

*Operating  
Systems:  
Internals  
and Design  
Principles*

# Chapter 5

# Concurrency:

# Mutual Exclusion

# and Synchronization

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# Multiple Processes

- Operating System design is concerned with the management of processes and threads:
  - Multiprogramming
  - Multiprocessing
  - Distributed Processing



# Concurrency

## Arises in Three Different Contexts:

### Multiple Applications

invented to allow processing time to be shared among active applications

### Structured Applications

extension of modular design and structured programming

### Operating System Structure

OS themselves implemented as a set of processes or threads

# Concurrency

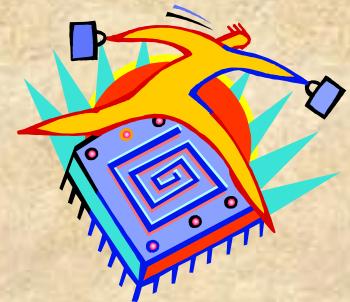
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<b>atomic operation</b>	A function or action implemented as a sequence of one or more instructions that appears to be indivisible; that is, no other process can see an intermediate state or interrupt the operation. The sequence of instruction is guaranteed to execute as a group, or not execute at all, having no visible effect on system state. Atomicity guarantees isolation from concurrent processes.
<b>critical section</b>	A section of code within a process that requires access to shared resources and that must not be executed while another process is in a corresponding section of code.
<b>deadlock</b>	A situation in which two or more processes are unable to proceed because each is waiting for one of the others to do something.
<b>livelock</b>	A situation in which two or more processes continuously change their states in response to changes in the other process(es) without doing any useful work.
<b>mutual exclusion</b>	The requirement that when one process is in a critical section that accesses shared resources, no other process may be in a critical section that accesses any of those shared resources.
<b>race condition</b>	A situation in which multiple threads or processes read and write a shared data item and the final result depends on the relative timing of their execution.
<b>starvation</b>	A situation in which a runnable process is overlooked indefinitely by the scheduler; although it is able to proceed, it is never chosen.

Table 5.1 Some Key Terms Related to Concurrency

# Principles of Concurrency

- Interleaving and overlapping
  - can be viewed as examples of concurrent processing
  - both present the same problems
- Uniprocessor – the relative speed of execution of processes cannot be predicted
  - depends on activities of other processes
  - the way the OS handles interrupts
  - scheduling policies of the OS



# Difficulties of Concurrency

- Sharing of global resources
- Difficult for the OS to manage the allocation of resources optimally
- Difficult to locate programming errors as results are not deterministic and reproducible



# Race Condition

- Occurs when multiple processes or threads read and write data items
- The final result depends on the order of execution
  - the “loser” of the race is the process that updates last and will determine the final value of the variable



# Operating System Concerns

- Design and management issues raised by the existence of concurrency:
- The OS must:
  - be able to keep track of various processes
  - allocate and de-allocate resources for each active process
  - protect the data and physical resources of each process against interference by other processes
  - ensure that the processes and outputs are independent of the processing speed



# Resource Competition

- Concurrent processes come into conflict when they are competing for use of the same resource
  - for example: I/O devices, memory, processor time, clock

In the case of competing processes three control problems must be faced:

- the need for mutual exclusion
- deadlock
- starvation



# Requirements for Mutual Exclusion

- Must be enforced
- A process that halts must do so without interfering with other processes
- No deadlock or starvation
- A process must not be denied access to a critical section when there is no other process using it
- No assumptions are made about relative process speeds or number of processes
- A process remains inside its critical section for a finite time only



# Mutual Exclusion: Hardware Support

- **Interrupt Disabling**

- uniprocessor system
- disabling interrupts guarantees mutual exclusion



- **Disadvantages:**

- the efficiency of execution could be noticeably degraded
- this approach will not work in a multiprocessor architecture



# Mutual Exclusion: Hardware Support

- Special Machine Instructions
- Compare&Swap Instruction
  - also called a “compare and exchange instruction”
  - a **compare** is made between a memory value and a test value
  - if the values are the same a **swap** occurs
  - carried out atomically



# Special Machine Instruction: Advantages

- ↑ Applicable to any number of processes on either a single processor or multiple processors sharing main memory
- ↑ Simple and easy to verify
- ↑ It can be used to support multiple critical sections; each critical section can be defined by its own variable



# Special Machine Instruction: Disadvantages

- Busy-waiting is employed, thus while a process is waiting for access to a critical section it continues to consume processor time
- Starvation is possible when a process leaves a critical section and more than one process is waiting
- Deadlock is possible



