

*Operating  
Systems:  
Internals  
and Design  
Principles*

# Chapter 5

# Concurrency:

# Mutual Exclusion

# and Synchronization

Eighth Edition  
Global Edition  
By William Stallings

# 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

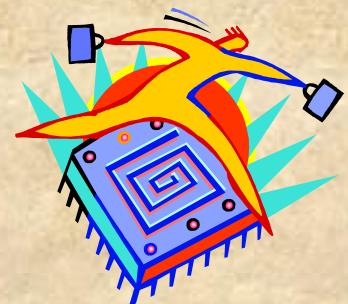
## Table 5.1

### Some Key Terms Related to Concurrency

<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.

# 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

**Table 5.2**  
**Process Interaction**

Degree of Awareness	Relationship	Influence that One Process Has on the Other	Potential Control Problems
Processes unaware of each other	Competition	<ul style="list-style-type: none"> <li>• Results of one process independent of the action of others</li> <li>• Timing of process may be affected</li> </ul>	<ul style="list-style-type: none"> <li>• Mutual exclusion</li> <li>• Deadlock (renewable resource)</li> <li>• Starvation</li> </ul>
Processes indirectly aware of each other (e.g., shared object)	Cooperation by sharing	<ul style="list-style-type: none"> <li>• Results of one process may depend on information obtained from others</li> <li>• Timing of process may be affected</li> </ul>	<ul style="list-style-type: none"> <li>• Mutual exclusion</li> <li>• Deadlock (renewable resource)</li> <li>• Starvation</li> <li>• Data coherence</li> </ul>
Processes directly aware of each other (have communication primitives available to them)	Cooperation by communication	<ul style="list-style-type: none"> <li>• Results of one process may depend on information obtained from others</li> <li>• Timing of process may be affected</li> </ul>	<ul style="list-style-type: none"> <li>• Deadlock (consumable resource)</li> <li>• Starvation</li> </ul>

# 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**



# Figure 5.1

## Illustration of Mutual Exclusion

<b>PROCESS 1 */</b>  <b>void P1</b> { <b>while</b> (true) { /* preceding code */; <b>entercritical</b> (Ra); /* critical section */; <b>exitcritical</b> (Ra); /* following code */; } }	<b>/* PROCESS 2 */</b>  <b>void P2</b> { <b>while</b> (true) { /* preceding code */; <b>entercritical</b> (Ra); /* critical section */; <b>exitcritical</b> (Ra); /* following code */; } }	...	<b>/* PROCESS n */</b>  <b>void Pn</b> { <b>while</b> (true) { /* preceding code */; <b>entercritical</b> (Ra); /* critical section */; <b>exitcritical</b> (Ra); /* following code */; } }
---	--	-----	--

# 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

## ■ 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



# Figure 5.2

## Hardware Support for Mutual Exclusion

```
/* program mutual exclusion */
const int n = /* number of processes */;
int bolt;
void P(int i)
{
    while (true) {
        while (compare_and_swap(&bolt, 0, 1) == 1)
            /* do nothing */;
        /* critical section */;
        bolt = 0;
        /* remainder */;
    }
}
void main()
{
    bolt = 0;
    parbegin (P(1), P(2), . . . , P(n));
}
```

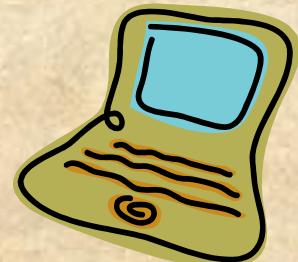
```
/* program mutual exclusion */
int const n = /* number of processes*/;
int bolt;
void P(int i)
{
    while (true) {
        int keyi = 1;
        do exchange (&keyi, &bolt)
        while (keyi != 0);
        /* critical section */;
        bolt = 0;
        /* remainder */;
    }
}
void main()
{
    bolt = 0;
    parbegin (P(1), P(2), . . . , P(n));
}
```

(a) Compare and swap instruction

(b) Exchange instruction

# 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



# Table 5.3

## 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

There is no way to know before a process decrements a semaphore whether it will block or not

There is no way to know which process will continue immediately on a uniprocessor system when two processes are running concurrently

You don't know whether another process is waiting so the number of unblocked processes may be zero or one

## Figure 5.3

### A Definition of Semaphore Primitives

```
struct semaphore {
    int count;
    queueType queue;
};

void semWait(semaphore s)
{
    s.count--;
    if (s.count < 0) {
        /* place this process in s.queue */;
        /* block this process */;
    }
}

void semSignal(semaphore s)
{
    s.count++;
    if (s.count <= 0) {
        /* remove a process P from s.queue */;
        /* place process P on ready list */;
    }
}
```

```
struct binary_semaphore {
    enum {zero, one} value;
    queueType queue;
};

void semWaitB(binary_semaphore s)
{
    if (s.value == one)
        s.value = zero;
    else {
        /* place this process in s.queue */;
        /* block this process */;
    }
}

void semSignalB(semaphore s)
{
    if (s.queue is empty())
        s.value = one;
    else {
        /* remove a process P from s.queue */;
        /* place process P on ready list */;
    }
}
```

