



Shared-Memory Programming: Pthread

National Tsing Hua University
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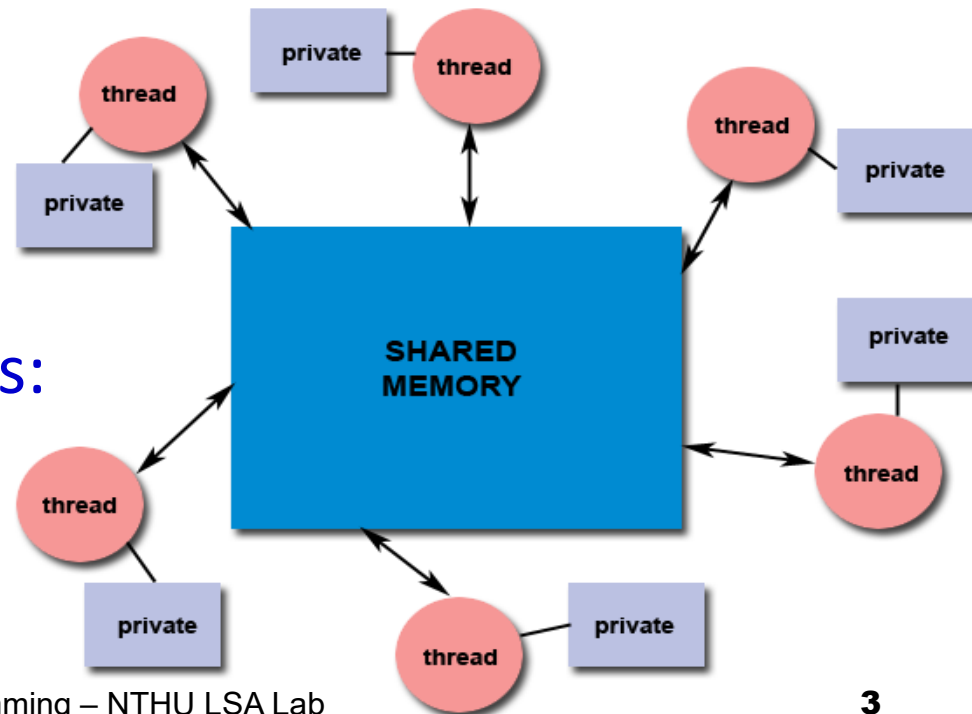


Outline

- Shared-memory Programming
- Pthread
- Synchronization Problem & Tools

Shared-Memory Programming

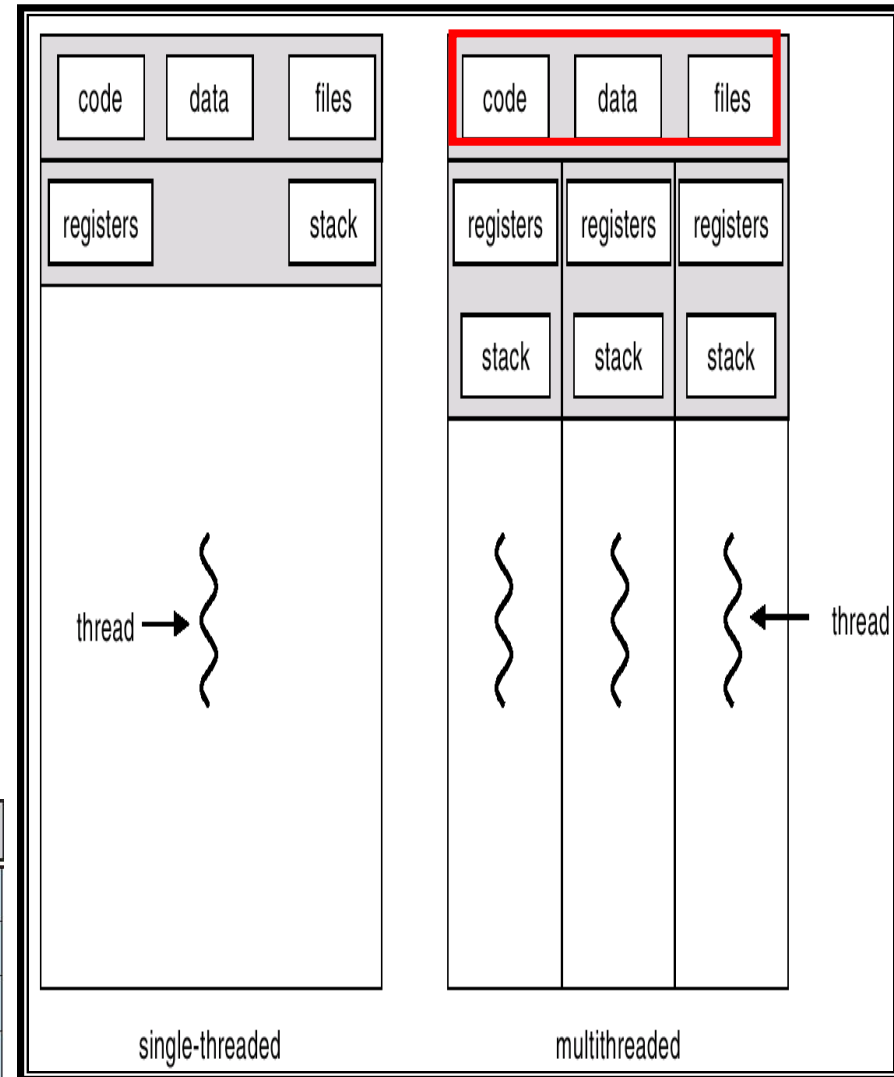
- **Definition:** Processes communicate or work together with each other **through a shared memory space** which can be accessed by all processes
 - **Faster & more efficient than message passing**
- **Many issues as well:**
 - **Synchronization**
 - **Deadlock**
 - **Cache coherence**
- **Programming techniques:**
 - **Parallelizing compiler**
 - **Unix processes**
 - **Threads (**Pthread**, Java)**