# Common Concurrency Mechanisms



<b>Semaphore</b>	An integer value used for signaling among processes. Only three operations may be performed on a semaphore, all of which are atomic: initialize, decrement, and increment. The decrement operation may result in the blocking of a process, and the increment operation may result in the unblocking of a process. Also known as a <b>counting semaphore</b> or a <b>general semaphore</b>
<b>Binary Semaphore</b>	A semaphore that takes on only the values 0 and 1.
<b>Mutex</b>	Similar to a binary semaphore. A key difference between the two is that the process that locks the mutex (sets the value to zero) must be the one to unlock it (sets the value to 1).
<b>Condition Variable</b>	A data type that is used to block a process or thread until a particular condition is true.
<b>Monitor</b>	A programming language construct that encapsulates variables, access procedures and initialization code within an abstract data type. The monitor's variable may only be accessed via its access procedures and only one process may be actively accessing the monitor at any one time. The access procedures are <i>critical sections</i> . A monitor may have a queue of processes that are waiting to access it.
<b>Event Flags</b>	A memory word used as a synchronization mechanism. Application code may associate a different event with each bit in a flag. A thread can wait for either a single event or a combination of events by checking one or multiple bits in the corresponding flag. The thread is blocked until all of the required bits are set (AND) or until at least one of the bits is set (OR).
<b>Mailboxes/Messages</b>	A means for two processes to exchange information and that may be used for synchronization.
<b>Spinlocks</b>	Mutual exclusion mechanism in which a process executes in an infinite loop waiting for the value of a lock variable to indicate availability.

# Semaphore

A variable that has an integer value upon which only three operations are defined:



There is no way to inspect or manipulate semaphores other than these three operations

- 1) May be initialized to a nonnegative integer value
- 2) The `semWait` operation decrements the value
- 3) The `semSignal` operation increments the value

# Consequences

Decrements a semaphore whether it will block or not

Uniprocessor system when two processes are running concurrently

Unblocked processes may be zero or one

# Strong/Weak Semaphores

- ☺ A queue is used to hold processes waiting on the semaphore

## *Strong Semaphores*

- the process that has been blocked the longest is released from the queue first (FIFO)

## *Weak Semaphores*

- the order in which processes are removed from the queue is not specified

# Example of Semaphore Mechanism

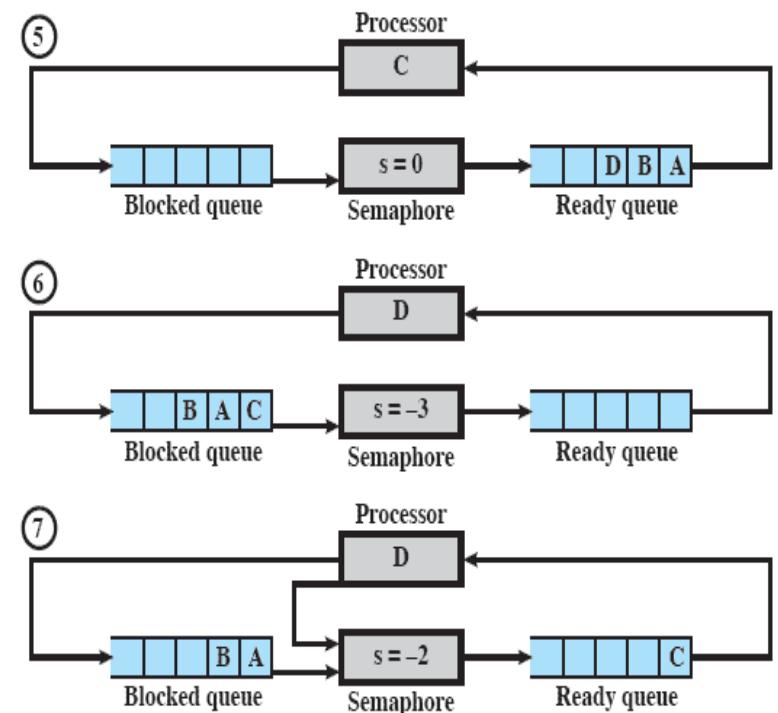
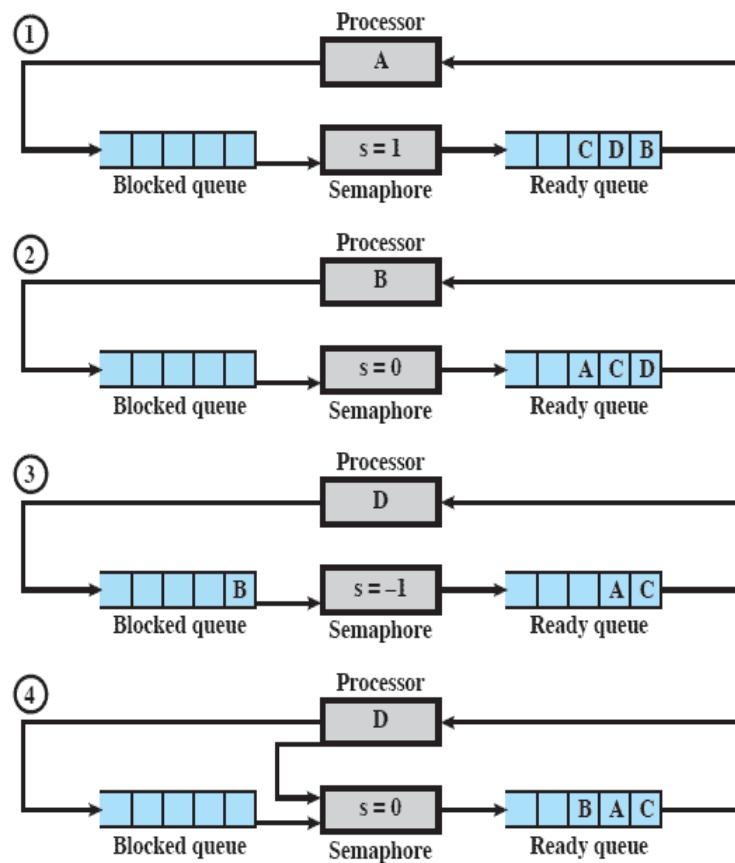