**Figure 5.4**  
**A Definition of Binary Semaphore Primitives**

# 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

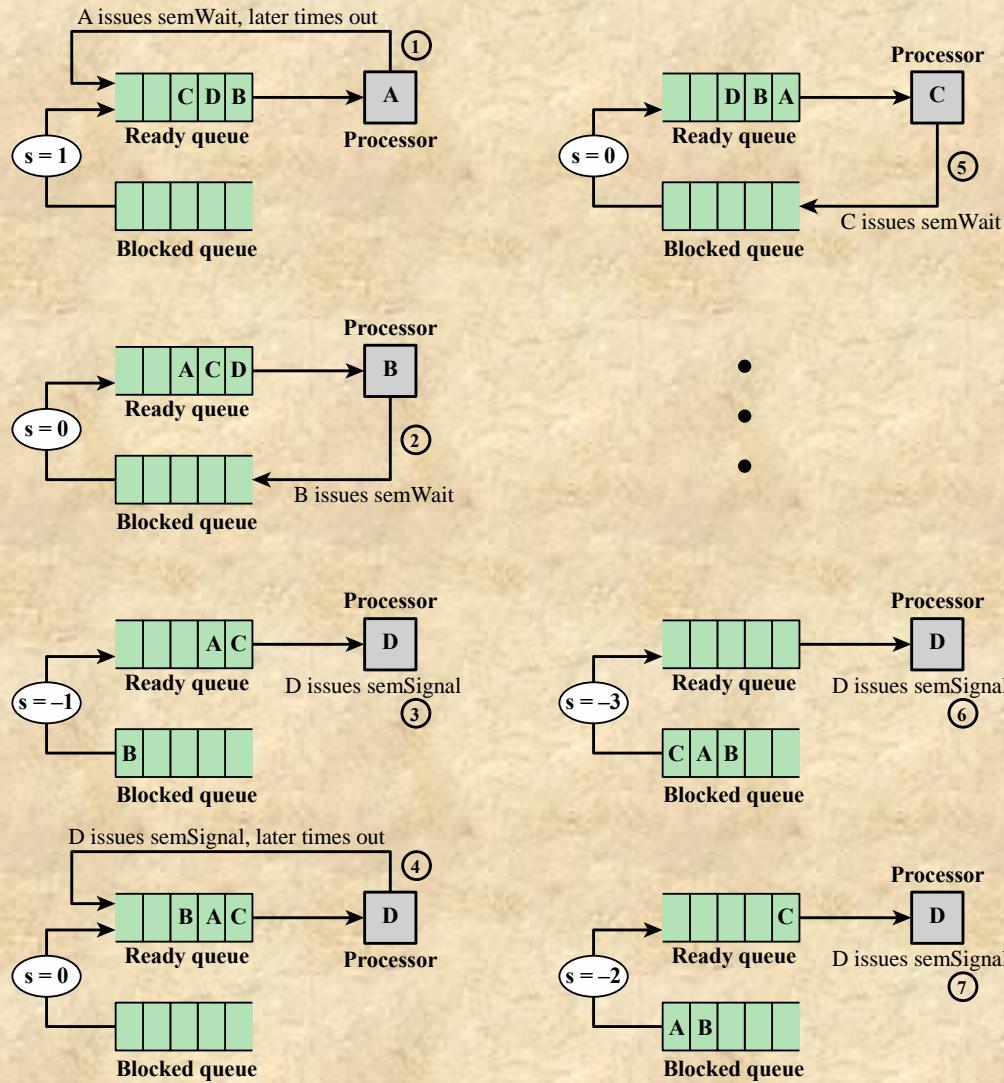
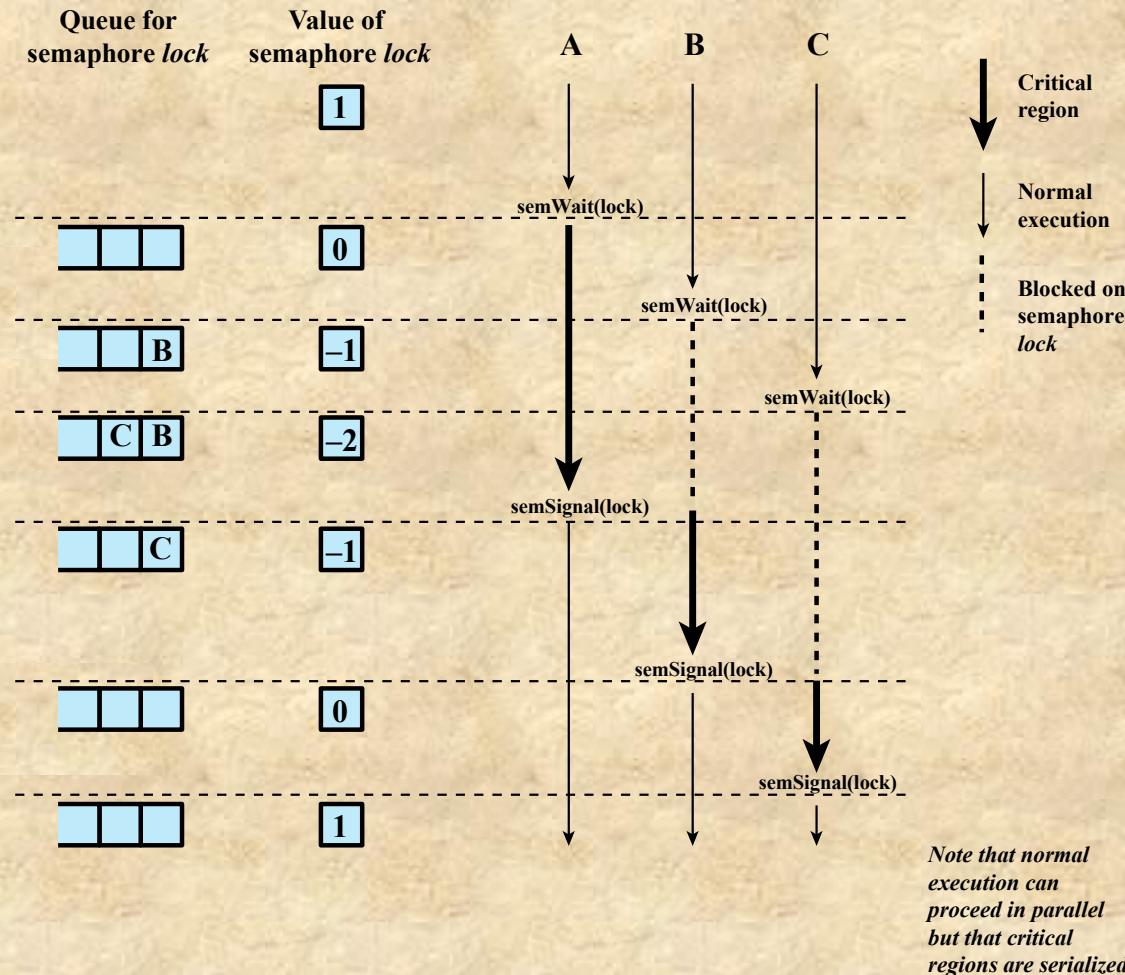