Threads vs. Processes

- **Process (heavyweight process):** complete separate program with its own variables, stack, heap, and everything else.
- **Thread (lightweight process):** share the **same memory space** for global variables, resources
- In Linux:
 - Threads are created via **clone a process** with a flag to indicate the **level of sharing**

flag	meaning
CLONE_FS	File-system information is shared.
CLONE_VM	The same memory space is shared.
CLONE_SIGHAND	Signal handlers are shared.
CLONE_FILES	The set of open files is shared.



Why Thread?

■ Lower creation/management cost vs. Process

platform	fork()	pthread_create()	speedup
AMD 2.4 GHz Opteron	17.6	1.4	15.6x
IBM 1.5 GHz POWER4	104.5	2.1	49.8x
INTEL 2.4 GHz Xeon	54.9	1.6	34.3x
INTEL 1.4 GHz Itanium2	54.5	2.0	27.3x

■ Faster inter-process communication vs. MPI

platform	MPI Shared Memory BW (GB/sec)	Pthreads Worst Case Memory-to-CPU BW (GB/sec)	speedup
AMD 2.4 GHz Opteron	1.2	5.3	4.4x
IBM 1.5 GHz POWER4	2.1	4	1.9x
INTEL 2.4 GHz Xeon	0.3	4.3	14.3x
INTEL 1.4 GHz Itanium2	1.8	6.4	3.6x

Outline

- Shared-memory Programming
- Pthread
 - What is Pthread
 - Pthread Creation
 - Pthread Joining & Detaching
- Synchronization Problem & Tools