Figure 5.5 Example of Semaphore Mechanism

# Shared Data Protected by a Semaphore

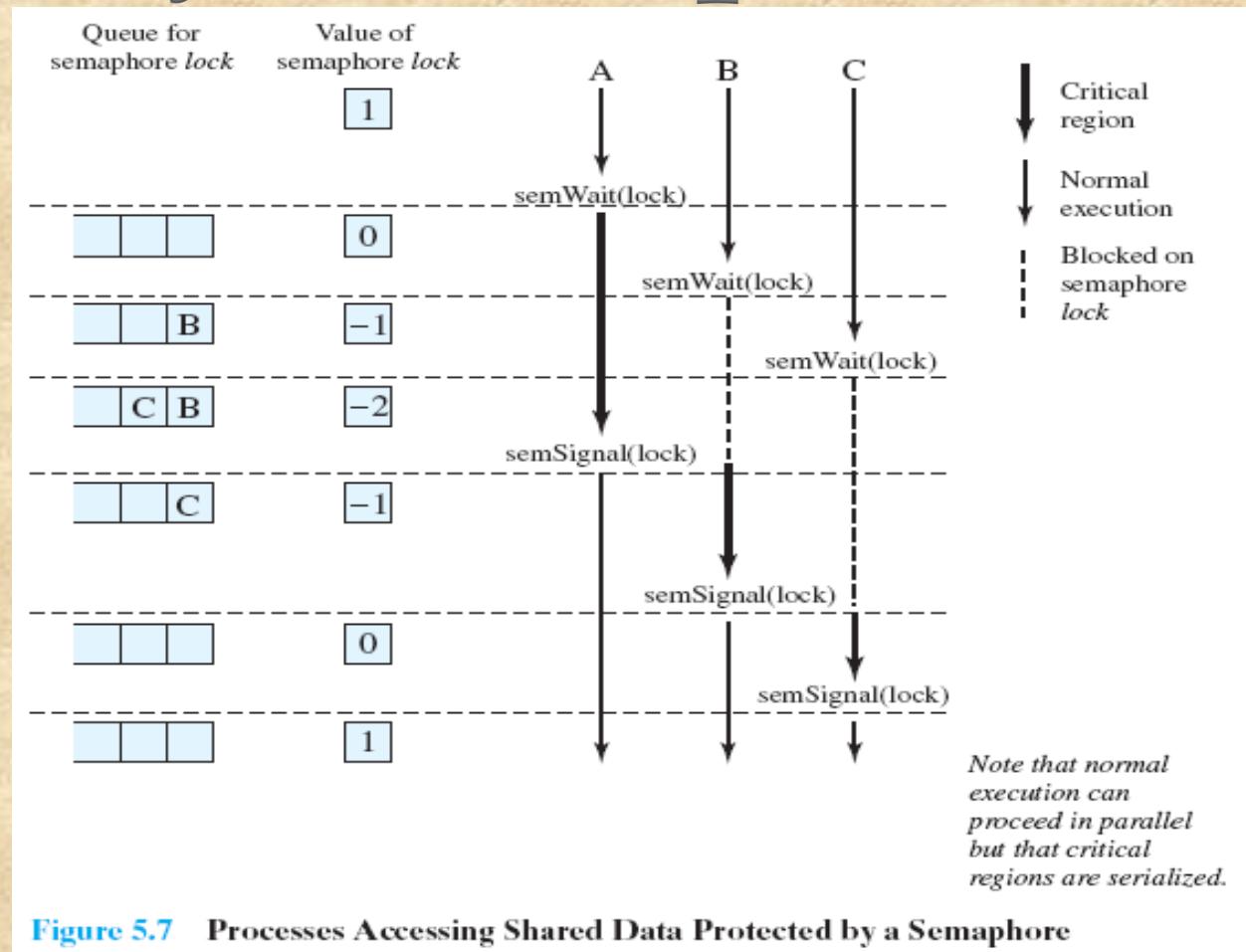


Figure 5.7 Processes Accessing Shared Data Protected by a Semaphore

# Producer/Consumer Problem

## General Situation:

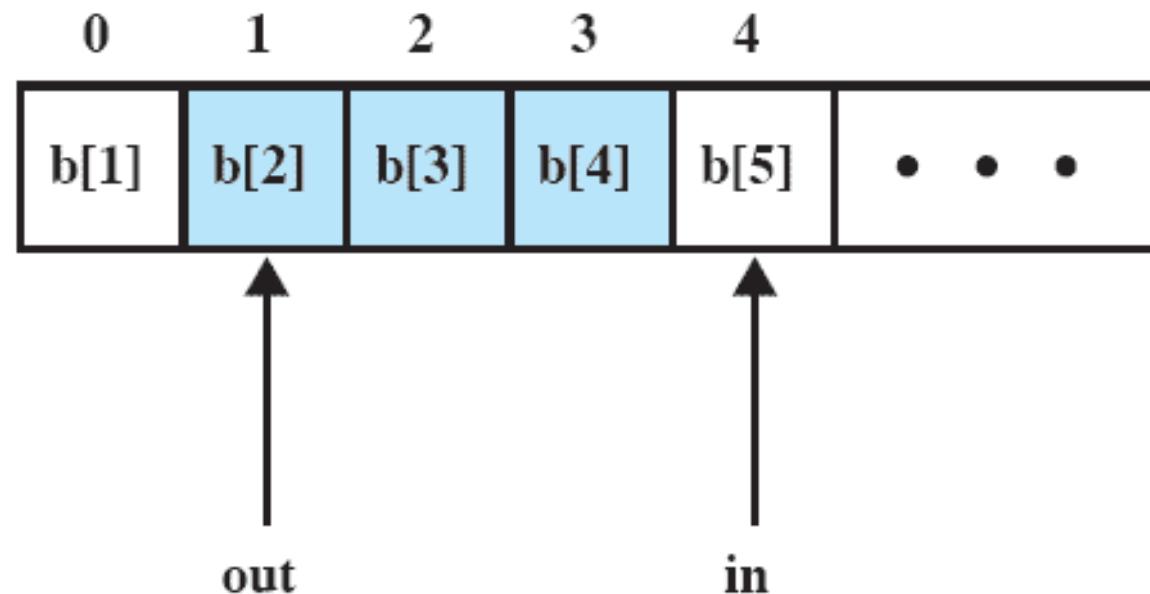
- one or more producers are generating data and placing these in a buffer
- a single consumer is taking items out of the buffer one at time
