Operating System Concepts

Che-Wei Chang

chewei@mail.cgu.edu.tw

Department of Computer Science and Information Engineering, Chang Gung University

Contents

Chapter 6. Synchronization

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 examine several classical process-synchronization problems
- To explore several tools that are used to solve process synchronization problems

A Consumer-Producer Example

- Producer

```
while (1) {
    while (counter == BUFFER_SIZE)
        ;
    produce an item in nextp;
    buffer[in] = nextp;
    in = (in+1) % BUFFER_SIZE;
    counter++;
}
```

- Consumer:

```
while (1) {
    while (counter == 0)
        ;
    nextc = buffer[out];
    out = (out +1) % BUFFER_SIZE;
    counter--;
    consume an item in nextc;
}
```

Race Condition

- One counter++ and one counter--

```
r1 = counter              r2 = counter
r1 = r1 + 1               r2 = r2 - 1
counter = r1              counter = r2
```

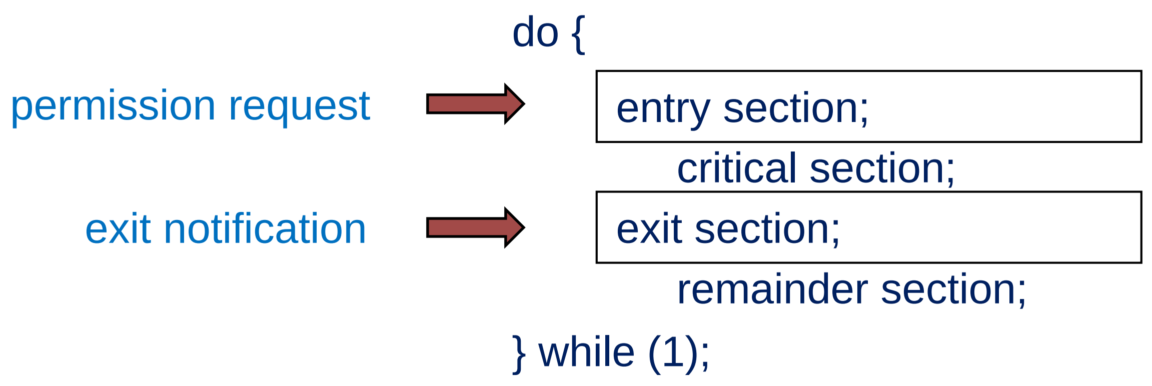
- Initially, let counter = 5

1. P: r1 = counter
2. P: r1 = r1 + 1
3. C: r2 = counter
4. C: r2 = r2 – 1 $\Rightarrow$ A Race Condition!
5. P: counter = r1
6. C: counter = r2 = 4

- The result can be 4, 5 or 6

Process Synchronization

- A Race Condition:
  - A situation where the outcome of the execution depends on the particular order of process scheduling
- The Critical-Section Problem:
  - Design a protocol that processes can use to cooperate
    - Each process has a segment of code, called a critical section, whose execution must be mutually exclusive
    - A general structure for the critical-section design



```
do {
        entry section;
            critical section;
        exit section;
            remainder section;
} while (1);
```

Solution of the Critical Section Problem

- Three Requirements
  - Mutual Exclusion:

    Only one process can be in its critical section
  - 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
  - Bounded Waiting:

    A waiting process only waits for a bounded number of processes to enter its critical section

