Lecture # 6.1
Synchronization Among Threads

Course: **Advance Operating System**

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Source Code files available at: **https://bitbucket.org/arifpucit/spvl-repo/src**
Lecture Slides available at: **http://arifbutt.me**

Today's Agenda

- Recap of POSIX Threads
- Overview of Synchronization
- Race Condition and Critical Section Problem
- Data Sharing among Threads
- Thread Safety and Re-entrant Functions
- Solution to CSP using `pthread_mutex_t`
- Mutex Attribute Object `pthread_mutexattr_t`
- Producer Consumer Problem
- Condition Variables

POSIX Threads
A Quick Recap

Overview of Synchronization

Overview of Synchronization

- In computer science synchronization refers to the relationships among events, e.g., before, during or after
- There are two constraints of synchronization:
  - **Serialization**: Event A must happen before event B
  - **Mutual Exclusion**: Event A and B must not happen at the same time
- In multi-threaded programs, the programmer has no control over when a thread runs, as the scheduler makes this decision
- Concurrent programs are often non-deterministic, which means it is not possible to tell, by looking at the program what will happen when it will execute
- Concurrent access to shared data may result in data inconsistency, so we need to apply some concurrency control mechanism using which multiple threads can access shared data without any conflict

Example: Deposit and Withdrawal

Consider a bank account having a balance of Rs.100/. A deposit process deposits Rs. 25/- thus updating the balance of that account to Rs.125/. A withdrawal process runs and withdraws Rs.10/-, thus updating the balance of that account to Rs.115/. The instruction that updates the balance variable can be written in assembly as shown below:

Deposit Process

```
D1: MOV R1, balance
D2: ADD R1, deposit_amt
D3: MOV balance, R1
```

Withdrawal Process

```
W1: MOV R2, balance
W2: SUB R2, wdr_amt
W3: MOV balance, R2
```

Suppose both the processes run concurrently

- Scenario 1: D1, D2, D3, W1, W2, W3 (balance = Rs.115/-)
- Scenario 2: D1, D2, W1, W2, D3, W3 (balance = Rs.90/-)
- Scenario 2: D1, D2, W1, W2, W3, D3 (balance = Rs.125/-)

Race Condition and Critical Section Proof of Concept

`race1.c, race2.c`

Data Sharing Among Threads

Normally modifying an object requires several steps. While these steps are being carried out the object is typically not in a well formed state. If another thread tries to access the object during that time, it will likely get a corrupt information. The entire program might have undefined behavior after wards

What data is shared?

- Global data and static local data. The case of static local data is only significant if two (or more) threads execute the function containing static local variable at the same time
- Dynamically allocated data (in heap) that has had its address put into a global/static variable
- Data members of a class object that has two (or more) of its member functions called by different threads at the same time

Data Sharing among Threads (cont...)

What Data is not Shared ?

- Local variables are not shared. Even if two threads call the same function they will have different copies of the local variable in that function. This is because the local variables are kept on stack and every thread has its own stack
- Function parameters are not shared. In Languages like **C**, the parameters of function are also put on the stack & thus every thread will have its own copy of those as well

