Operating Systems

Process Synchronization

Process Synchronization

- Background
- The Critical-Section Problem
- Peterson’s Solution
- Synchronization Hardware
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples

Objectives

- To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data
- To present both software and hardware solutions of the critical-section problem
- To introduce the concept of an atomic transaction and describe mechanisms to ensure atomicity

Background

- Concurrent access to shared data may result in data inconsistency
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes
- Suppose that we wanted to provide a solution to the consumer-producer problem that fills **all** the buffers. We can do so by having an integer **count** that keeps track of the number of full buffers. Initially, count is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer

```
while (true) {

    /*  produce an item and put in nextProduced  */
     while (counter == BUFFER_SIZE)
            ; // do nothing
        buffer [in] = nextProduced;
        in = (in + 1) % BUFFER_SIZE;
        counter++;
}
```

Consumer

```
while (true)  {
        while (counter == 0)
                ; // do nothing
                nextConsumed =  buffer[out];
                 out = (out + 1) % BUFFER_SIZE;
                  counter--;

                    /*  consume the item in nextConsumed  */
 }
```

Race Condition

counter++ could be implemented as

register1 = counter
register1 = register1 + 1
counter = register1

counter-- could be implemented as

register2 = counter
register2 = register2 - 1
count = register2

Consider this execution interleaving with “count = 5” initially:

S0: producer execute register1 = counter {register1 = 5}
S1: producer execute register1 = register1 + 1 {register1 = 6}
S2: consumer execute register2 = counter {register2 = 5}
S3: consumer execute register2 = register2 - 1 {register2 = 4}
S4: producer execute counter = register1 {count = 6 }
S5: consumer execute counter = register2 {count = 4}

Critical Section Problem

- Consider system of n processes $\{p_0, p_1, \ldots p_{n-1}\}$
- Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc
  - When one process in critical section, no other may be in its critical section
- Critical section problem is to design protocol to solve this
- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**
- Especially challenging with preemptive kernels

Critical Section

General structure of process p_i is

```
do {
        entry section
            critical section
        exit section
            remainder section
} while (TRUE);
```

Figure 6.1 General structure of a typical process P_i.

Solution to Critical-Section Problem

1. **Mutual Exclusion** - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely
3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted
   - Assume that each process executes at a nonzero speed
   - No assumption concerning **relative speed** of the n

Peterson's Solution

Two process solution

Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted

The two processes share two variables:

int **turn**;

Boolean **flag[2]**

The variable **turn** indicates whose turn it is to enter the critical section

The **flag** array is used to indicate if a process is ready to enter the critical section. **flag[i]** = true implies that process P_i is ready!

Algorithm for Process P_i

```
do {
        flag[i] = TRUE;
        turn = j;
        while (flag[j] && turn == j);
                critical section
        flag[i] = FALSE;
                remainder section
   } while (TRUE);
```

Provable that

1. Mutual exclusion is preserved
2. Progress requirement is satisfied
3. Bounded-waiting requirement is met

Synchronization Hardware

Many systems provide hardware support for critical section code

Uniprocessors – could disable interrupts
- Currently running code would execute without preemption
- Generally too inefficient on multiprocessor systems
  - Operating systems using this not broadly scalable

Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptable
- Either test memory word and set value
- Or swap contents of two memory words

Solution to Critical-section Problem Using Locks

```
do {
        acquire lock
                critical section
        release lock
                remainder section
   } while (TRUE);
```

Test And Set Instruction

Definition:

```
boolean TestAndSet (boolean *target)
 {
      boolean rv = *target;
      *target = TRUE;
      return rv:
 }
```

Solution using TestAndSet

Shared boolean variable lock, initialized to FALSE
Solution:

```
do {
        while ( TestAndSet (&lock ))
                ;   // do nothing

              //    critical section

        lock = FALSE;

              //      remainder section

} while (TRUE);
```

