Shared-Memory Programming: Pthread

National Tsing Hua University

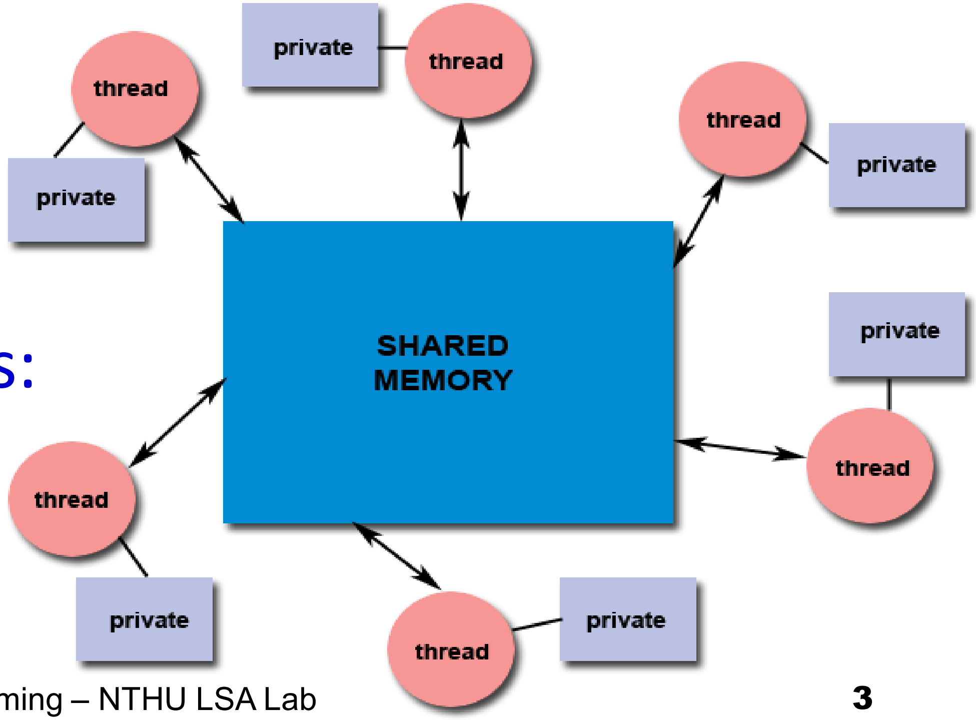
2025, Fall Semester

Outline

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

Shared-Memory Programming

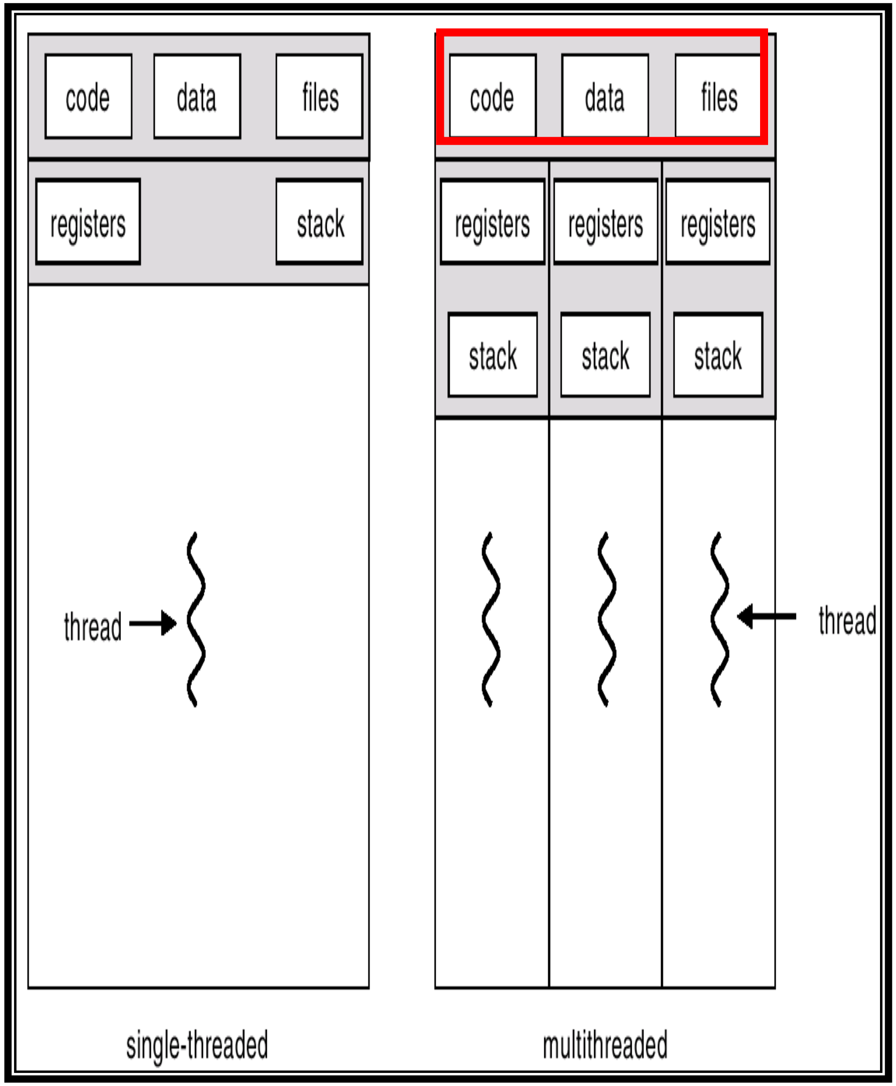
- **Definition**: Processes communicate or work together with each other through a shared memory space which can be accessed by all processes
  - Faster & more efficient than message passing
- Many issues as well:
  - Synchronization
  - Deadlock
  - Cache coherence
- Programming techniques:
  - Parallelizing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