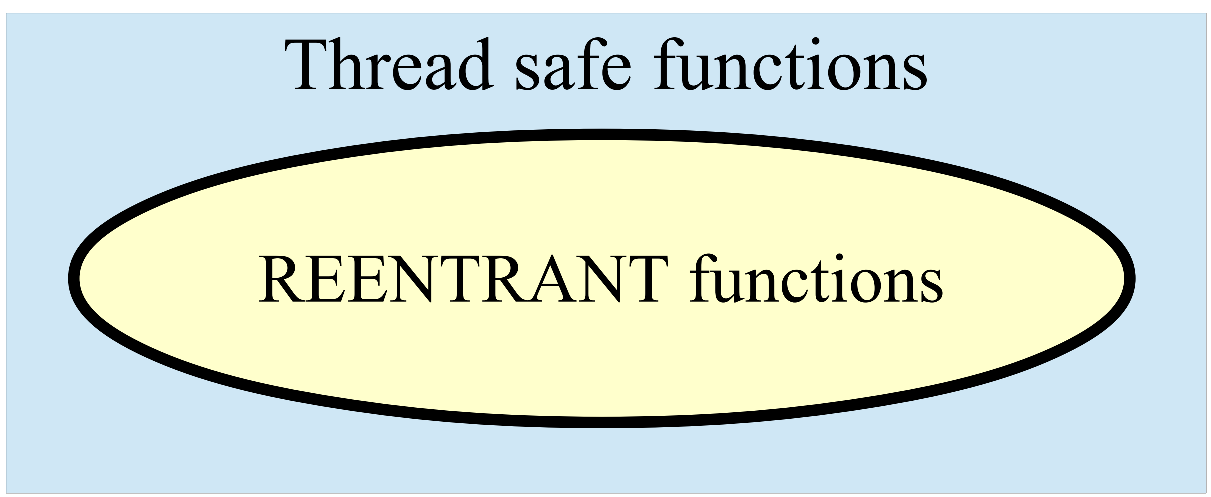
Data Sharing among Threads Proof of Concept

`shareddata.c`

Threads Safety

Thread Safe vs Reentrant Functions

- A **thread safe function** can be called simultaneously from multiple threads, even when the invocations use shared data. This is because each thread accesses shared data using some concurrency control mechanism
- A **reentrant function** can also be called simultaneously from multiple threads, but only if each invocation uses its own data
- Therefore, a thread-safe function is always reentrant, but a reentrant function is not always thread safe



REENTRANT Functions (cont...)

Thread Unsafe Functions	**Thread Safe Functions** (REENTRAMT versions)
`asctime()`	`asctime_r()`
`ctime()`	`ctime_r()`
`gethostbyname()`	`gethostbyname_r()`
`gethostbyaddr()`	`gethostbyaddr_r()`
`rand()`	`rand_r()`
`localtime()`	`localtime_r()`
`crypt()`	`crypt_r()`

So always compile your multi-threaded code with _REENTRANT defined:

```
$gcc -c thread1.c -D_REENTRANT
$gcc thread1.o -o thread1 -lpthread
```

OR

```
$gcc thread1.c -o thread1 -lpthread -D_REENTRANT
```

Four Classes of Thread Unsafe Functions

There are four classes of thread unsafe functions:

Class I: Failing to protect sheared variables

(Solution: Use locks to protect shared variable)

Class II: Relying on persistent state across invocations

(Solution: Do not use)

Class III: Returning a pointer to a static variable

(Solution: Do not use)

Class IV: Calling a thread unsafe function

(Solution: Call thread safe or re-entrant versions of functions)

Synchronization using Mutex

What is Mutex?

- A mutex is a **MUT**ual **EX**clusion device, and is useful for protecting shared data structures from concurrent modifications, and implementing critical sections
- A mutex has two possible states: unlocked (not owned by any thread), and locked (owned by one thread). It can never be owned by two different threads simultaneously
- A thread attempting to lock a mutex that is already locked by another thread is suspended until the owner thread unlocks the mutex
- Linux guarantees that race condition do not occur among threads attempting to lock a mutex

How to Use a Mutex?

i. Create and initialize a mutex variable

ii. Several threads attempt to lock the mutex

iii. Only one thread succeed and that thread owns the mutex

iv. The owner thread carry out operations on shared data

v. The owner threads unlock the mutex

vi. Another thread acquires the mutex and repeats the process

vii. Finally the mutex is destroyed

Mutex Initialization

Static Initialization: In case where default mutex attributes are appropriate, the following macro can be used to initialize a mutex that is statically allocated.

```
pthread_mutex_t mut = PTHREAD_MUTEX_INITIALIZER;
```