Swap Instruction

Definition:

```
void Swap (boolean *a, boolean *b)
{
        boolean temp = *a;
        *a = *b;
        *b = temp:
}
```

Solution using Swap

- Shared Boolean variable lock initialized to FALSE; Each process has a local Boolean variable key

Solution:

```
do {
        key = TRUE;
        while ( key == TRUE)
                Swap (&lock, &key );

                  //    critical section

         lock = FALSE;

                  //      remainder section

} while (TRUE);
```

Bounded-waiting Mutual Exclusion with TestandSet()

```
do {
        waiting[i] = TRUE;
        key = TRUE;

        while (waiting[i] && key)
                key = TestAndSet(&lock);
        waiting[i] = FALSE;
                // critical section
        j = (i + 1) % n;
        while ((j != i) && !waiting[j])
                j = (j + 1) % n;
        if (j == i)
                lock = FALSE;
        else
                waiting[j] = FALSE;
                // remainder section
} while (TRUE);
```

Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore *S* – integer variable
- Two standard operations modify S: wait() and signal()
  - Originally called P() and V()
- Less complicated
- Can only be accessed via two indivisible (atomic) operations

```
wait (S) {
        while S <= 0
           ; // no-op
          S--;
    }
signal (S) {
      S++;
   }
```

Semaphore as General Synchronization Tool

- **Counting** semaphore – integer value can range over an unrestricted domain
- **Binary** semaphore – integer value can range only between 0 and 1; can be simpler to implement
  - Also known as **mutex locks**
- Can implement a counting semaphore S as a binary semaphore
- Provides mutual exclusion

```
Semaphore mutex;    //  initialized to 1
do {
    wait (mutex);
       // Critical Section
    signal (mutex);
         // remainder section
} while (TRUE);
```

Semaphore Implementation

- Must guarantee that no two processes can execute wait () and signal () on the same semaphore at the same time
- Thus, implementation becomes the critical section problem where the wait and signal code are placed in the crtical section
  - Could now have busy waiting in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

Semaphore Implementation with no Busy waiting

With each semaphore there is an associated waiting queue

Each entry in a waiting queue has two data items:

- value (of type integer)
- pointer to next record in the list

Two operations:

- **block** – place the process invoking the operation on the appropriate waiting queue
- **wakeup** – remove one of processes in the waiting queue and place it in the ready queue

Semaphore Implementation with no Busy waiting(Cont.)

Implementation of wait:

```
wait(semaphore *S) {
        S->value--;
        if (S->value < 0) {
                add this process to S->list;
                block();
        }
}
```

Implementation of signal:

```
signal(semaphore *S) {
        S->value++;
        if (S->value <= 0) {
                remove a process P from S->list;
                wakeup(P);
        }
}
```

Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let S and Q be two semaphores initialized to 1

P_0	P_1
wait (S);	wait (Q);
wait (Q);	wait (S);
.	.
.	.
.	.
signal (S);	signal (Q);
signal (Q);	signal (S);

- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**

Classical Problems of Synchronization

Classical problems used to test newly-proposed synchronization schemes

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded-Buffer Problem

N buffers, each can hold one item

Semaphore mutex initialized to the value 1

Semaphore full initialized to the value 0

Semaphore empty initialized to the value N

Bounded Buffer Problem (Cont.)

The structure of the producer process

```
do  {

        //   produce an item in nextp

    wait (empty);
    wait (mutex);

        //  add the item to the  buffer

     signal (mutex);
     signal (full);
 } while (TRUE);
```

Bounded Buffer Problem (Cont.)