Figure 5.5 Example of Semaphore Mechanism

```
/* program mutualexclusion */
const int n = /* number of processes */;
semaphore s = 1;
void P(int i)
{
    while (true) {
        semWait(s);
        /* critical section */;
        semSignal(s);
        /* remainder */;
    }
}
void main()
{
    parbegin (P(1), P(2), . . . , P(n));
}
```

**Figure 5.6**  
**Mutual Exclusion Using Semaphores**



**Figure 5.7 Processes Accessing Shared Data Protected by a Semaphore**

# Producer/Consumer Problem

General Statement:

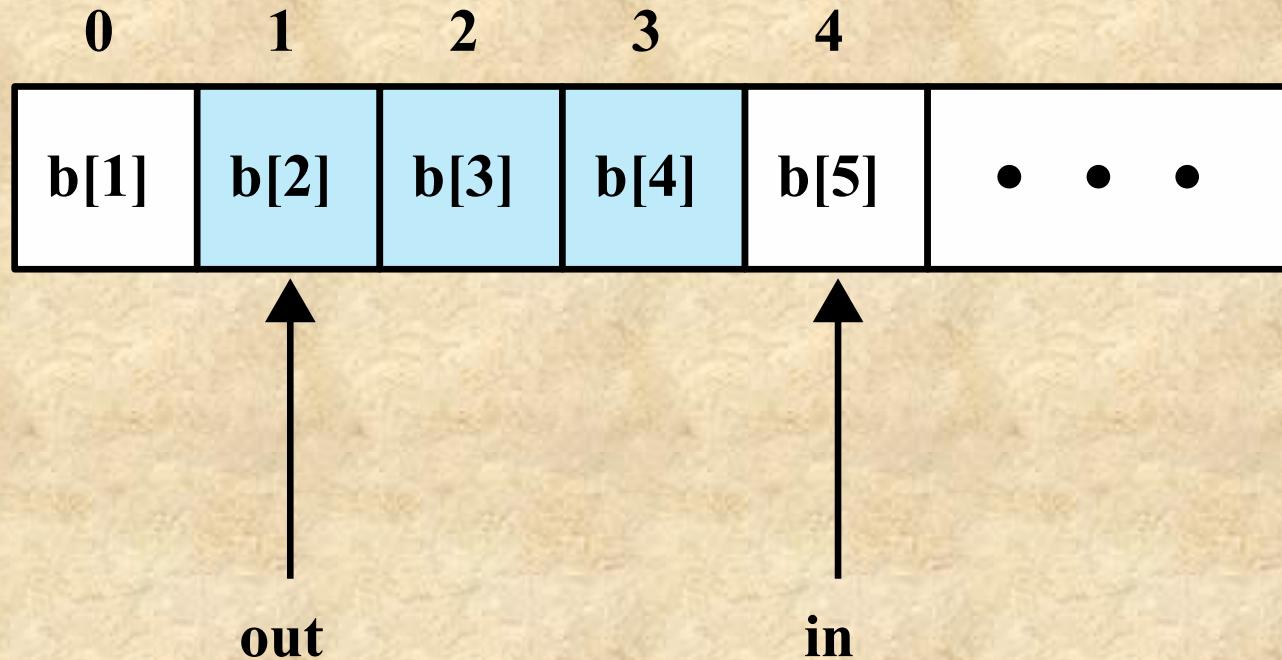
one or more producers are generating data and placing these in a buffer