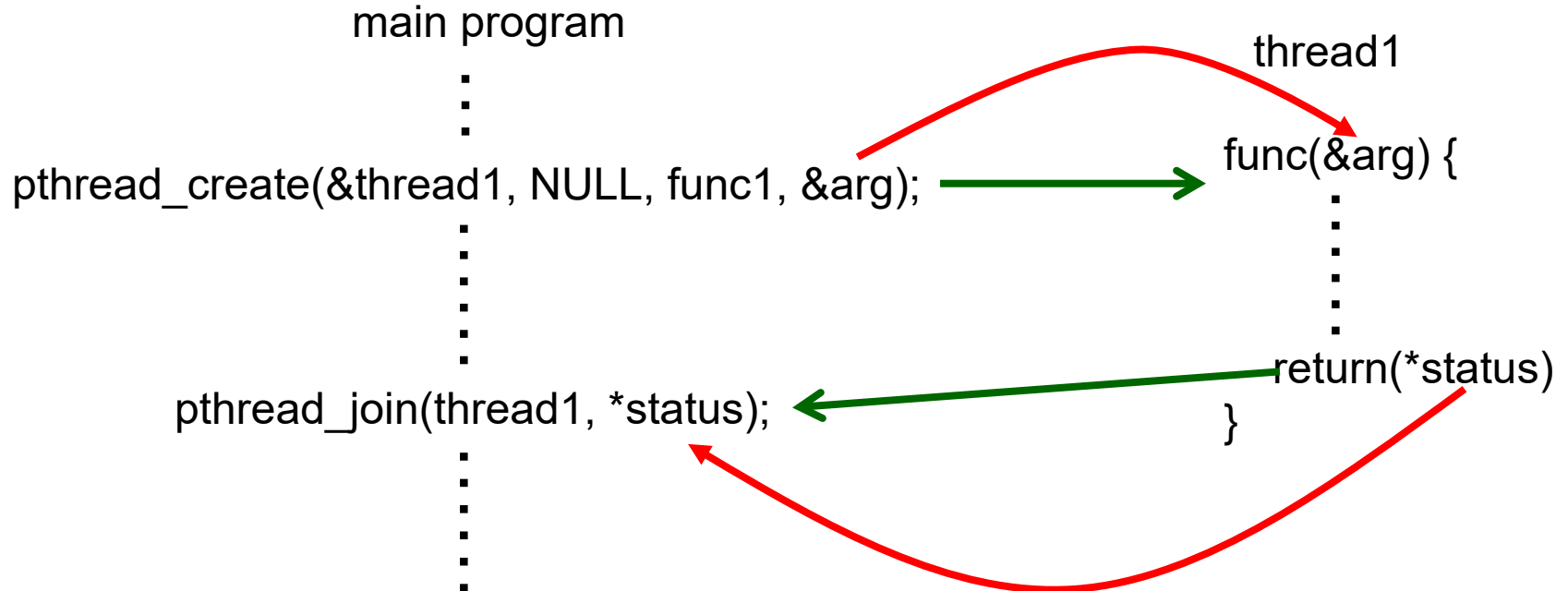
What is Pthread?

- Historically, hardware vendors have implemented their own proprietary versions of threads
- **POSIX** (Potable Operating System Interface) standard is specified for portability across Unix-like systems
 - Similar concept as MPI for message passing libraries
- **Pthread** library is the implementation of **POSIX standard** for thread
 - Same relation between MPICH and MPI

Pthread Creation

■ pthread_create(thread,attr,routine,arg)

- **thread**: An **unique identifier** (token) for the new thread
- **attr**: It is used to set **thread attributes**. NULL for the default values
- **routine**: The routine that the thread will execute once it is created
- **arg**: A **single argument** that may be **passed to routine**



Example

```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

void *PrintHello(void *threadId) {
    int* data = static_cast<int*> (threadId);
    printf("Hello World! It's me, thread #%d!\n", *data);
    pthread_exit(NULL);
}

int main (int argc, char *argv[]) {
    pthread_t threads[NUM_THREADS];
    int tids[NUM_THREADS];
    for(int i=0; i<NUM_THREADS; i++){
        tids[i] = i;
        pthread_create(&threads[i], NULL, PrintHello, (void *)&tids[i]);
    }
    /* Last thing that main() should do */
    pthread_exit(NULL);
}
```

Pthread Joining & Detaching

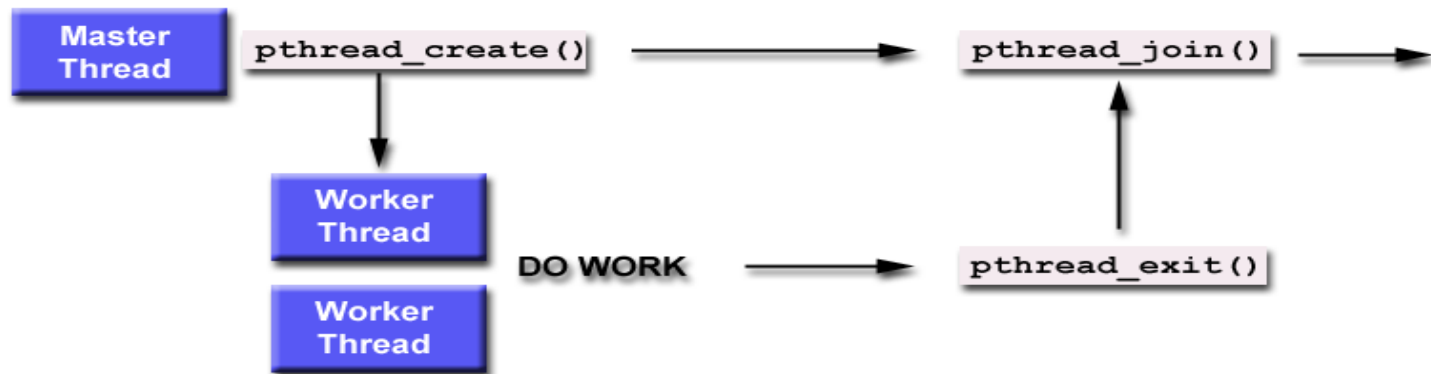
■ pthread_join(threadId, status)