The structure of the consumer process

```
do {
    wait (full);
    wait (mutex);

        //  remove an item from  buffer to nextc

    signal (mutex);
    signal (empty);

        //  consume the item in nextc

} while (TRUE);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do **not** perform any updates
  - Writers – can both read and write
- Problem – allow multiple readers to read at the same time. Only one single writer can access the shared data at the same time
- Several variations of how readers and writers are treated – all involve priorities
- Shared Data
  - Data set
  - Semaphore mutex initialized to 1
  - Semaphore wrt initialized to 1
  - Integer readcount initialized to 0

Readers-Writers Problem (Cont.)

The structure of a writer process

```
do {
        wait (wrt) ;

            //    writing is performed

        signal (wrt) ;
} while (TRUE);
```

Readers-Writers Problem (Cont.)

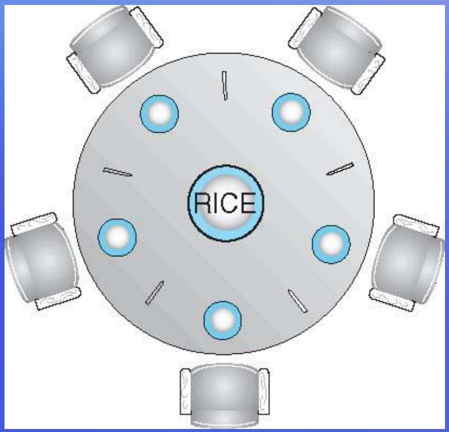
The structure of a reader process

```
do {
        wait (mutex) ;
        readcount ++ ;
        if (readcount == 1)
                wait (wrt) ;
        signal (mutex)

            // reading is performed

        wait (mutex) ;
        readcount  - - ;
        if (readcount  == 0)
                signal (wrt) ;
        signal (mutex) ;
    } while (TRUE);
```

Readers-Writers Problem Variations

- *First* variation – no reader kept waiting unless writer has permission to use shared object
- *Second* variation – once writer is ready, it performs write asap
- Both may have starvation leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem



- Philosophers spend their lives thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers
  - Shared data
    - Bowl of rice (data set)
    - Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem Algorithm

The structure of Philosopher *i*:

```
do  {
        wait ( chopstick[i] );
        wait ( chopStick[ (i + 1) % 5] );

            //  eat

        signal ( chopstick[i] );
        signal (chopstick[ (i + 1) % 5] );