Run time initialization: In all other cases, we must dynamically initialize the mutex using `pthread_mutex_init()`

```
int pthread_mutex_init (pthread_mutex_t* mptr,
                        const pthread_mutexattr_t * attr);
```

- This function initializes the mutex object pointed to by `mptr` according to the mutex attributes specified in `attr`. If `attr` is `NULL`, default attributes are used instead

Locking, Unlocking and Destroying mutex

```
int pthread_mutex_lock(pthread_mutex_t *mptr);
int pthread_mutex_unlock(pthread_mutex_t *mptr);
int pthread_mutex_trylock(pthread_mutex_t *mptr);
int pthread_mutex_destroy(pthread_mutex_t *mptr);
```

- The **`lock()`** call will lock the `pthread_mutex_t` object referenced by `mptr`. If mutex is already locked, the calling thread blocks until the mutex is unlocked
- The **`trylock()`** is similar to lock except that if the mutex object is currently locked, the call returns immediately with the error code `EBUSY`
- The **`unlock()`** call release the mutex object. The manner in which a mutex is released is dependent on the mutex's attribute type. If there are threads blocked on the mutex object referenced by `mptr` when `unlock()` is called, the scheduling policy shall determine which thread shall acquire the mutex
- The **`destroy()`** call destroys the mutex object

Mutex Dead Locks

Be sure to observe following points to avoid dead locks while using mutexes:

i. No thread should attempt to lock or unlock a mutex that has not been initialized

ii. Only the owner thread of the mutex (i.e the one which has locked the mutex) should unlock it

iii. Do not lock a mutex that is already locked

iv. Do not unlock a mutex that is not locked

v. Do not destroy a locked mutex

Handling CSP using `pthread_mutex_t` Proof of Concept `solrace1.c, solrace2.c`

Mutex Attributes: type

Mutex Attributes

PTHREAD_MUTEX_INITIALIZER (fast mutex)

- Locking an already locked mutex results in suspending the calling thread
- Unlocking an already unlocked mutex results in undefined behavior
- Unlocking a mutex that is not locked by calling thread results in undefined behavior

PTHREAD_ERRORCHECK_MUTEX_INITIALIZER_NP(error checking mutex)

- Locking an already locked mutex returns immediately with an error `EDEADLK`
- Unlocking an already unlocked mutex returns an error
- Unlocking a mutex that is not locked by calling thread returns an error

PTHREAD_RECURSIVE_MUTEX_INITIALIZER_NP (recursive mutex)

- Locking an already locked mutex returns immediately with a success return code. The number of times the thread owning the mutex has locked it is recorded in the mutex. The owning thread must call pthread_mutex_unlock() the same number of times before the mutex returns to the unlocked state
- Unlocking an unlocked mutex returns an error
- Unlocking a mutex that is not locked by calling thread results in undefined behavior

Mutex Attributes

```
int pthread_mutexattr_init(pthread_mutexattr_t *attr);
int pthread_mutexattr_settype(pthread_mutexattr_t *attr,
                               int kind);
```

- A mutex has a set of attributes which can be set before creating it and passed to the `pthread_mutex_init()` function as its second argument. (which we have kept NULL in previous examples)
- The **`pthread_mutexattr_init()`** function initializes the mutex attribute object `attr` and fills it with default values for the attributes
- The `pthread_mutexattr_settype()` sets the mutex kind attribute in `attr` to the value specified by second argument `kind`
- LinuxThreads supports only one mutex attribute, the mutex kind:
  - `PTHREAD_MUTEX_FAST_NP` for fast mutex
  - `PTHREAD_MUTEX_RECURSIVE_NP` for recursive mutex
  - `PTHREAD_MUTEX_ERRORCHECK_NP` for error checking mutex