a single consumer is taking items out of the buffer one at a 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



Note: shaded area indicates portion of buffer that is occupied

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

```

/* program producerconsumer */
int n;
binary semaphore s = 1, delay = 0;
void producer()
{
    while (true) {
        produce();
        semWaitB(s);
        append();
        n++;
        if (n==1) semSignalB(delay);
        semSignalB(s);
    }
}
void consumer()
{
    semWaitB(delay);
    while (true) {
        semWaitB(s);
        take();
        n--;
        semSignalB(s);
        consume();
        if (n==0) semWaitB(delay);
    }
}
void main()
{
    n = 0;
    parbegin (producer, consumer);
}

```

# Figure 5.9

## An Incorrect Solution to the Infinite-Buffer Producer/Consumer Problem Using Binary Semaphores

**Table 5.4**  
**Possible Scenario for the Program of Figure 5.9**

	Producer	Consumer	s	n	Delay
1			1	0	0
2	semWaitB(s)		0	0	0
3	n++		0	1	0
4	<b>if</b> (n==1) (semSignalB(delay))		0	1	1
5	semSignalB(s)		1	1	1
6		semWaitB(delay)	1	1	0
7		semWaitB(s)	0	1	0
8		n--	0	0	0
9		semSignalB(s)	1	0	0
10	semWaitB(s)		0	0	0
11	n++		0	1	0
12	<b>if</b> (n==1) (semSignalB(delay))		0	1	1
13	semSignalB(s)		1	1	1
14		<b>if</b> (n==0) (semWaitB(delay))	1	1	1
15		semWaitB(s)	0	1	1
16		n--	0	0	1
17		semSignalB(s)	1	0	1
18		<b>if</b> (n==0) (semWaitB(delay))	1	0	0
19		semWaitB(s)	0	0	0
20		n--	0	-1	0
21		semSignalB(s)	1	-1	0

Note: White areas represent the critical section controlled by semaphore s.

## Figure 5.10

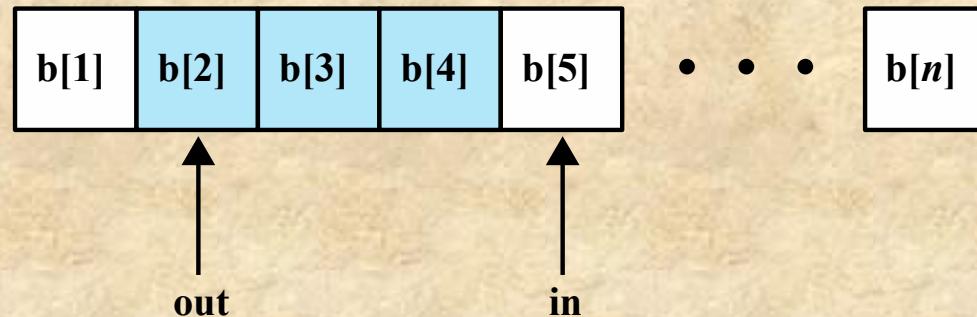
# A Correct Solution to the Infinite-Buffer Producer/Consumer Problem Using Binary Semaphores

```
/* program producerconsumer */
int n;
binary_semaphore s = 1, delay = 0;
void producer()
{
    while (true) {
        produce();
        semWaitB(s);
        append();
        n++;
        if (n==1) semSignalB(delay);
        semSignalB(s);
    }
}
void consumer()
{
    int m; /* a local variable */
    semWaitB(delay);
    while (true) {
        semWaitB(s);
        take();
        n--;
        m = n;
        semSignalB(s);
        consume();
        if (m==0) semWaitB(delay);
    }
}
void main()
{
    n = 0;
    parbegin (producer, consumer);
}
```