- Blocks until the specified *threadId* thread terminates
- One way to accomplish synchronization between threads
- Example: to create a pthread barrier

```
for (int i=0; i<n; i++) pthread_join(thread[i], NULL);
```

■ pthread_detach(threadId)

- Once a thread is **detached**, it can **never** be joined
- Detach a thread could free some system resources



Outline

- Shared-memory Programming
- Pthread
- Synchronization Problem & Tools
 - Pthread
 - ◆ Mutually exclusion Lock
 - ◆ Condition variable
 - POSIX Semaphore
 - JAVA Monitor
- Other issues

Synchronization Problem

- The outcome of data content should **NOT** be decided by the **execution order among processes**

- **Instructions** of individual processes/threads may be **interleaved** in time

- E.g.: Assume variable **“counter”** is **shared by processes**

```
Process0  
main() {  
    ...  
    counter++;  
    ...  
}
```

```
Process1  
main() {  
    ...  
    counter--;  
    ...  
}
```

- The statement **“counter++”** & **“counter--”** may be implemented in machine language as:

```
move ax, counter  
add  ax, 1  
move counter, ax
```

```
move bx, counter  
sub   bx, 1  
move counter, bx
```

Instruction Interleaving

- Assume counter is initially 5. One interleaving of statement is:

producer: move ax, counter → ax = 5

producer: add ax, 1 → ax = 6

context switch

consumer: move bx, counter → bx = 5

consumer: sub bx, 1 → bx = 4

context switch

producer: move counter, ax → counter = 6

context switch

consumer: move counter, bx → counter = 4

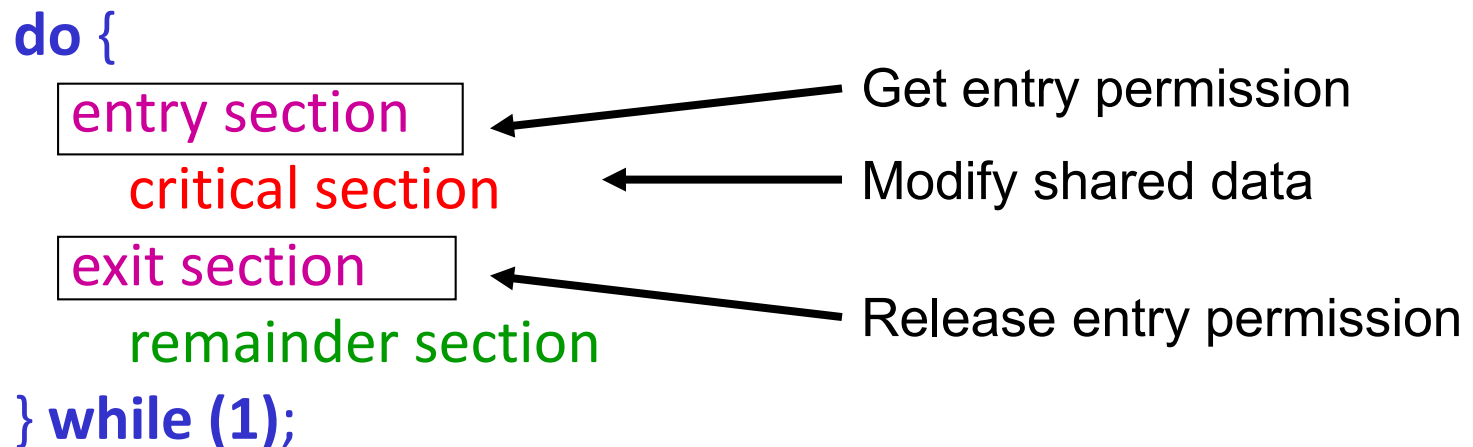
- The value of counter may be either 4, 5, or 6
- The ONLY correct result is 5!