            //  think

} while (TRUE);
```

What is the problem with this algorithm?

Problems with Semaphores

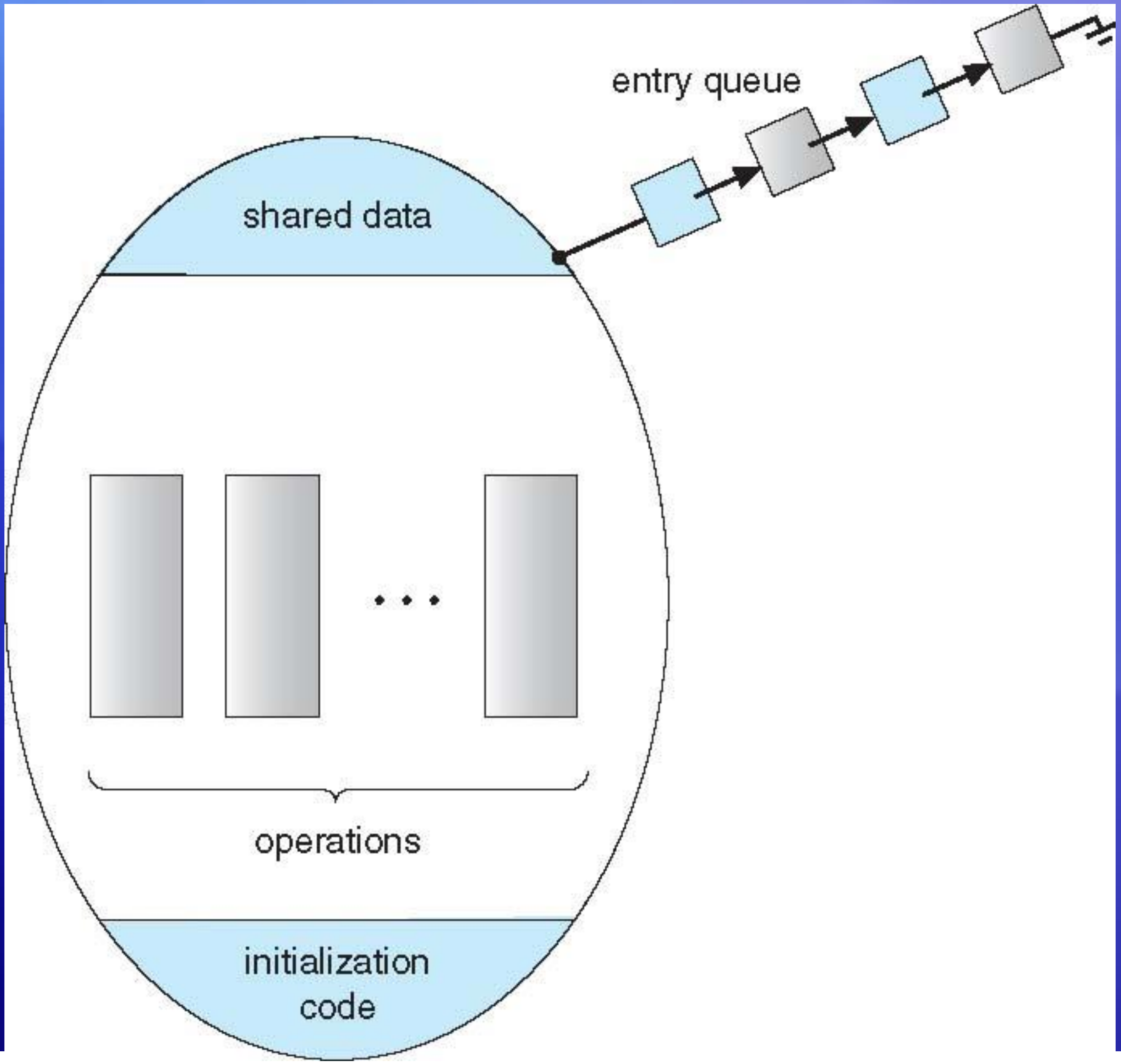
- Incorrect use of semaphore operations:
  - signal (mutex) …. wait (mutex)
  - wait (mutex) … wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)
- Deadlock and starvation

Monitors

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- *Abstract data type*, internal variables only accessible by code within the procedure
- Only one process may be active within the monitor at a time
- But not powerful enough to model some synchronization schemes

```
monitor monitor-name
{
        // shared variable declarations
        procedure P1 (…) { …. }