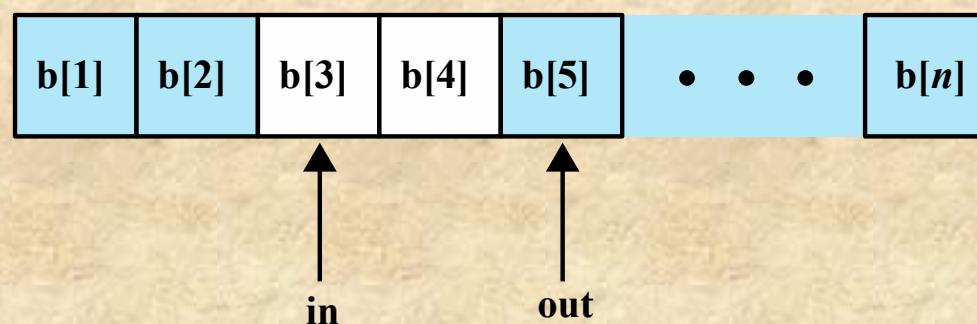
## Figure 5.11

### A Solution to the Infinite- Buffer Producer/C onsumer Problem Using Semaphores

```
/* program producerconsumer */
semaphore n = 0, s = 1;
void producer()
{
    while (true) {
        produce();
        semWait(s);
        append();
        semSignal(s);
        semSignal(n);
    }
}
void consumer()
{
    while (true) {
        semWait(n);
        semWait(s);
        take();
        semSignal(s);
        consume();
    }
}
void main()
{
    parbegin (producer, consumer);
}
```



(a)



(b)

Figure 5.12 Finite Circular Buffer for the Producer/Consumer Problem

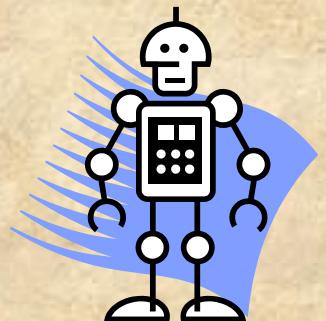
# Figure 5.13

## A Solution to the Bounded- Buffer Producer/Con- sumer Problem Using Semaphores

```
/* program boundedbuffer */
const int sizeofbuffer = /* buffer size */;
semaphore s = 1, n= 0, e= sizeofbuffer;
void producer()
{
    while (true) {
        produce();
        semWait(e);
        semWait(s);
        append();
        semSignal(s);
        semSignal(n);
    }
}
void consumer()
{
    while (true) {
        semWait(n);
        semWait(s);
        take();
        semSignal(s);
        semSignal(e);
        consume();
    }
}
void main()
{
    parbegin (producer, consumer);
}
```

# Implementation of Semaphores

- Imperative that the semWait and semSignal operations be implemented as atomic primitives
- 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



# Figure 5.14

## Two Possible Implementations of Semaphores

```
semWait(s)
{
    while (compare_and_swap(s.flag, 0 , 1) == 1)
        /* do nothing */;
    s.count--;
    if (s.count < 0) {
        /* place this process in s.queue*/;
        /* block this process (must also set s.flag to 0)
    */;
    }
    s.flag = 0;
}

semSignal(s)
{
    while (compare_and_swap(s.flag, 0 , 1) == 1)
        /* do nothing */;
    s.count++;
    if (s.count <= 0) {
        /* remove a process P from s.queue */;
        /* place process P on ready list */;
    }
    s.flag = 0;
}
```

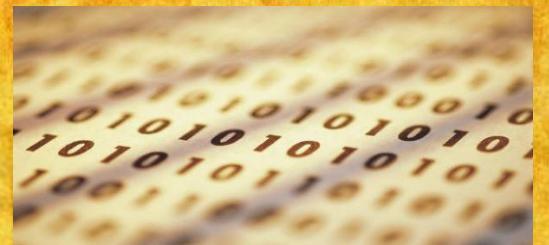
(a) Compare and Swap Instruction

```
semWait(s)
{
    inhibit interrupts;
    s.count--;
    if (s.count < 0) {
        /* place this process in s.queue*/;
        /* block this process and allow interrupts */;
    }
    else
        allow interrupts;
}

semSignal(s)
{
    inhibit interrupts;
    s.count++;
    if (s.count <= 0) {
        /* remove a process P from s.queue */;
        /* place process P on ready list */;
    }
    allow interrupts;
}
```

(b) Interrupts

# 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



Process enters monitor by invoking one of its procedures



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

# Synchronization

- Achieved by the use of **condition variables** that are contained within the monitor and accessible only within the monitor
  - 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