- only one producer or consumer may access the buffer at any one time



## The Problem:

- ensure that the producer can't add data into full buffer and consumer can't remove data from an empty buffer

# Buffer Structure

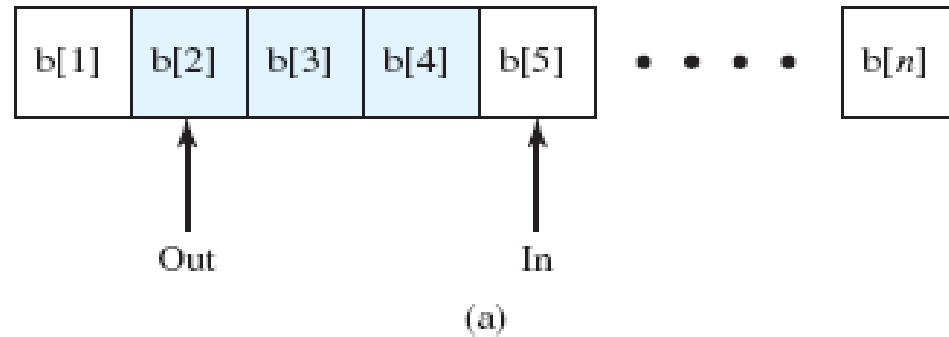


Note: shaded area indicates portion of buffer that is occupied

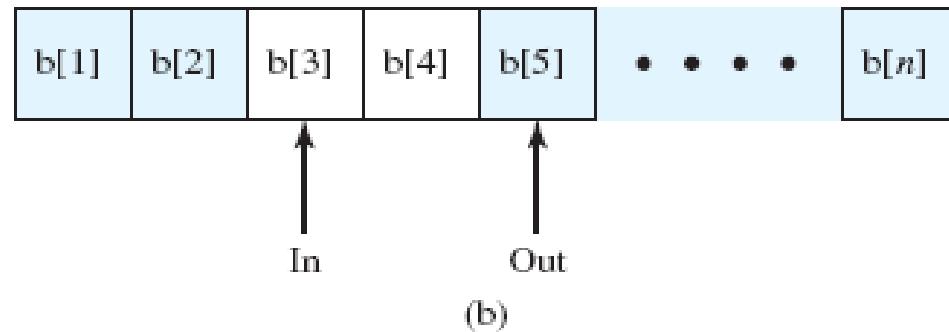
**Figure 5.8 Infinite Buffer for the Producer/Consumer Problem**