        procedure Pn (…) {……}

    Initialization code (…) { … }

}
```

Schematic view of a Monitor

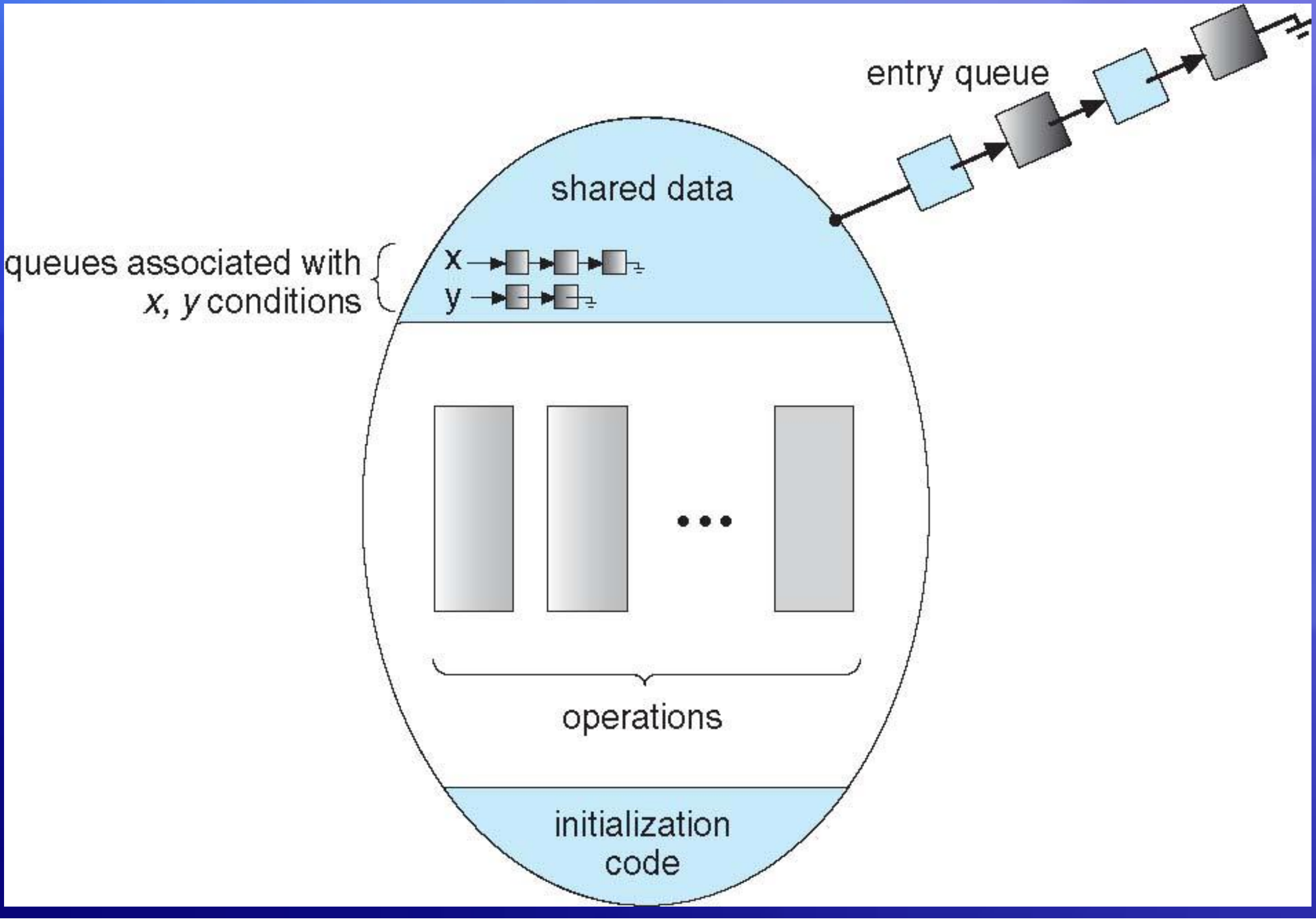


Condition Variables

- condition x, y;

- Two operations on a condition variable:
    - x.wait () – a process that invokes the operation is suspended until x.signal ()
    - x.signal () – resumes one of processes (if any) that invoked x.wait ()
        - If no x.wait () on the variable, then it has no effect on the variable

Monitor with Condition Variables



Condition Variables Choices

- If process P invokes x.signal (), with Q in x.wait () state, what should happen next?
  - If Q is resumed, then P must wait
- Options include
  - **Signal and wait** – P waits until Q leaves monitor or waits for another condition
  - **Signal and continue** – Q waits until P leaves the monitor or waits for another condition
  - Both have pros and cons – language implementer can decide
  - Monitors implemented in Concurrent Pascal compromise
    - P executing signal immediately leaves the monitor, Q is resumed
  - Implemented in other languages including Mesa, C#, Java

Solution to Dining Philosophers

```
monitor DiningPhilosophers
  {
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5];

    void pickup (int i) {
           state[i] = HUNGRY;
           test(i);
           if (state[i] != EATING) self [i].wait;
    }

     void putdown (int i) {
           state[i] = THINKING;
                  // test left and right neighbors
            test((i + 4) % 5);
            test((i + 1) % 5);
      }
```

Solution to Dining Philosophers (Cont.)