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Critical Section & Mutual Exclusion

- **Critical Section** is a piece of code that can only be accessed by one process/thread at a time
- **Mutual exclusion** is the problem to insure only one process/thread can be in a critical section
- E.g.: The design of entry section & exit section provides mutual exclusion for the critical section



Locks

- Lock: the simplest mechanism for ensuring mutual exclusion of critical section

➤ Spinlock is one of the implementation:

```
while (lock == 1);           /* no operation in while loop */
lock = 1;                   /* enter critical section */
.
critical section
.
lock = 0;                   /* leave critical section */
```

- Locks are implemented in Pthreads by a special type of variables “mutex”
- **Mutex** is abbreviation of “mutual exclusion”

Pthread Lock/Mutex Routines

- To use mutex, it must be declared as of type `pthread_mutex_t` and initialized with `pthread_mutex_init()`
- A mutex is destroyed with `pthread_mutex_destroy()`
- A critical section can then be protected using `pthread_mutex_lock()` and `pthread_mutex_unlock()`
- Example:

```
#include "pthread.h"
pthread_mutex_t  mutex;
pthread_mutex_init (&mutex, NULL);
pthread_mutex_lock(&mutex);

    Critical Section

pthread_mutex_unlock(&mutex);
pthread_mutex_destroy(&mutex);
```

specify default attribute for the mutex

// enter critical section

// leave critical section

Bounded-Buffer Problem

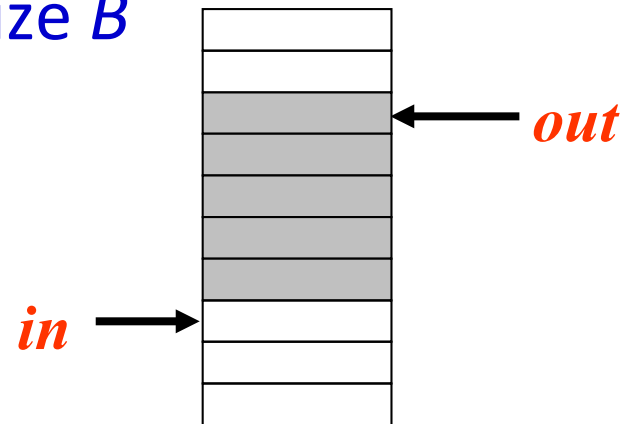
- A pool of n buffers, each capable of holding one item
- Producer:
 - grab an empty buffer
 - place an item into the buffer
 - waits if no empty buffer is available
- Consumer:
 - grab a buffer and retracts the item
 - place the buffer back to the free pool
 - waits if all buffers are empty

Bounded-Buffer Problem

- **Producer** process produces information that is consumed by a **Consumer** process

- Buffer as a circular array with size B

- next free: in
- first available: out
- empty: $in = out$
- full: $(in+1) \% B = out$



- The solution allows at most $(B-1)$ item in the buffer
 - Otherwise, cannot tell the buffer is full or empty

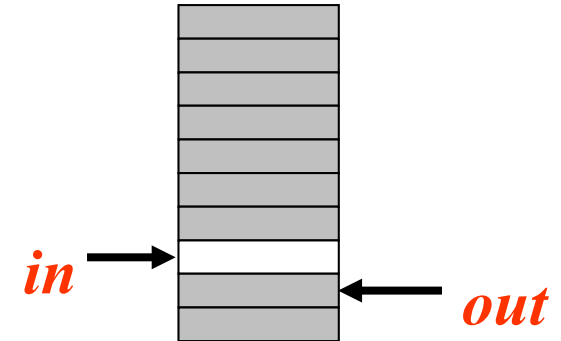
Shared-Memory Solution

```
/*producer*/  
while (1) {  
    while (((in + 1) % BUFFER_SIZE) == out)  
        ; //wait if buffer is full  
    buffer[in] = nextProduced;  
    in = (in + 1) % BUFFER_SIZE;  
}
```

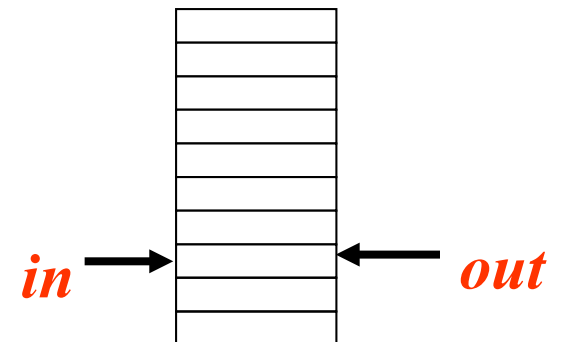
“in” only modified by producer

```
/*consumer*/  
while (1) {  
    while (in == out); //wait if buffer is empty  
    nextConsumed = buffer[out];  
    out = (out + 1) % BUFFER_SIZE;  
}
```