# Finite Circular Buffer

Block on:	Unblock on:
Producer: insert in full buffer	Consumer: item inserted
Consumer: remove from empty buffer	Producer: item removed



(a)

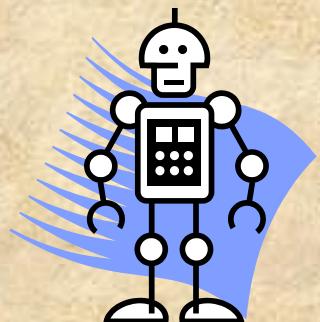


(b)

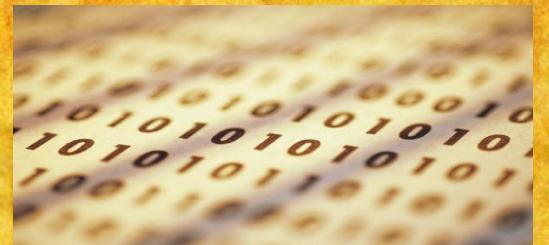
**Figure 5.12** Finite Circular Buffer for the Producer/Consumer Problem

# Implementation of Semaphores

- Imperative that the semWait and semSignal
- Can be implemented in hardware or firmware
- Software schemes such as Dekker's or Peterson's algorithms can be used
- Use one of the hardware-supported schemes for mutual exclusion



# Monitors

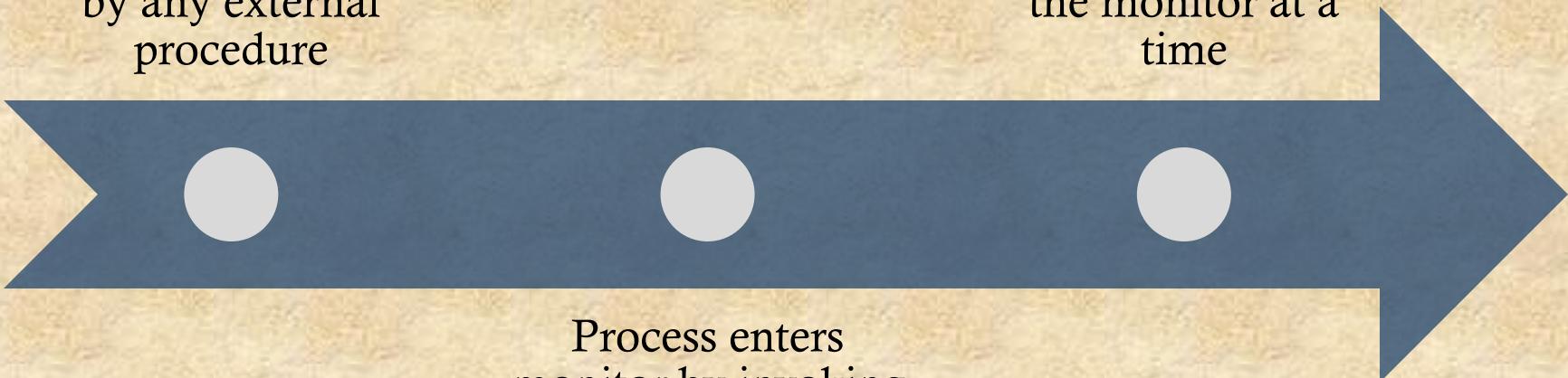


- Programming language construct that provides equivalent functionality to that of semaphores and is easier to control
- Implemented in a number of programming languages
  - including Concurrent Pascal, Pascal-Plus, Modula-2, Modula-3, and Java
- Has also been implemented as a program library
- Software module consisting of one or more procedures, an initialization sequence, and local data

# Monitor Characteristics

Local data variables  
are accessible only  
by the monitor's  
procedures and not  
by any external  
procedure

Only one process  
may be executing in  
the monitor at a  
time



Process enters  
monitor by invoking  
one of its  
procedures

# Synchronization

- Achieved by the use of **condition variables**
- Condition variables are operated on by two functions:
  - `cwait(c)`: suspend execution of the calling process on condition c
  - `csignal(c)`: resume execution of some process blocked after a `cwait` on the same condition