```
void test (int i) {
        if ( (state[(i + 4) % 5] != EATING) &&
        (state[i] == HUNGRY) &&
        (state[(i + 1) % 5] != EATING) ) {
             state[i] = EATING ;
             self[i].signal () ;
         }
 }

 initialization_code() {
       for (int i = 0; i < 5; i++)
       state[i] = THINKING;
}
}
```

Solution to Dining Philosophers (Cont.)

Each philosopher *i* invokes the operations pickup() and putdown() in the following sequence:

DiningPhilosophers.pickup (i);

EAT

DiningPhilosophers.putdown (i);

No deadlock, but starvation is possible

Monitor Implementation Using Semaphores

Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next_count = 0;
```

Each procedure ***F*** will be replaced by

```
wait(mutex);
    …
        body of F;

    …
if (next_count > 0)
    signal(next)
else
    signal(mutex);
```

Mutual exclusion within a monitor is ensured

Monitor Implementation – Condition Variables

For each condition variable ***x***, we have:

```
semaphore x_sem; // (initially  = 0)
int x_count = 0;
```

The operation x.wait can be implemented as:

```
x-count++;
if (next_count > 0)
        signal(next);
else
        signal(mutex);
wait(x_sem);
x-count--;
```

Monitor Implementation (Cont.)

The operation x.signal can be implemented as:

```
if (x-count > 0) {
    next_count++;
    signal(x_sem);
    wait(next);
    next_count--;
}
```

Resuming Processes within a Monitor

If several processes queued on condition x, and x.signal() executed, which should be resumed?

FCFS frequently not adequate

conditional-wait construct of the form x.wait(c)

- Where c is **priority number**
- Process with lowest number (highest priority) is scheduled next

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
      boolean busy;
      condition x;
      void acquire(int time) {
                  if (busy)
                        x.wait(time);
                  busy = TRUE;
      }
      void release() {
                  busy = FALSE;
                  x.signal();
      }
initialization code() {
       busy = FALSE;
      }
}
```

Synchronization Examples

Solaris

Windows XP

Linux

Pthreads

Solaris Synchronization

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses **adaptive mutexes** for efficiency when protecting data from short code segments
  - Starts as a standard semaphore spin-lock
  - If lock held, and by a thread running on another CPU, spins
  - If lock held by non-run-state thread, block and sleep waiting for signal of lock being released
- Uses **condition variables**
- Uses **readers-writers** locks when longer sections of code need access to data
- Uses **turnstiles** to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock
  - Turnstiles are per-lock-holding-thread, not per-object
- Priority-inheritance per-turnstile gives the running thread the highest of the priorities of the threads in its turnstile

Windows XP Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems
- Uses **spinlocks** on multiprocessor systems
  - Spinlocking-thread will never be preempted
- Also provides **dispatcher objects** user-land which may act mutexes, semaphores, events, and timers
  - **Events**
    - An event acts much like a condition variable
  - Timers notify one or more thread when time expired
  - Dispatcher objects either **signaled-state** (object available) or **non-signaled state** (thread will block)

Linux Synchronization

- Linux:
  - Prior to kernel Version 2.6, disables interrupts to implement short critical sections
  - Version 2.6 and later, fully preemptive
- Linux provides:
  - semaphores
  - spinlocks
  - reader-writer versions of both
- On single-cpu system, spinlocks replaced by enabling and disabling kernel preemption

Pthreads Synchronization

Pthreads API is OS-independent

It provides:

- mutex locks
- condition variables

Non-portable extensions include:

- read-write locks
- spinlocks

Reference Book

“Operating System Concepts” by Silberchartz, Galvin, Gagne, Wiley India Publications.