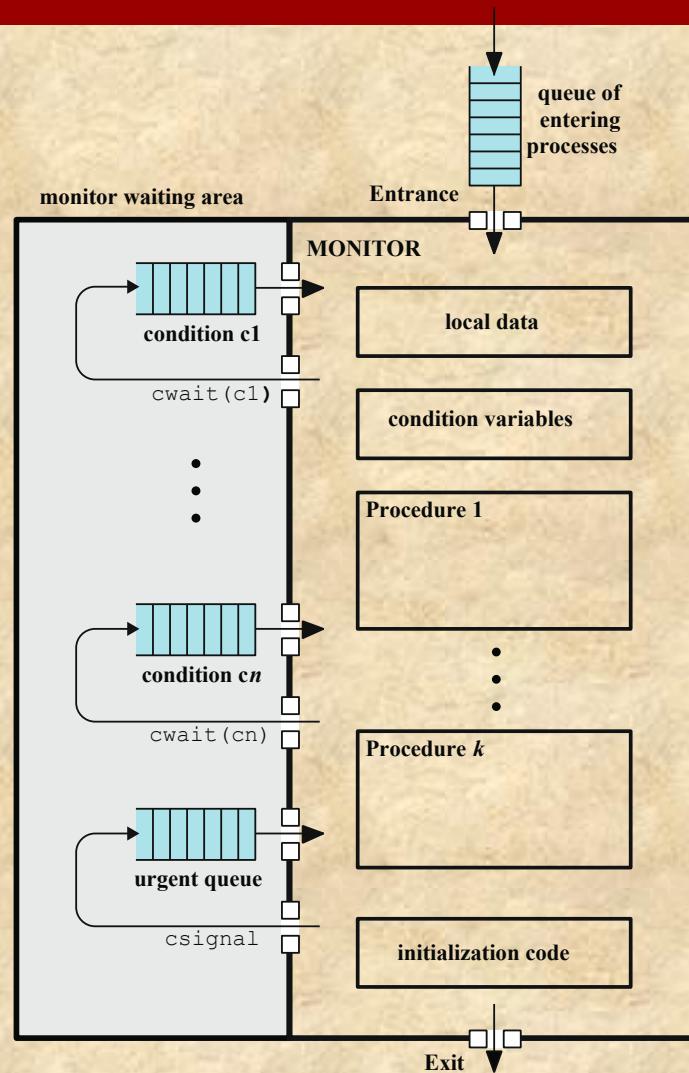


Figure 5.15 Structure of a Monitor

```

/* program producerconsumer */
monitor boundedbuffer;
char buffer [N];
int nextin, nextout;                                /* space for N items */
int count;                                         /* buffer pointers */
int count;                                         /* number of items in buffer */
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 */
}
{
    nextin = 0; nextout = 0; count = 0;           /* monitor body */
                                                /* 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

```

void append (char x)
{
    while(count == N) cwait(notfull); /* buffer is full; avoid overflow */
    buffer[nextin] = x;
    nextin = (nextin + 1) % N;
    count++;                                /* one more item in buffer */
    cnotify(notempty);                      /* notify any waiting consumer */
}