# Structure of a Monitor

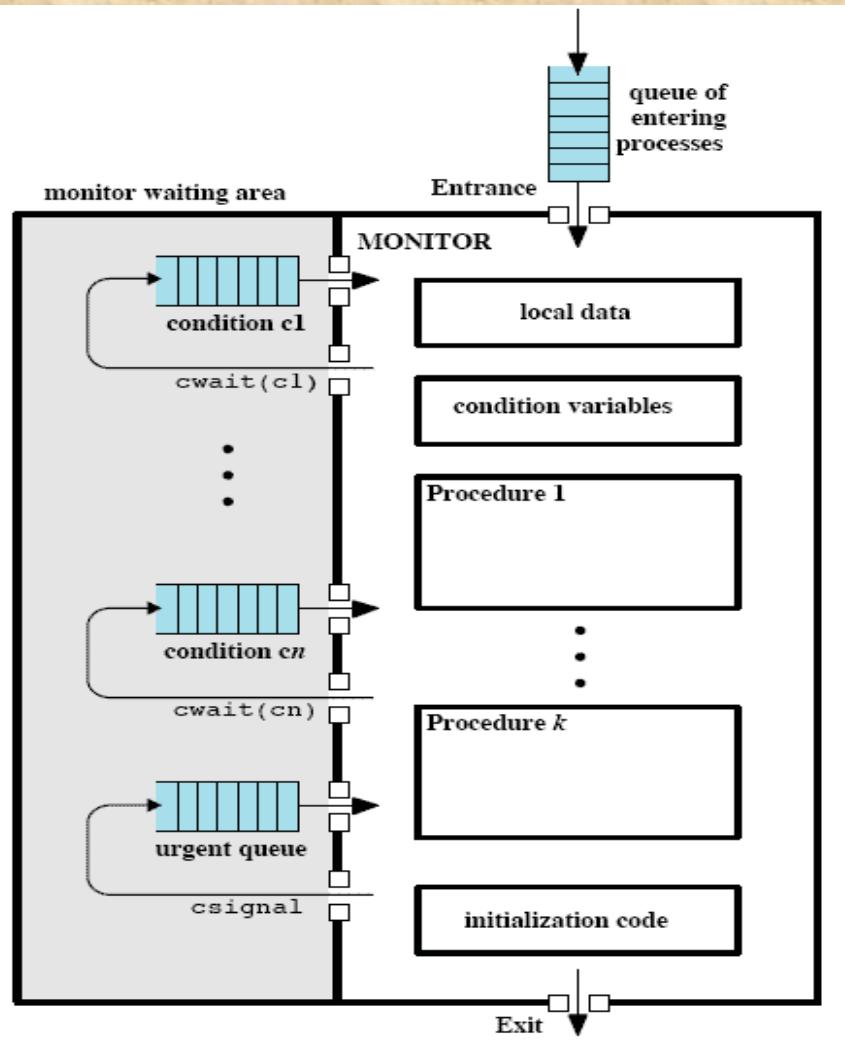
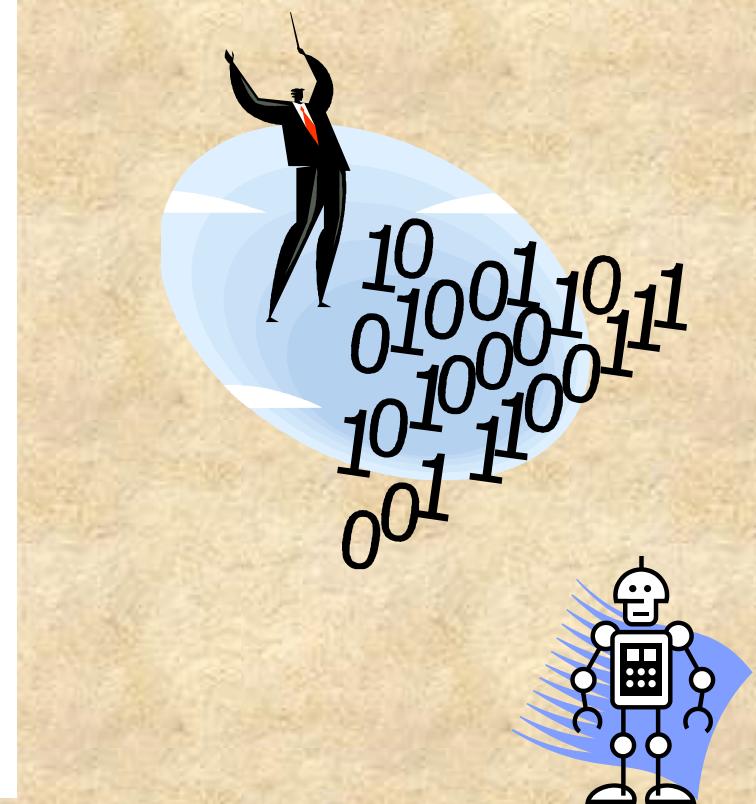


Figure 5.15 Structure of a Monitor





# Problem Solution Using a Monitor

```
/* program producerconsumer */
monitor boundedbuffer;
char buffer [N];
int nextin, nextout;
int count;
cond notfull, notempty;           /* condition variables for synchronization */

void append (char x)
{
    if (count == N) cwait(notfull);    /* buffer is full; avoid overflow */
    buffer[nextin] = x;
    nextin = (nextin + 1) % N;
    count++;
    /* one more item in buffer */
    csignal(notempty);               /* resume any waiting consumer */
}
void take (char x)
{
    if (count == 0) cwait(notempty);   /* buffer is empty; avoid underflow */
    x = buffer[nextout];
    nextout = (nextout + 1) % N;
    count--;
    /* one fewer item in buffer */
    csignal(notfull);               /* resume any waiting producer */
}
{                                /* monitor body */
    nextin = 0; nextout = 0; count = 0;      /* buffer initially empty */
}
```

```
void producer()
{
    char x;
    while (true) {
        produce(x);
        append(x);
    }
}

void consumer()
{
    char x;
    while (true) {
        take(x);
        consume(x);
    }
}

void main()
{
    parbegin (producer, consumer);
}
```