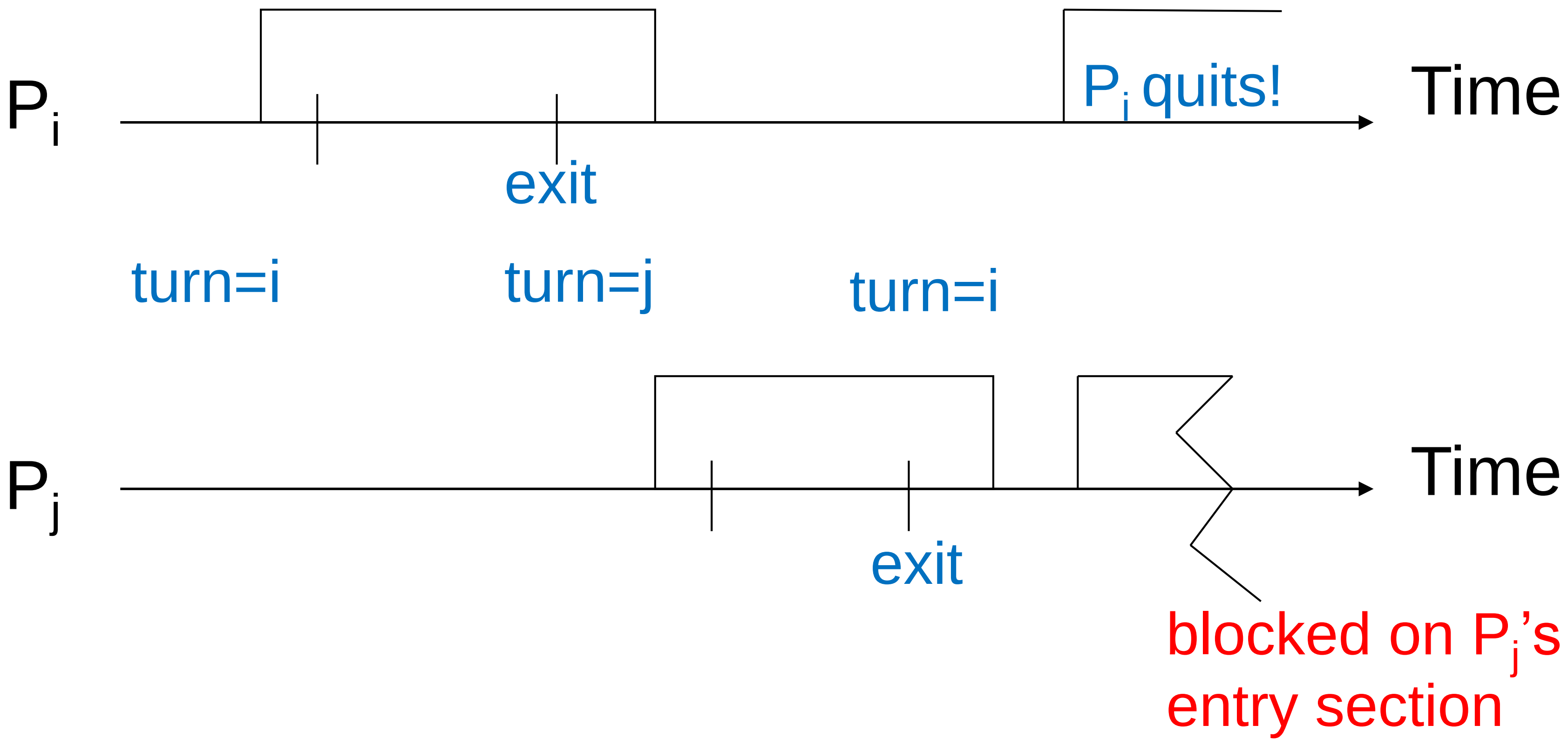
Peterson's Solution (1/5)

- Notation
  - Processes P_i and P_j
- Assumption
  - Every basic machine-language instruction is atomic
- Algorithm 1
  - Idea: Remember which process is allowed to enter its critical section. That is, P_i can enter its critical section if turn = i

```
do {
    while (turn != i) ;
    critical section
    turn=j;
    remainder section
}  while (1);
```

Peterson's Solution (2/5)

- Algorithm 1 fails the progress requirement:



Peterson's Solution (3/5)

- Algorithm 2
  - Idea: Remember the state of each process
  - flag[i]==true → P_i is ready to enter its critical section
  - Algorithm 2 fails the progress requirement when flag[i] == flag[j] == true

Initially, flag[i]=flag[j]=false

```
do {
    flag[i]=true;
    while (flag[j]) ;
    critical section
    flag[i]=false;
    remainder section
}  while (1);
```

Peterson's Solution (4/5)

- Algorithm 3
  - Idea: Combine the ideas of Algorithms 1 and 2
  - When (flag[i] && turn=i), P_j must wait
  - Initially, flag[i]=flag[j]=false, and turn = i or j

```
do {
    flag[i]=true;
    turn=j;
    while (flag[j] && turn==j) ;
    critical section
    flag[i]=false;
    remainder section
} while (1);
```

Peterson’s Solution (5/5)

- Properties of Algorithm 3
  - Mutual Exclusion
    - The eventual value of *turn* determines which process enters the critical section
  - Progress
    - A process can only be stuck in the while loop, and the process which can keep it waiting must be in its critical sections
  - Bounded Waiting
    - Each process wait at most one entry by the other process

Peterson’s Solution (4/5)

Process P_i 的程式碼:

```
do {
    flag[i]=true;
    turn=j;
    while (flag[j] && turn==j) ;
    critical section
    flag[i]=false;
    remainder section
}  while (1);
```

Process P_j 的程式碼:

```
do {
    flag[j]=true;
    turn=i;
    while (flag[i] && turn==i) ;
    critical section
    flag[j]=false;
    remainder section
}  while (1);
```

Brainstorming!