“out” only modified by consumer



```
/* global data structure */  
#define BUFSIZE 10  
item buffer[BUFSIZE];  
int in = out = 0;
```



Using Mutex Lock

```
/*producer*/
```

```
while (1) {  
    nextItem = getItem( );  
    while (counter == BUFFER_SIZE) ;  
    buffer[in] = nextItem;  
    in = (in + 1) % BUFFER_SIZE;  
    mutex_lock(mutex);  
    counter++;  
    mutex_unlock(mutex);  
}
```

```
/*consumer*/
```

```
while (1) {  
    while (counter == 0) ;  
    item = buffer[out];  
    out = (out + 1) % BUFFER_SIZE;  
    mutex_lock(mutex);  
    counter--;  
    mutex_unlock(mutex);  
}
```

Condition Variables (CV)

- CV represent some **condition** that a thread can:
 - Wait on, until the condition occurs; or
 - Notify other waiting threads that the condition has occurred
- Three operations on condition variables:
 - **wait()** --- **Block** until another thread calls **signal()** or **broadcast()** on the CV
 - **signal()** --- Wake up **one thread** waiting on the CV
 - **broadcast()** --- Wake up **all threads** waiting on the CV
- In Pthread, CV **type** is a **pthread_cond_t**
 - Use **pthread_cond_init()** to initialize
 - **pthread_cond_wait (&theCV, &somelock)**
 - **pthread_cond_signal (&theCV)**
 - **pthread_cond_broadcast (&theCV)**

Using Condition Variable

■ Example:

- A threads is designed to **take action when x=0**
- Another thread is responsible for decrementing the counter

```
pthread_cond_t  cond;  
pthread_cond_init (cond, NULL);
```

```
pthread_mutex_t  mutex;  
pthread_mutex_init (mutex, NULL);
```

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
        pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
```

```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
    pthread_mutex_unlock (&mutex);  
}
```

- All condition variable operation **MUST** be performed while a mutex is **locked!!!**

Why is the lock necessary???

Using Condition Variable

```
pthread_cond_t  cond;  
pthread_cond_init (cond, NULL);
```

```
pthread_mutex_t  mutex;  
pthread_mutex_init (mutex, NULL);
```

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
        pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
```

```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
    pthread_mutex_unlock (&mutex);  
}
```

Because event counter “x” is a **SHARED** variable

- If no lock on thread action()...
 - Wait after **any thread** (i.e. not counter) sets “x” to 0
- If no lock on thread counter()...
 - No guarantee that decrement and test of “x” is **atomic**
- Requiring CV operations to be done while holding a lock
prevents a lot of common programming mistakes

Using Condition Variable

```
action() {  
→ pthread_mutex_lock (&mutex)  
  if (x != 0)  
    pthread_cond_wait (cond, mutex);  
  pthread_mutex_unlock (&mutex);  
  take_action();  
}
```

```
→ counter() {  
  pthread_mutex_lock (&mutex)  
  x--;  
  if (x==0)  
    pthread_cond_signal (cond);  
  pthread_mutex_unlock (&mutex);  
}
```

■ What really happens...

1. Lock mutex

Using Condition Variable

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
→   pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
```

```
counter() {  
→   pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
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}
```

■ What really happens...

1. Lock mutex
2. Wait()
 1. Put the thread into **sleep & releases the lock**

1. Lock mutex

Using Condition Variable

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action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
        pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
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```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
    pthread_mutex_unlock (&mutex);  
}
```

■ What really happens...

1. Lock mutex

2. Wait()

1. Put the thread into **sleep & releases the lock**

1. **Waked up**, but the **thread is locked**

1. Lock mutex

2. Signal()

Using Condition Variable

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
→   pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
```

```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
→   pthread_mutex_unlock (&mutex);  
}
```

■ What really happens...

1. Lock mutex

2. Wait()

1. Put the thread into **sleep & releases the lock**

1. **Waked up**, but the **thread is locked**

2. **Re-acquire lock** and **resume execution**

1. Lock mutex

2. Signal()

3. Releases the lock

Using Condition Variable

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
        pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
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```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
    pthread_mutex_unlock (&mutex);  
}
```

■ What really happens...