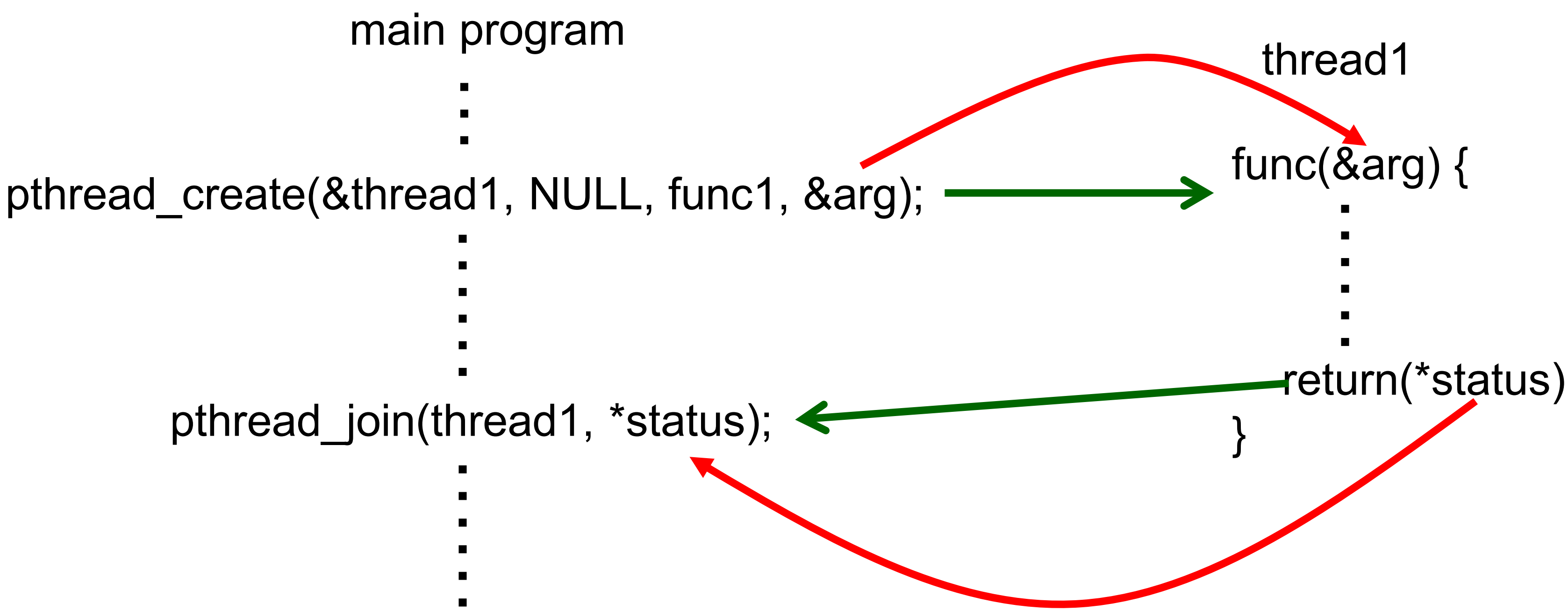
- Shared-memory Programming
- Pthread
  - What is Pthread
  - Pthread Creation
  - Pthread Joining & Detaching
- Synchronization Problem & Tools