- Could we move turn=i; and turn=j; as follows:

Process P_i:

```
do {
    flag[i]=true;
    while (flag[j] && turn==j) ;
    critical section
    turn=j;
    flag[i]=false;
    remainder section
} while (1);
```

Process P_j:

```
do {
    flag[j]=true;
    while (flag[i] && turn==i) ;
    critical section
    turn=i;
    flag[j]=false;
    remainder section
} while (1);
```

答案是不行，卷哥Peterson應該也有想過這個問題。

- 不行的原因如下，如果照以下方式執行，Mutual Exclusion的條件會被違反：
  - 不失一般性，我們假設turn的初始值是i
  - P_j第一次開始執行時P_i尚未被執行過
    - 由於此時P_i還沒執行所以flag[i] 應為false
    - 所以P_j可以順利進入critical section
  - 在P_j進入critical section的這段期間內P_i也接著開始執行
    - 由於turn的初始值是i
    - 所以P_i也可以順利進入critical section
  - 這時候P_j和P_i同時在critical section裡 ➔違反Mutual Exclusion
  - 可是Peterson’s Solution提出的做法(第一頁)不會有這個問題，大家可以自己想想

Synchronization Hardware

- Motivation:
  - Hardware features make programming easier and improve system efficiency
- Approach:
  - Disable Interrupt → No Preemption
    - Infeasible in multiprocessor environments
    - Potential impacts on interrupt-driven system clocks
  - Atomic Hardware Instructions
    - Test-and-set, Swap, etc.

Test and Set

Meaning

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

Usage

```
do {
    while (TestAndSet(&lock)) ;
      critical section
    lock=false;
      remainder section
} while (1);
```

Swap

Meaning

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

Usage

```
do {
    key=true;
    while (key == true)
        Swap(&lock, &key);
      critical section
     lock=false;
      remainder section
} while (1);
```

Case Study of Test and Set

- Problem
  - n tasks want to access some share data
- Mutual Exclusion
  - Pass if key== F or waiting[i]== F
- Progress
  - Exit process sends a process in
- Bounded Waiting
  - Wait at most n-1 times

```
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 (1);
```

Mutex Locks (1/2)

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Product critical regions with it by first **`acquire()`** a lock then **`release()`** it
  - Boolean variable indicating if lock is available or not
- Calls to **`acquire()`** and **`release()`** must be atomic
  - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

Mutex Locks (2/2)

Meaning

```
acquire() {
   while (!available)
      ; /* busy wait */
   available = false;
}
release() {
   available = true;
}
```

Usage

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

Semaphores (1/3)

- Motivation:
  - A high-level solution for more complex problems
- Semaphore
  - A variable S only accessible by two atomic operations:

```
wait(S) {        /* P */
      while (S <= 0) ;
      S--;
}
```

```
signal(S) {     /* V */
      S++;
}
```

Semaphores (2/3)

- Critical Sections

```
do {
        wait(S);
        critical section
        signal(S);
        remainder section
 } while (1);
```

- Precedence Enforcement

```
P1:
    S1;
    signal(S);

P2:
    wait(S);
    S2;
```

Semaphores (3/3)

- Implementation
  - Spinlock: A Busy-Waiting Semaphore
    - "while (S <= 0)" causes the wasting of CPU cycles!
    - Advantage:
      - When locks are held for a short time, spinlocks are useful since no context switching is involved.
  - Semaphores with Blocked-Waiting
    - No busy waiting from the entry to the critical section!