Note: NP means, these are non-portable extension to POSIX standard

Attributes of `pthread_mutex_t`
Proof of Concept
`attr1.c, attr2.c`

Condition Variables

Producer-Consumer Problem

- Producer produces information that is consumed by a consumer process.To allow producer and consumer run concurrently we must have a buffer that can be filled by the producer and emptied by the consumer.The buffer can be bounded or unbounded
- **Unbounded Buffer:** Places no practical limit on the size of the buffer. The consumer may have to wait for new items if the buffer is empty, but the producer can always produce new items
- **Bounded Buffer:** Assumes a fixed size buffer. The consumer must wait if the buffer is empty and the producer must wait if the buffer is full

While an item is being added to or removed from the buffer, the buffer is in an inconsistent state. Therefore, threads must have exclusive access to the buffer. If a consumer thread arrives while the buffer is empty, it blocks until a producer adds a new item

Producer-Consumer Problem (cont...)

Implicit Synchronization:

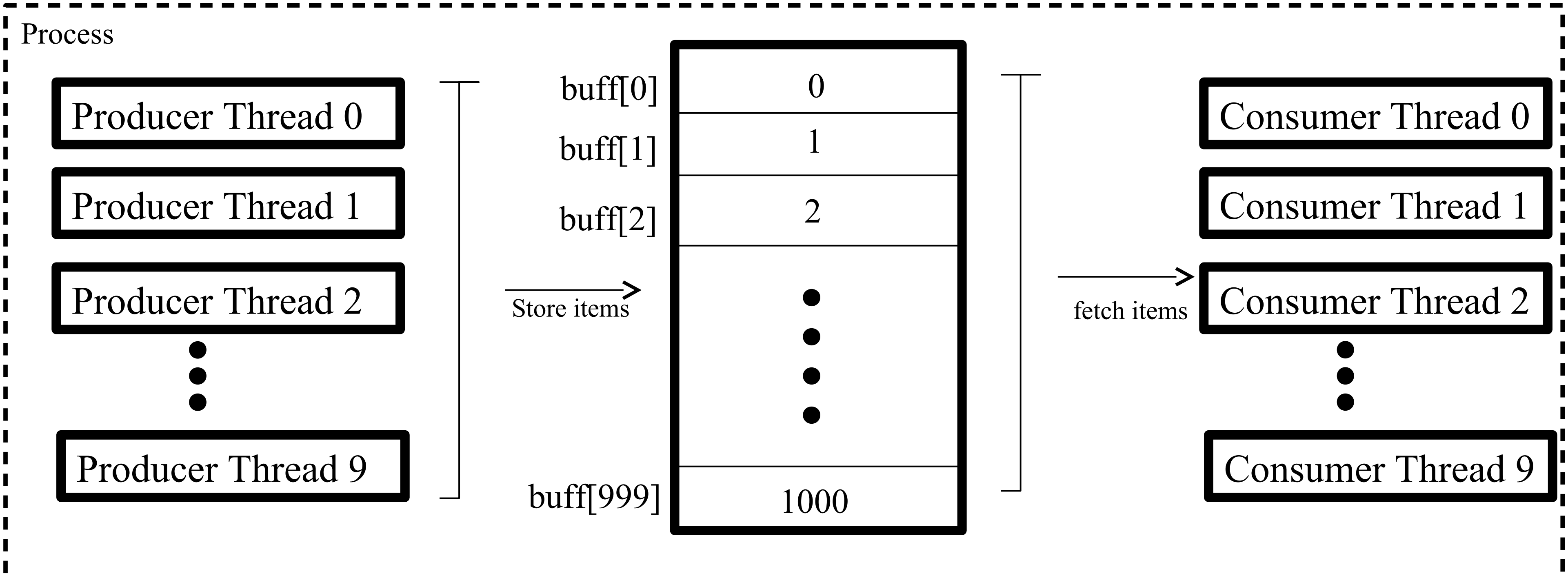
```
$ grep prog1.c | wc -l
```

`grep` is a producer process and **`wc`** is a consumer process. **`grep`** writes into the pipe and **`wc`** reads from the pipe. The required synchronization is handled implicitly by the kernel. If producer gets ahead of the consumer (i.e. the pipe fills up), the kernel puts the producer to sleep when it calls **`write()`**, until more room is available in the pipe. If consumer gets ahead of the producer (i.e. the pipe is empty), the kernel puts the consumer to sleep when it calls **`read()`**, until some data is there in the pipe