void take (char x)
{
    while(count == 0) cwait(notempty); /* buffer is empty; avoid underflow */
    x = buffer[nextout];
    nextout = (nextout + 1) % N;
    count--;                                /* one fewer item in buffer */
    cnotify(notfull);                      /* notify any waiting producer */
}

```

**Figure 5.17 Bounded Buffer Monitor Code for Mesa 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)
- A process sends information in the form of a *message* to another process designated by a *destination*
- A process receives information by executing the receive primitive, indicating the *source* and the *message*

<b>Synchronization</b>	<b>Format</b>
Send	Content
blocking	Length
nonblocking	fixed
Receive	variable
blocking	
nonblocking	
test for arrival	
<b>Addressing</b>	<b>Queueing Discipline</b>
Direct	FIFO
send	
receive	
explicit	
implicit	
Indirect	Priority
static	
dynamic	
ownership	

**Table 5.5**  
**Design Characteristics of Message Systems for**  
**Interprocess Communication and Synchronization**

# 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

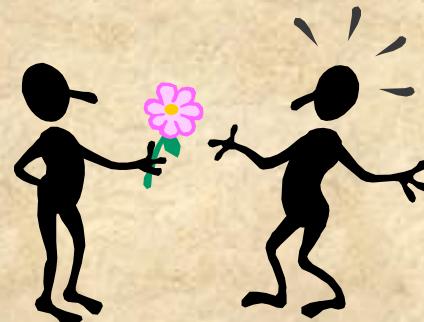
When a receive primitive is executed in a process there are two possibilities:

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
- Sometimes referred to as a *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 destinations as quickly as possible
- example -- a service process that exists to provide a service or resource to other processes

## 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 includes a specific identifier of the destination process
- 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
    - source parameter of the receive primitive possesses a value returned when the receive operation has been performed



# Indirect Addressing

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

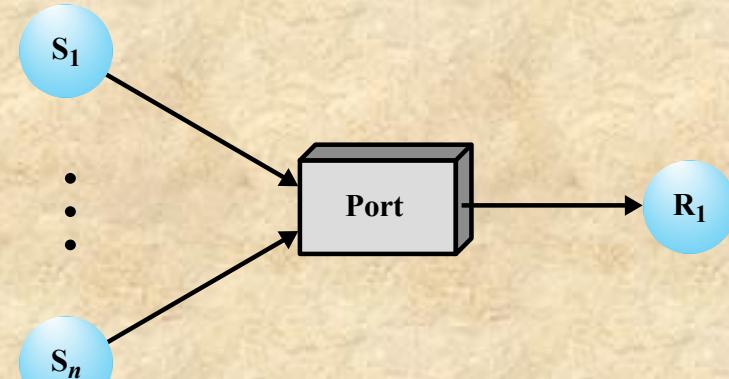
Queues are referred to as *mailboxes*

Allows for greater flexibility in the use of messages

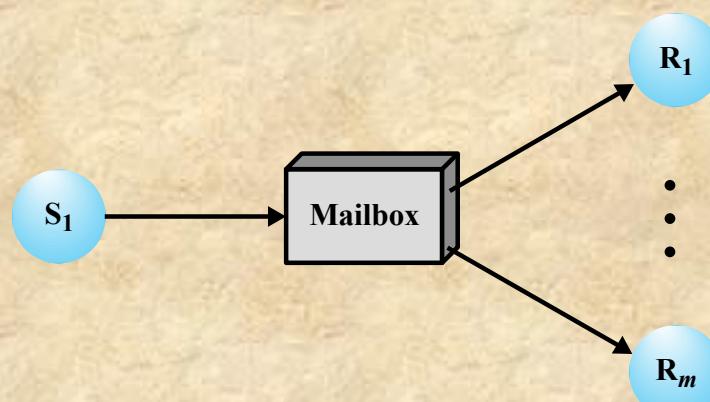
One process sends a message to the mailbox and the other process picks up the message from the mailbox



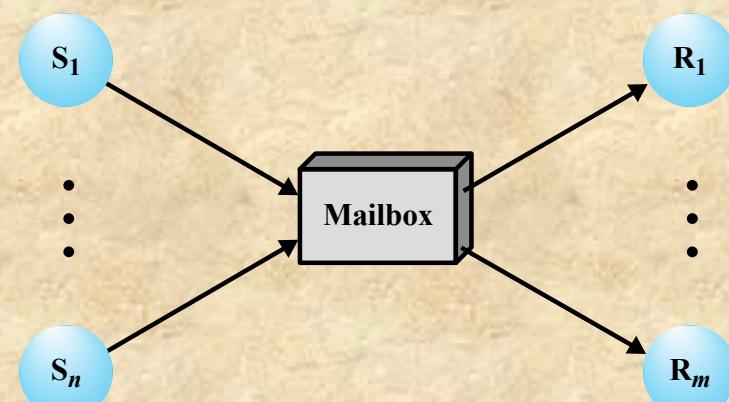
(a) One to one



(b) Many to one

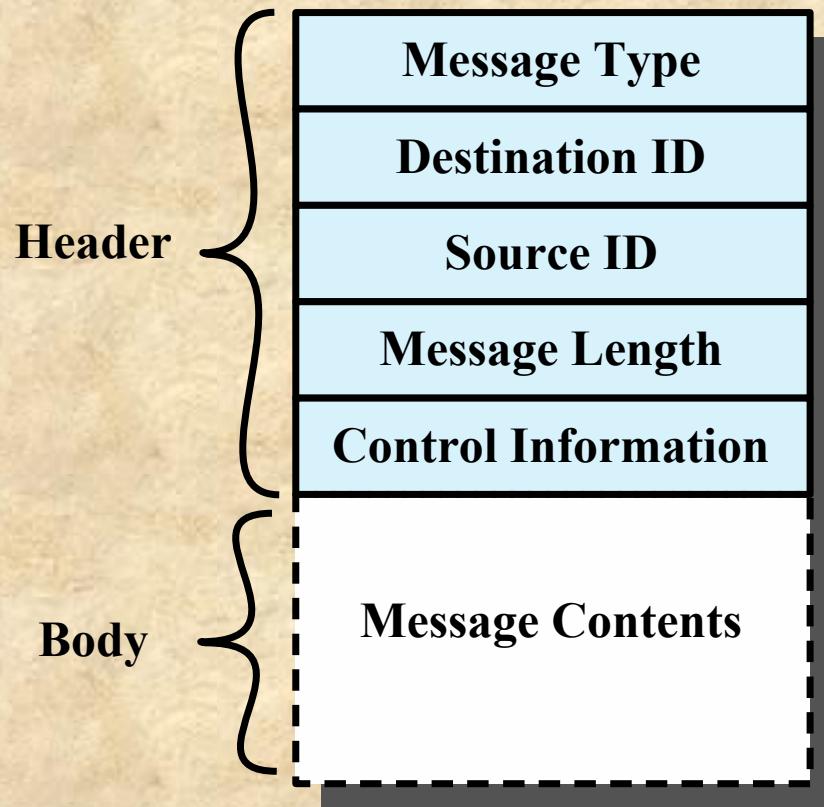


(c) One to many



(d) Many to many

Figure 5.18 Indirect Process Communication



**Figure 5.19 General Message Format**