Figure 5.16 A Solution to the Bounded-Buffer Producer/Consumer Problem Using a Monitor

# Message Passing

- When processes interact with one another two fundamental requirements must be satisfied:

synchronization

communication

- to enforce mutual exclusion

- to exchange information

- Message Passing is one approach to providing both of these functions
  - works with distributed systems *and* shared memory multiprocessor and uniprocessor systems

# Message Passing



- The actual function is normally provided in the form of a pair of primitives:
  - send (destination, message)
  - receive (source, message)
- Sends information in the form of a *message* to another,
  - *Destination*
- Receives information by executing the receive primitive,

# Synchronization

Communication of a message between two processes implies synchronization between the two

the receiver cannot receive a message until it has been sent by another process

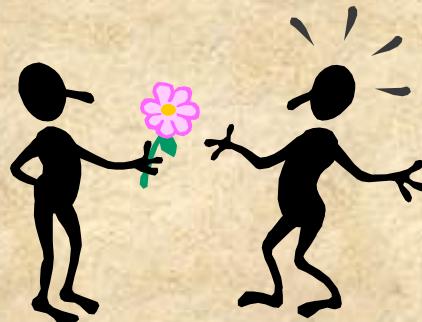
When a receive primitive is executed in a process there are two possibilities:

if there is no waiting message the process is blocked until a message arrives or the process continues to execute, abandoning the attempt to receive

if a message has previously been sent the message is received and execution continues

# Blocking Send, Blocking Receive

- Both sender and receiver are blocked until the message is delivered
  - *rendezvous*
- Allows for tight synchronization between processes



# Nonblocking Send

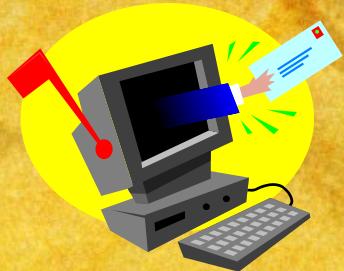
Nonblocking send, blocking receive

- sender continues on but receiver is blocked until the requested message arrives
- most useful combination
- sends one or more messages to a variety of destination

Nonblocking send, nonblocking receive

- neither party is required to wait





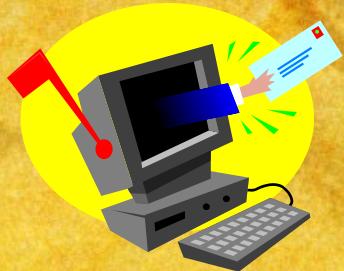
# Addressing

- ❖ Schemes for specifying processes in send and receive primitives fall into two categories:

Direct  
addressing

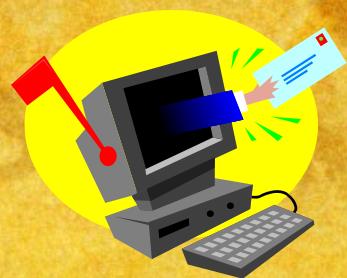
Indirect  
addressing





# Direct Addressing

- Send primitive (specific identifier)
- Receive primitive can be handled in one of two ways:
  - require that the process explicitly designate a sending process
    - effective for cooperating concurrent processes
  - implicit addressing
    - Receive primitive possesses (value)
    - receive operation has been performed



# Indirect Addressing

Messages are sent to a shared data structure consisting of queues that can temporarily hold messages

Queues are referred to as *mailboxes*

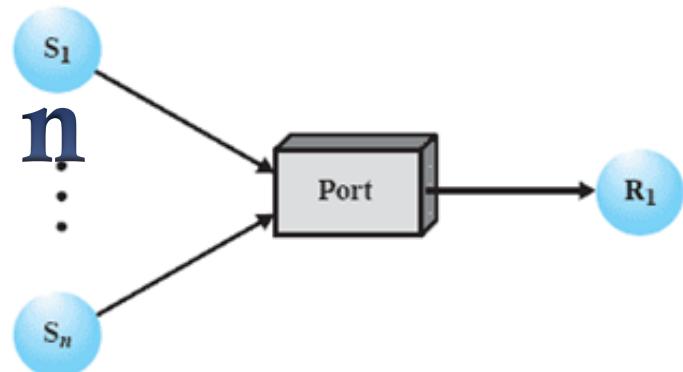
Allows for greater flexibility in the use of messages

One process sends a message to the mailbox and the other process picks up the message from the mailbox