Explicit Synchronization:

When we as programmers are using some shared memory/data structure, we use some form of IPC between the procedure and the consumer for data transfer. We also need to ensure that some type of explicit synchronization must be performed between the producer and consumer

Producer-Consumer Example



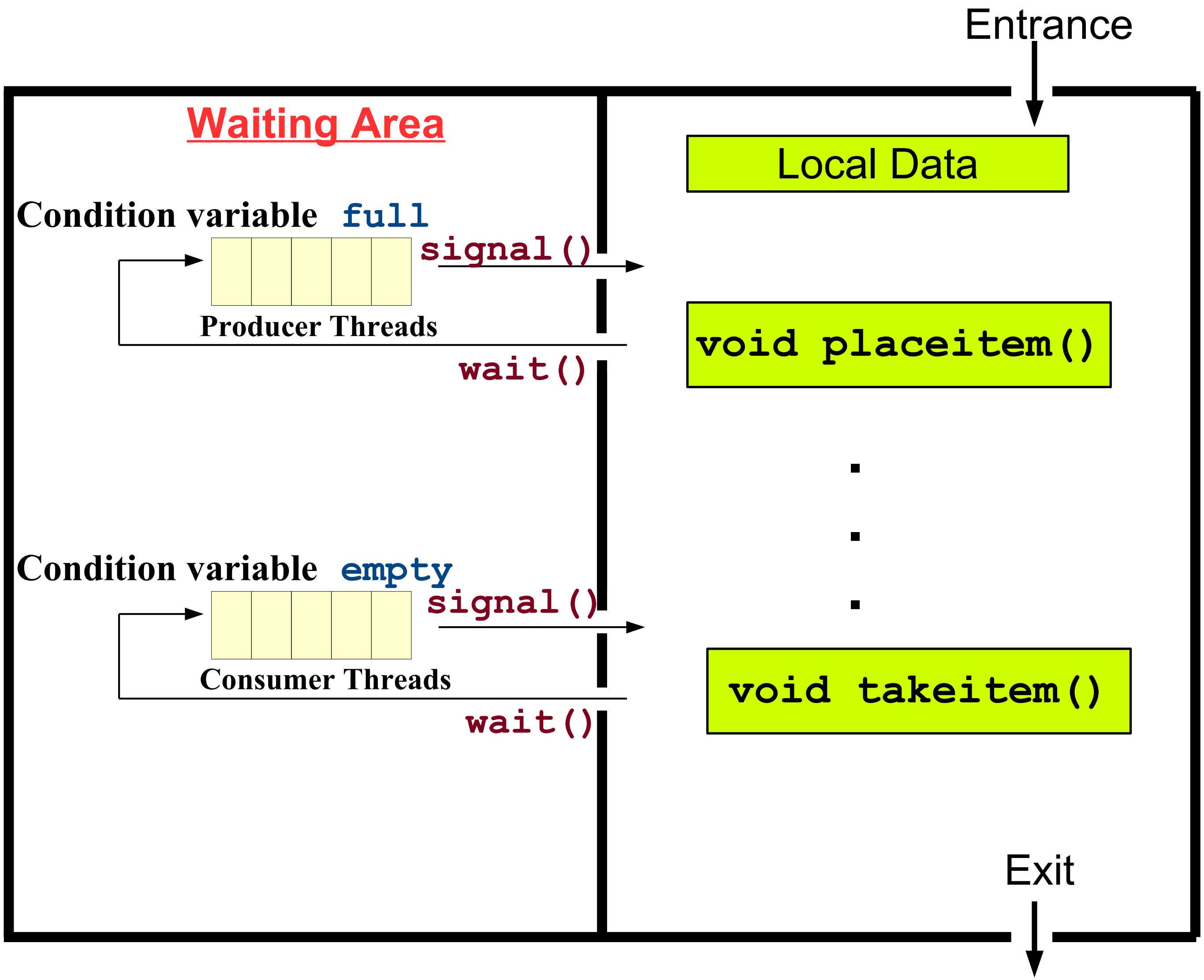
Each producer thread obtains a mutex lock and then accesses the buffer at the location pointed to by **in** and places a number **val** at that location.