```
/* program mutualexclusion */
const int n = /* number of processes */;
void P(int i)
{
    message msg;
    while (true) {
        receive (box, msg);
        /* critical section */
        send (box, msg);
        /* remainder */
    }
}
void main()
{
    create_mailbox (box);
    send (box, null);
    parbegin (P(1), P(2), . . . , P(n));
}
```

**Figure 5.20**  
**Mutual Exclusion Using Messages**

```

const int
    capacity = /* buffering capacity */ ;
    null =/* empty message */ ;
int i;
void producer()
{
    message pmsg;
    while (true) {
        receive (mayproduce, pmsg);
        pmsg = produce();
        send (mayconsume, pmsg);
    }
}
void consumer()
{
    message cmsg;
    while (true) {
        receive (mayconsume, cmsg);
        consume (cmsg);
        send (mayproduce, null);
    }
}

void main()
{
    create_mailbox (mayproduce);
    create_mailbox (mayconsume);
    for (int i = 1; i <= capacity; i++) send (mayproduce,
null);
    parbegin (producer, consumer);
}

```

**Figure 5.21**

**A Solution to the  
Bounded-Buffer  
Producer/Consum  
er Problem Using  
Messages**

# Readers/Writers Problem

---

- 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

```

/* program readersandwriters */
int readcount;
semaphore x = 1, wsem = 1;
void reader()
{
    while (true) {
        semWait (x);
        readcount++;
        if (readcount == 1) semWait (wsem);
        semSignal (x);
        READUNIT();
        semWait (x);
        readcount--;
        if (readcount == 0) semSignal (wsem);
        semSignal (x);
    }
}
void writer()
{
    while (true) {
        semWait (wsem);
        WRITEUNIT();
        semSignal (wsem);
    }
}

void main()
{
    readcount = 0;
    parbegin (reader, writer);
}

```

## Figure 5.22

# A Solution to the Readers/Write rs Problem Using Semaphores: Readers Have Priority

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**

```

/* program readersandwriters */
int readcount, writecount;
semaphore x = 1, y = 1, z = 1, wsem = 1, rsem = 1;
void reader()
{
    while (true) {
        semWait (z);
        semWait (rsem);
        semWait (x);
        readcount++;
        if (readcount == 1) semWait (wsem);
        semSignal (x);
        semSignal (rsem);
        semSignal (z);
        READUNIT();
        semWait (x);
        readcount--;
        if (readcount == 0) semSignal (wsem);
        semSignal (x);
    }
}
void writer ()
{
    while (true) {
        semWait (y);
        writecount++;
        if (writecount == 1) semWait (rsem);
        semSignal (y);
        semWait (wsem);
        WRITEUNIT();
        semSignal (wsem);
        semWait (y);
        writecount--;
        if (writecount == 0) semSignal (rsem);
        semSignal (y);
    }
}
void main()
{
    readcount = writecount = 0;
    parbegin (reader, writer);
}

```

## Figure 5.23

A Solution to the Readers/Writers Problem Using Semaphores:  
Writers Have Priority

```

void reader(int i)
{
    message rmsg;
    while (true) {
        rmsg = i;
        send (readrequest, rmsg);
        receive (mbox[i], rmsg);
        READUNIT ();
        rmsg = i;
        send (finished, rmsg);
    }
}

void writer(int j)
{
    message rmsg;
    while(true) {
        rmsg = j;
        send (writerequest, rmsg);
        receive (mbox[j], rmsg);
        WRITEUNIT ();
        rmsg = j;
        send (finished, rmsg);
    }
}

void controller()
{
    while (true)
    {
        if (count > 0) {
            if (!empty (finished)) {
                receive (finished, msg);
                count++;
            }
            else if (!empty (writerequest)) {
                receive (writerequest, msg);
                writer id = msg.id;
                count = count - 100;
            }
            else if (!empty (readrequest)) {
                receive (readrequest, msg);
                count--;
                send (msg.id, "OK");
            }
        }
        if (count == 0) {
            send (writer id, "OK");
            receive (finished, msg);
            count = 100;
        }
        while (count < 0) {
            receive (finished, msg);
            count++;
        }
    }
}

```

**Figure 5.24**

**A Solution to the Readers/Writers Problem Using Message Passing**

# Summary

- Principles of concurrency
  - Race condition
  - OS concerns
  - Process interaction
  - Requirements for mutual exclusion
- Mutual exclusion: hardware support
  - Interrupt disabling
  - Special machine instructions
- Semaphores
  - Mutual exclusion
  - Producer/consumer problem
  - Implementation of semaphores
- Monitors
  - Monitor with signal
  - Alternate model of monitors with notify and broadcast
- Message passing
  - Synchronization
  - Addressing
  - Message format
  - Queueing discipline
  - Mutual exclusion
- Readers/writers problem
  - Readers have priority
  - Writers have priority