# Indirect Process



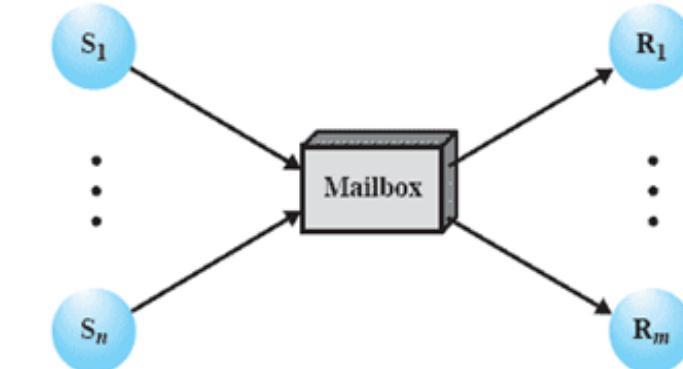
(a) One to one



(b) Many to one



(c) One to many



(d) Many to many

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# General Message Format

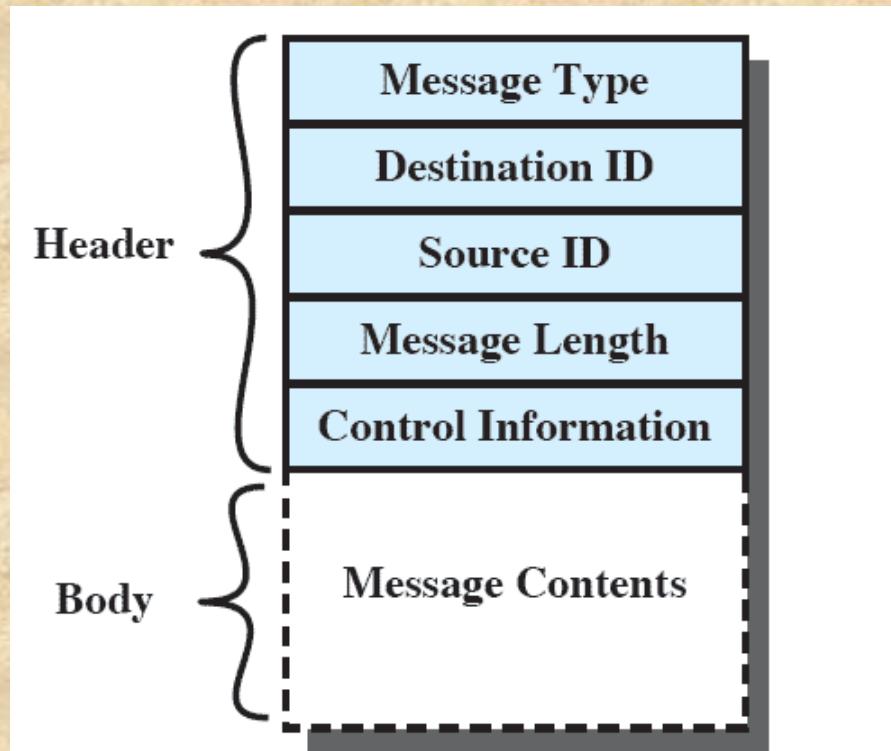


Figure 5.19 General Message Format



# Readers/Writers Problem

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- A data area is shared among many processes
  - some processes only read the data area, (readers) and some only write to the data area (writers)
- Conditions that must be satisfied:
  1. any number of readers may simultaneously read the file
  2. only one writer at a time may write to the file
  3. if a writer is writing to the file, no reader may read it

# State of the Process Queues

Readers only in the system	<ul style="list-style-type: none"><li>• <math>wsem</math> set</li><li>• no queues</li></ul>
Writers only in the system	<ul style="list-style-type: none"><li>• <math>wsem</math> and <math>rsem</math> set</li><li>• writers queue on <math>wsem</math></li></ul>
Both readers and writers with read first	<ul style="list-style-type: none"><li>• <math>wsem</math> set by reader</li><li>• <math>rsem</math> set by writer</li><li>• all writers queue on <math>wsem</math></li><li>• one reader queues on <math>rsem</math></li><li>• other readers queue on <math>z</math></li></ul>
Both readers and writers with write first	<ul style="list-style-type: none"><li>• <math>wsem</math> set by writer</li><li>• <math>rsem</math> set by writer</li><li>• writers queue on <math>wsem</math></li><li>• one reader queues on <math>rsem</math></li><li>• other readers queue on <math>z</math></li></ul>

Table 5.6 State of the Process Queues for Program of Figure 5.23

## Messages

# Summary

- Useful for the enforcement of mutual exclusion discipline



## Operating system themes are:

- Multiprogramming, multiprocessing, distributed processing
- Fundamental to these themes is concurrency
  - issues of conflict resolution and cooperation arise

## Mutual Exclusion

- Condition in which there is a set of concurrent processes, only one of which is able to access a given resource or perform a given function at any time
- One approach involves the use of special purpose machine instructions

## Semaphores

- Used for signaling among processes and can be readily used to enforce a mutual exclusion discipline