Semaphores with Block Waiting

```
typedef struct{
   int value;
   struct process *list;
} semaphore;
```

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

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

Deadlocks and Starvation

- Deadlock
  - A set of processes is in a deadlock state when every process in the set is waiting for an event that can be caused only by another process in the set

```
P0:  wait(S);          P1: wait(Q);
     wait(Q);              wait(S);
       …                     …
     signal(S);            signal(Q);
     signal(Q);            signal(S);
```

- Starvation (or Indefinite Blocking)
  - e.g., a LIFO (last-in, first-out) queue

Classical Problems of Synchronization

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

Bounded-Buffer Problem (1/2)

empty is initialized to *n*

mutex is initialized to *1*

full is initialized to *0*

<u>Producer:</u>

```
do {
        produce an item in nextp;
        …….
        wait(empty);  /* control buffer availability */
        wait(mutex);  /* mutual exclusion */
        ……
        add nextp to buffer;
        signal(mutex);
        signal(full);  /* increase item counts */
} while (1);
```

Bounded-Buffer Problem (2/2)

Consumer:

```
do {
        wait(full);  /* control buffer availability */
        wait(mutex);  /* mutual exclusion */
        …….
        remove an item from buffer to nextp;
        ……
        signal(mutex);
        signal(empty);  /* increase item counts */
        consume nextp;
} while (1);
```

Readers and Writers Problem (1/2)

- 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

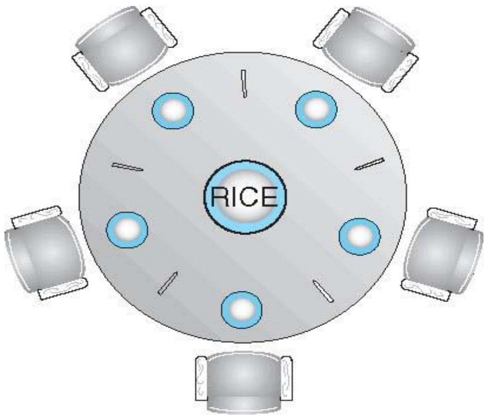
Readers and Writers Problem (2/2)

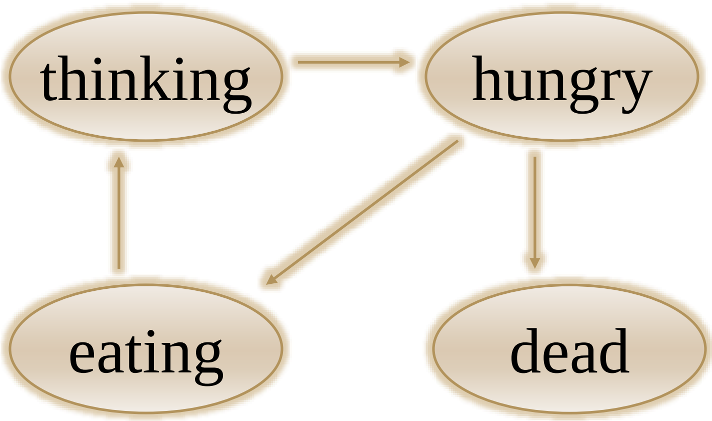
```
semaphore wrt, mutex;
  (initialized to 1);
int readcount=0;

Writer:
    wait(wrt);
    ……
    writing is performed
    ……
    signal(wrt)
```

```
Reader:
wait(mutex);
readcount++;
if (readcount == 1)
        wait(wrt);
signal(mutex);
… reading…
wait(mutex);
readcount--;
if (readcount== 0)
        signal(wrt);
signal(mutex);
```

Dining-Philosopher Problem (1/3)

- Each philosopher must pick up one chopstick beside him/her at a time
- When two chopsticks are picked up, the philosopher can eat



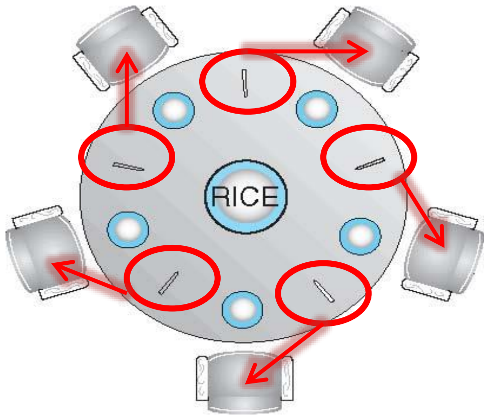


Dining-Philosophers Problem (2/3)

```
semaphore chopstick[5];
do {
        wait(chopstick[i]);
        wait(chopstick[(i + 1) % 5 ]);
        … eat …
        signal(chopstick[i]);
        signal(chopstick[(i+1) % 5]);
        …think …
} while (1);
```

Dining-Philosophers Problem (3/3)

- This algorithm could create a deadlock
- Several possible remedies to the deadlock problem:
  - Allow at most four philosopher
  - Allow a philosopher to pick up chopsticks only if both are available
  - Asymmetric solution