1. Lock mutex

2. Wait()

1. Put the thread into **sleep & releases the lock**

1. **Waked up**, but the **thread is locked**

2. **Re-acquire lock** and **resume execution**

3. Release the lock

1. Lock mutex

2. Signal()

3. Releases the lock

Using Condition Variable

```
action() {  
    pthread_mutex_lock (&mutex)  
    if (x != 0)  
        pthread_cond_wait (cond, mutex);  
    pthread_mutex_unlock (&mutex);  
    take_action();  
}
```

```
counter() {  
    pthread_mutex_lock (&mutex)  
    x--;  
    if (x==0)  
        pthread_cond_signal (cond);  
    pthread_mutex_unlock (&mutex);  
}
```

■ What really happens...

1. Lock mutex

2. Wait()

1. Put the thread into sleep &

releases the lock

1. Waked up, but the thread is locked

2. **Re-acquire lock** and resume execution

3. Release the lock

1. Lock mutex

2. Signal()

3. Releases the lock

Another reason why
condition variable op.
MUST within mutex lock

Thread Pools

- Create a number of threads in a pool where they await work
- Advantages
 - Usually slightly faster to service a request with an existing thread than create a new thread
 - Allows the number of threads in the application(s) to be bound to the size of the pool
- # of threads: # of CPUs, expected # of requests, amount of physical memory

ThreadPool Implementation

Task structure

```
typedef struct {  
    void (*function)(void *);  
    void *argument;  
} threadpool_task_t;
```

Threadpool structure

```
struct threadpool_t {  
    pthread_mutex_t lock;  
    pthread_cond_t notify;  
    pthread_t *threads;  
    threadpool_task_t *queue;  
    int thread_count;  
    int queue_size;  
    int head;  
    int tail;  
    int count;  
    int shutdown;  
    int started;  
};
```

Allocate thread and task queue

```
/* Allocate thread and task queue */  
pool->threads = (pthread_t *) malloc(sizeof(pthread_t) * thread_count);  
pool->queue = (threadpool_task_t *) malloc(sizeof(threadpool_task_t) * queue_size);
```


ThreadPool Implementation

```
static void *threadpool_thread(void *threadpool) ← thread handler  
function  
{  
    threadpool_t *pool = (threadpool_t *)threadpool;  
    threadpool_task_t task;  
  
    for(;;) {  
        /* Lock must be taken to wait on conditional variable */  
        pthread_mutex_lock(&(pool->lock));  
  
        /* Wait on condition variable, check for spurious wakeups.  
         * When returning from pthread_cond_wait(), we own the lock. */  
        while((pool->count == 0) && (!pool->shutdown)) {  
            pthread_cond_wait(&(pool->notify), &(pool->lock));  
        }  
    }  
}
```

ThreadPool Implementation

```
/* Grab our task */  
task.function = pool->queue[pool->head].function;  
task.argument = pool->queue[pool->head].argument;  
pool->head += 1;  
pool->head = (pool->head == pool->queue_size) ? 0 : pool->head;  
pool->count -= 1;  
  
/* Unlock */  
pthread_mutex_unlock(&(pool->lock));  
  
/* Get to work */  
(*task.function)(task.argument);  
}
```

Semaphore

- A tool to generalize the synchronization problem
 - **Deadlock** may occur if not use appropriately !
- More specifically...
 - a record of **how many units** of a particular resource are available
 - ◆ If #record = 1 ➔ **binary semaphore, mutex lock**
 - ◆ If #record > 1 ➔ **counting semaphore**
 - accessed only through 2 *atomic* ops: **wait** & **signal**
- **Spinlock** implementation:
 - Semaphore is an **integer variable**

```
wait (S) {                                signal (S) {  
    while (S <= 0) ;                        S++;  
    S--;                                    }  
}
```

POSIX Semaphore

- Semaphore is part of **POSIX** standard BUT it is **not** belonged to Pthread
 - It can be used with or **without** thread
- POSIX Semaphore routines:
 - **sem_init**(sem_t *sem, int pshared, unsigned int value)
 - **sem_wait**(sem_t *sem)
 - **sem_post**(sem_t *sem)
 - **sem_getvalue**(sem_t *sem, int *valp)
 - **sem_destroy**(sem_t *sem)

Initial value of the semaphore

Current value of the semaphore

■ Example:

```
#include <semaphore.h>
sem_t sem;
sem_init(&sem);
sem_wait(&sem);
    // critical section
sem_post(&sem);
sem_destroy(&sem);
```

Semaphore Drawback

- Although semaphores provide a convenient and effective synchronization mechanism, its correctness is depending on the programmer
 - All processes access a shared data object must execute `wait()` and `signal()` in the right order and right place
 - This may not be true because honest programming error or uncooperative programmer