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

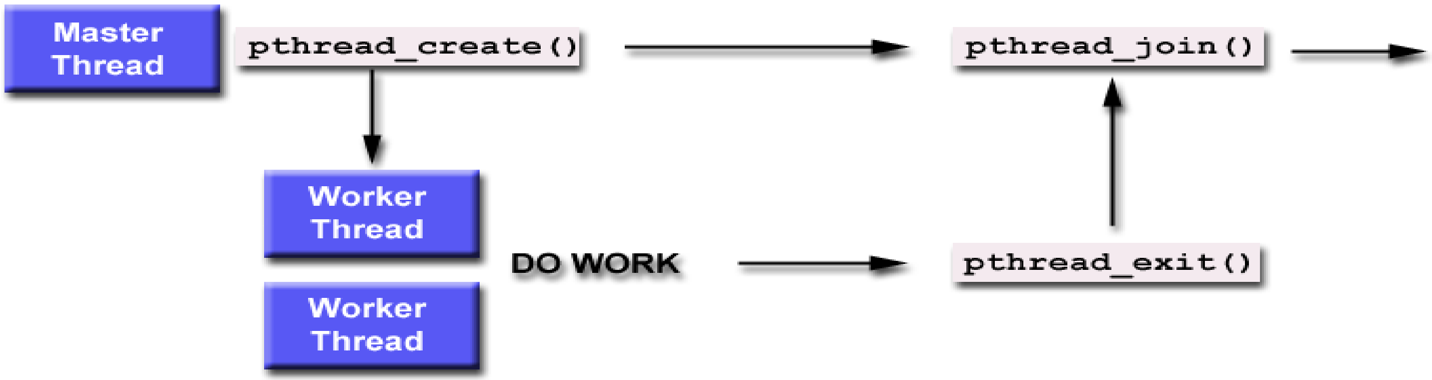
```
#include <pthread.h>
#include <stdio.h>
#define NUM_THREADS 5

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                    Process1
 main() {                    main() {
    :                           :
    counter++;                  counter--;
    :                           :
 }                           }
```

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

```
move ax, counter        move  bx, counter
add    ax, 1             sub    bx, 1
move counter, ax         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

```
do {
    entry section          <- Get entry permission
        critical section   <- Modify shared data
    exit section           <- Release entry permission
        remainder section
} while (1);
```

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:

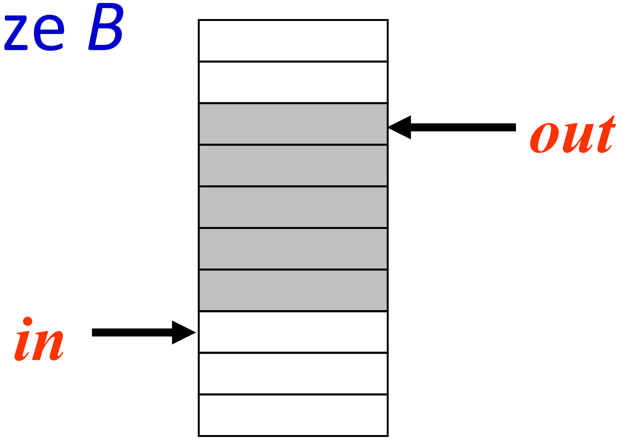
```
#include "pthread.h"
pthread_mutex_t   mutex;
pthread_mutex_init (&mutex, NULL);        specify default attribute for the mutex
pthread_mutex_lock(&mutex);               // enter critical section

