
//In pthread function
for(int i = 0; i < 100000000; i++) atomic_fetch_add(a, 1);
```

- What are some downsides to atomic operations? What would be faster: keeping a local variable or many atomic operations?
- What is the critical section?
- Once you have identified a critical section, what is one way of assuring that only one thread will be in the section at a time?
- Identify the critical section here

```

struct linked_list;
struct node;
void add_linked_list(linked_list *ll, void* elem){
    node* packaged = new_node(elem);
    if(ll->head){
        ll->head =
    }else{
        packaged->next = ll->head;
        ll->head = packaged;
        ll->size++;
    }
}

void* pop_elem(linked_list *ll, size_t index){
    if(index >= ll->size) return NULL;

    node *i, *prev;
    for(i = ll->head; i && index; i = i->next, index--){
        prev = i;
    }

    //i points to the element we need to pop, prev before
    if(prev->next) prev->next = prev->next->next;
    ll->size--;
    void* elem = i->elem;
    destroy_node(i);
    return elem;
}

```

- How tight can you make the critical section?
- What is a producer consumer problem? How might the above be a producer consumer problem be used in the above section? How is a producer consumer problem related to a reader writer problem?
- What is a condition variable? Why is there an advantage to using one over a while loop?
- Why is this code dangerous?

```

if(not_ready){
    pthread_cond_wait(&cv, &mtx);
}

```

- What is a counting semaphore? Give me an analogy to a cookie jar/pizza box/limited food item.
- What is a thread barrier?
- Use a counting semaphore to implement a barrier.
- Write up a Producer/Consumer queue, How about a producer consumer stack?
- Give me an implementation of a reader-writer lock with condition variables, make a struct with whatever you need, it just needs to be able to support the following functions

```
void reader_lock(rw_lock_t* lck);  
void writer_lock(rw_lock_t* lck);  
void reader_unlock(rw_lock_t* lck);  
void writer_unlock(rw_lock_t* lck);
```

The only specification is that in between `reader_lock` and `reader_unlock`, no writers can write. In between the writer locks, only one writer may be writing at a time.

- Write code to implement a producer consumer using ONLY three counting semaphores. Assume there can be more than one thread calling enqueue and dequeue. Determine the initial value of each semaphore.
- Write code to implement a producer consumer using condition variables and a mutex. Assume there can be more than one thread calling enqueue and dequeue.
- Use CVs to implement `add(unsigned int)` and `subtract(unsigned int)` blocking functions that never allow the global value to be greater than 100.
- Use CVs to implement a barrier for 15 threads.
- How many of the following statements are true?
- There can be multiple active readers
- There can be multiple active writers
- When there is an active writer the number of active readers must be zero
- If there is an active reader the number of active writers must be zero
- A writer must wait until the current active readers have finished

Bibliography

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