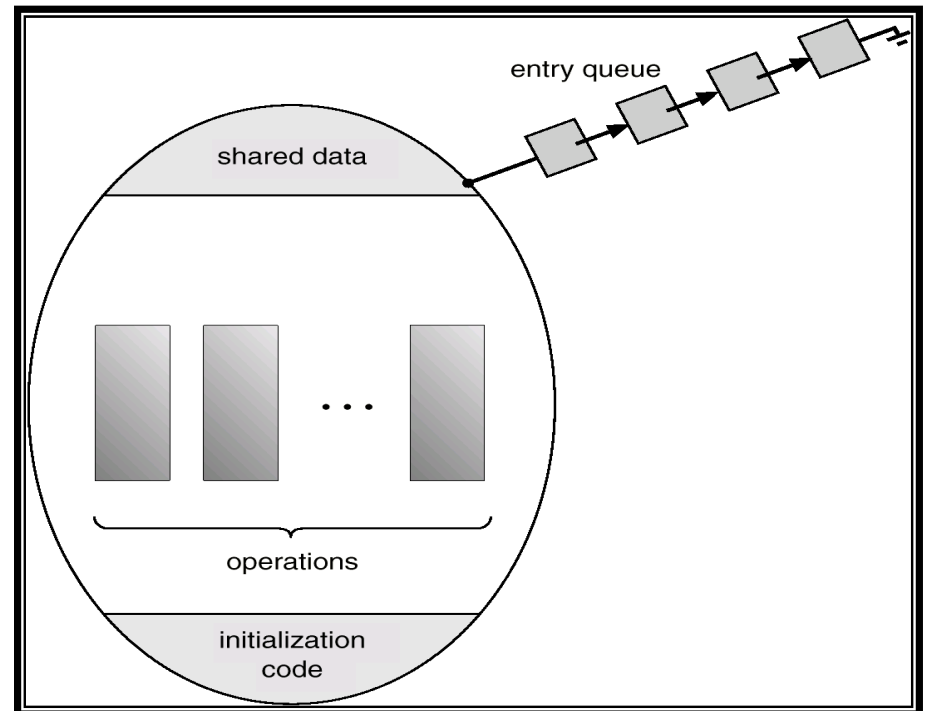
Monitor

- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes

Syntax

```
monitor monitor-name {  
    // shared variable declarations  
    procedure body P1 (...) {  
        ...  
    }  
    procedure body P2 (...) {  
        ...  
    }  
    procedure body Pn (...) {  
        ...  
    }  
    initialization code {  
    }  
}
```

Schematic View



Synchronized Tools in JAVA

■ Synchronized Methods (Monitor)

- Synchronized method uses the method receiver as a lock
- Two invocations of synchronized **methods cannot interleave on the same object**
- When one thread is executing a synchronized method for an object, all other threads that invoke synchronized methods for the same object block until the first thread exist the object

```
public class SynchronizedCounter {  
    private int c = 0;  
    public synchronized void increment() { c++; }  
    public synchronized void decrement() { c--; }  
    public synchronized int value() { return c; }  
}
```

Synchronized Tools in JAVA

■ Synchronized Statement (Mutex Lock)

- Synchronized blocks uses the **expression** as a lock
- A synchronized Statement can only be executed once the thread has obtained a **lock for the object or the class that has been referred to in the statement**
- useful for improving concurrency **with fine-grained**

```
public void run()
{
    synchronized(p1)
    {
        int i = 10; // statement without locking requirement
        p1.display(s1);
    }
}
```


The Big Picture

- Getting **synchronization** right is hard!
- How to pick between locks, semaphores, convars, monitors???
- **Locks** are very **simple** for many cases
 - But may not be the most efficient solution
- **Condition variables** **allow threads to sleep** while holding a lock
 - Be aware whether they use Mesa or Hoare semantics
- **Semaphores** provide **general functionality**
 - But also make it really easy to mess up or cause deadlock
- **Monitors** are a **“pattern”** for using locks and condition variables

Reference

- Textbook:
 - Parallel Computing Chap8
- Pthread Tutorial
 - <https://computing.llnl.gov/tutorials/pthreads/>
- Synchronization Tools:
 - <http://www.eecs.harvard.edu/~mdw/course/cs61/mediawiki/images/7/7e/Lectures-semaphores.pdf>
- Pthread API:
 - <http://www.yolinux.com/TUTORIALS/LinuxTutorialPosixThreads.html>
- JAVA Synchronized methods
 - <http://docs.oracle.com/javase/tutorial/essential/concurrency/syncmeth.html>