        Critical Section

pthread_mutex_unlock(&mutex);             // leave critical section
pthread_mutex_destroy(&mutex);
```

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: $(in+1)\ \%\ B = out$

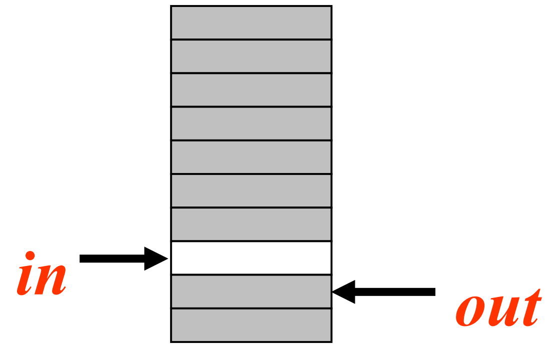


- The solution allows at most (B-1) item in the buffer
  - Otherwise, cannot tell the buffer is fall or empty

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;
}
```

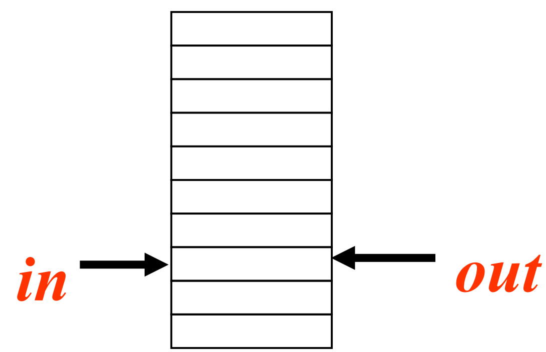
"in" only modified by producer




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

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

"out" only modified by consumer



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_mutex_t    mutex;
pthread_cond_init (cond, NULL);         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_mutex_t    mutex;
pthread_cond_init (cond, NULL);           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);
  pthread_mutex_unlock (&mutex);
}
```

- What really happens…

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

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);
  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();
}
```

```
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

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;
};
```

Task structure

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

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)
 {
     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));
         }
```

thread handler function

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) {
   while (S <= 0) ;
   S--;
}

signal (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 *valptr)
  - **sem_destory**(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

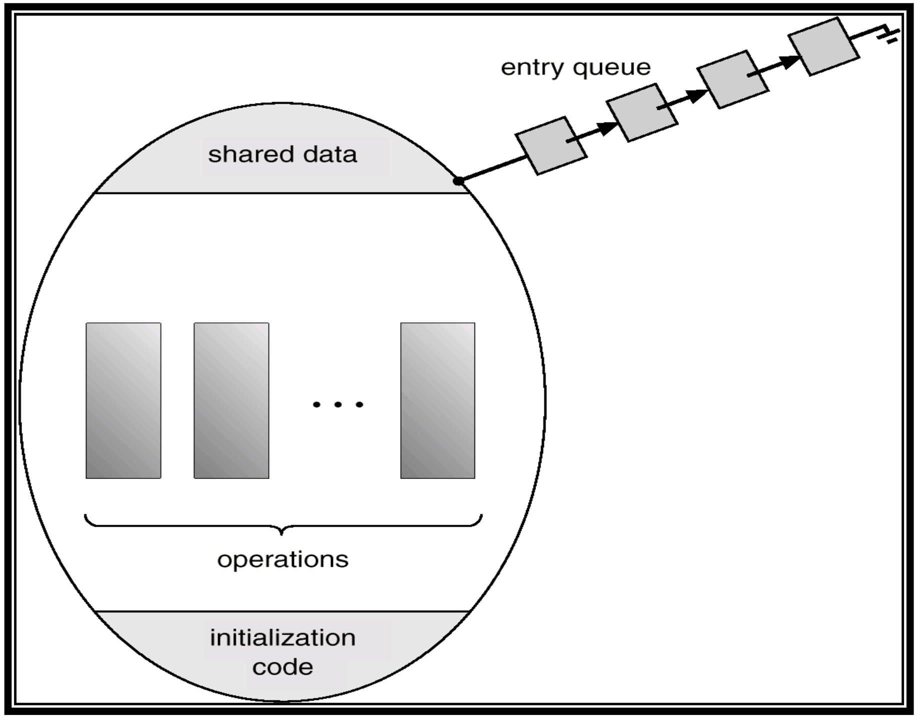
Monitor

- 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 mass 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/
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