Problems with Semaphores

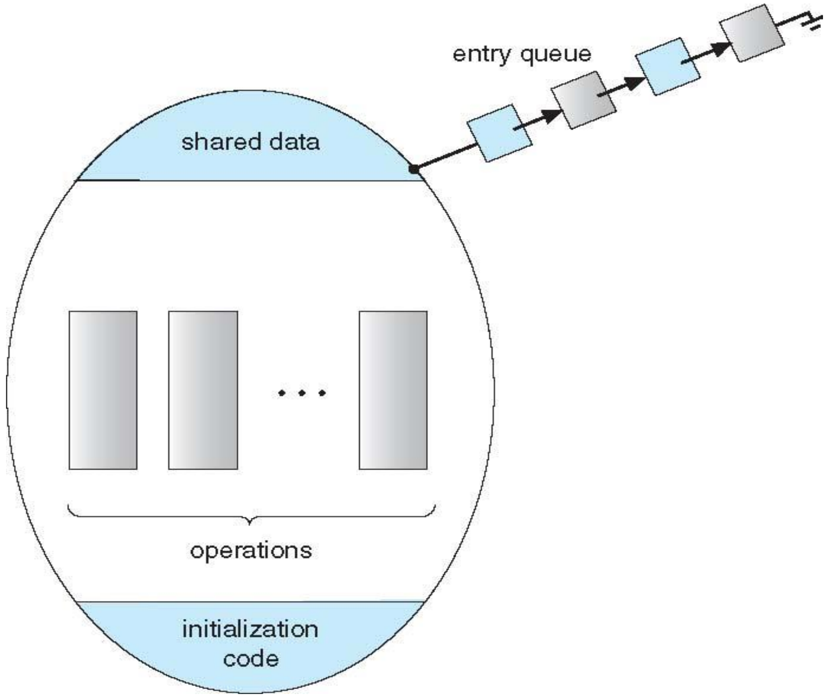
- Incorrect use of semaphore operations:
  - signal (mutex) …. wait (mutex)
  - wait (mutex) … wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)
- Deadlock and starvation

➔A high-level abstraction that provides a convenient and effective mechanism for process synchronization

Monitor (1/2)

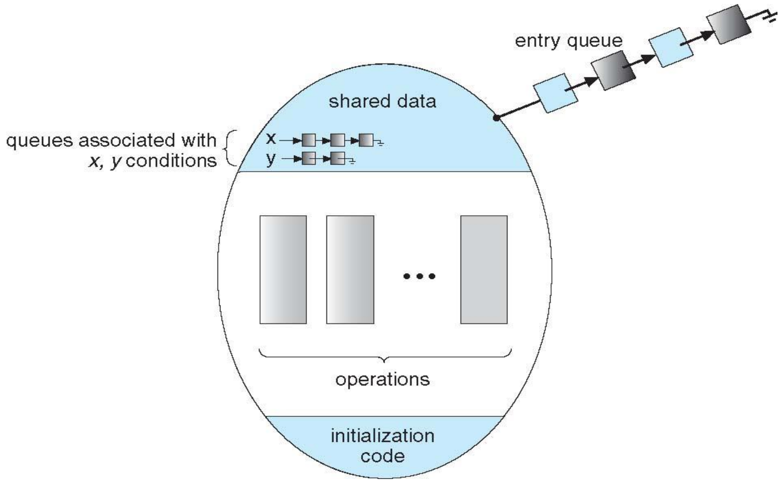
- Components
  - Variables
    - Monitor states
  - Procedures
    - Only access local variables or formal parameters

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



Monitor (2/2)

- Condition Variables
  - 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



Solution to Dining Philosophers (1/2)

```
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);
      }

        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 (2/2)

- 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

- Semaphores
  - *mutex* – to protect the monitor
  - *next* – being initialized to zero, on which processes may suspend themselves
    - *next-count*
- For each external function *F*

```
wait(mutex);
…
body of F;
…
if (next-count > 0)
    signal(next);
else signal(mutex);
```

Monitor Implementation Using Condition Variables

- For every condition *x*
  - A semaphore *x-sem*
  - An integer variable *x-count*
  - Implementation of x.wait() and x.signal :

- x.wait()

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

- x.signal()

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

* x.wait() and x.signal() are invoked within a monitor

Resuming Processes within a monitor

- How do we determine which of the suspended processes should be resumed next ?
  - FCFS ordering
  - Conditional-wait construct x.wait(c);
  - Monitor-scheduling algorithm
    - Built-in

      or
    - User define