Each consumer thread obtains a mutex lock and then accesses the buffer at the location pointed to by **out** and removes the number **val** from that location.

Condition Variables

- Solution to such problems like the producer-consumer, reader-writer, barber-shop and so on are condition variables
- A condition variable is a synchronization construct that allows threads to suspend execution and relinquish the processors until some condition is satisfied
- The two basic operations on condition variables are:
- **`signal():`** Wake up a sleeping thread on this condition variable
- **`wait():`** Release lock, goto sleep, reacquire lock after you are awoken up
- So we can say that a condition variable enable a thread to sleep inside a CS. Any lock held by the thread is automatically released when the thread is put to sleep
- A **mutex** is for **locking** and a **condition variable** is for **waiting**

Producer Consumer with Condition Variables



With every condition variable there is an associated mutex variable. Whenever a thread wants to invoke **wait()** or **signal()** operation, it must hold the mutex associated with that condition variable

Initializing pthread_cond_t Variable

Static Initialization: In case where default attributes are appropriate, the following macro can be used to initialize a pthread_cond_t variable

```
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
```

Run time initialization: In all other cases, we must dynamically initialize the condition variable using pthread_cond_init()

```
int pthread_cond_init(pthread_cond_t *cond,
                      pthread_condattr_t *attr);
```

- This function initializes the condition variable object pointed to by cond using the condition attributes specified in attr. If attr is NULL, default attributes are used instead. LinuxThreads implementation supports no attributes for conditions, hence the attr parameter is actually ignored

Operations on pthread_cond_t Variable

```
int pthread_cond_signal(pthread_cond_t *cond);
int pthread_cond_wait(pthread_cond_t *cond,
                        pthread_mutex_t *mutex);
```

- The **pthread_cond_signal()** restarts one of the threads that are waiting on the condition variable cond. If no threads are waiting on cond, nothing happens. If several threads are waiting on cond, exactly one is restarted, but it is not specified which
- The thread that calls **pthread_cond_wait()** atomically unlocks its second argument mutex and waits for the condition variable cond to be signaled by suspending its execution

Example: wait() and signal()

- Consider the buffer protected by mutex `mut`, and a condition variable `empty`
- A call to **`pthread_cond_wait()`** should be done as part of a conditional statement, e.g., the consumer thread will wait on condition variable `empty` only when the buffer gets empty
- The producer thread will give a signal on condition variable `empty`, when it places the first item in the buffer
- When the condition variable `cond` is signaled by a consumer thread, **`pthread_cond_wait()`** will implicitly lock the mutex again before returning. That is the reason the **`pthread_mutex_unlock()`** statement is required after modifying the buffer by the producer thread

Consumer Thread

```
pthread_mutex_lock(&mut);
while(buffercount == 0)
   pthread_cond_wait(&empty, &mut);
//modify the buffer
pthread_mutex_unlock(&mut);
```

Producer Thread

```
pthread_mutex_lock(&mut);
//modify the buffer
if(buffercount == 1)
   pthread_cond_signal(&empty);
pthread_mutex_unlock(&mut);
```

Solution to Producer Consumer Problem
Home Task

`producer_consumer.c`

Things To Do

If you have problems visit me in counseling hours. . . .