Unit 3

Process Concurrency

(Inter-process Communication)

Mutual Exclusion
and
Synchronization

Outline

- Principles of Concurrency
- Mutual Exclusion : Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem

1. Multiple Processes

- Central to the design of modern Operating Systems is managing multiple processes
  - Multiprogramming
  - Multiprocessing
  - Distributed Processing
- Big Issue is Concurrency
  - Managing the interaction of all of these processes

2. Concurrency

Concurrency arises in:

- Multiple applications
  - Sharing time
- Structured applications
  - Extension of modular design
- Operating system structure
  - OS themselves implemented as a set of processes or threads

Interleaving and Overlapping Processes

- Earlier we saw that processes may be interleaved on uniprocessors

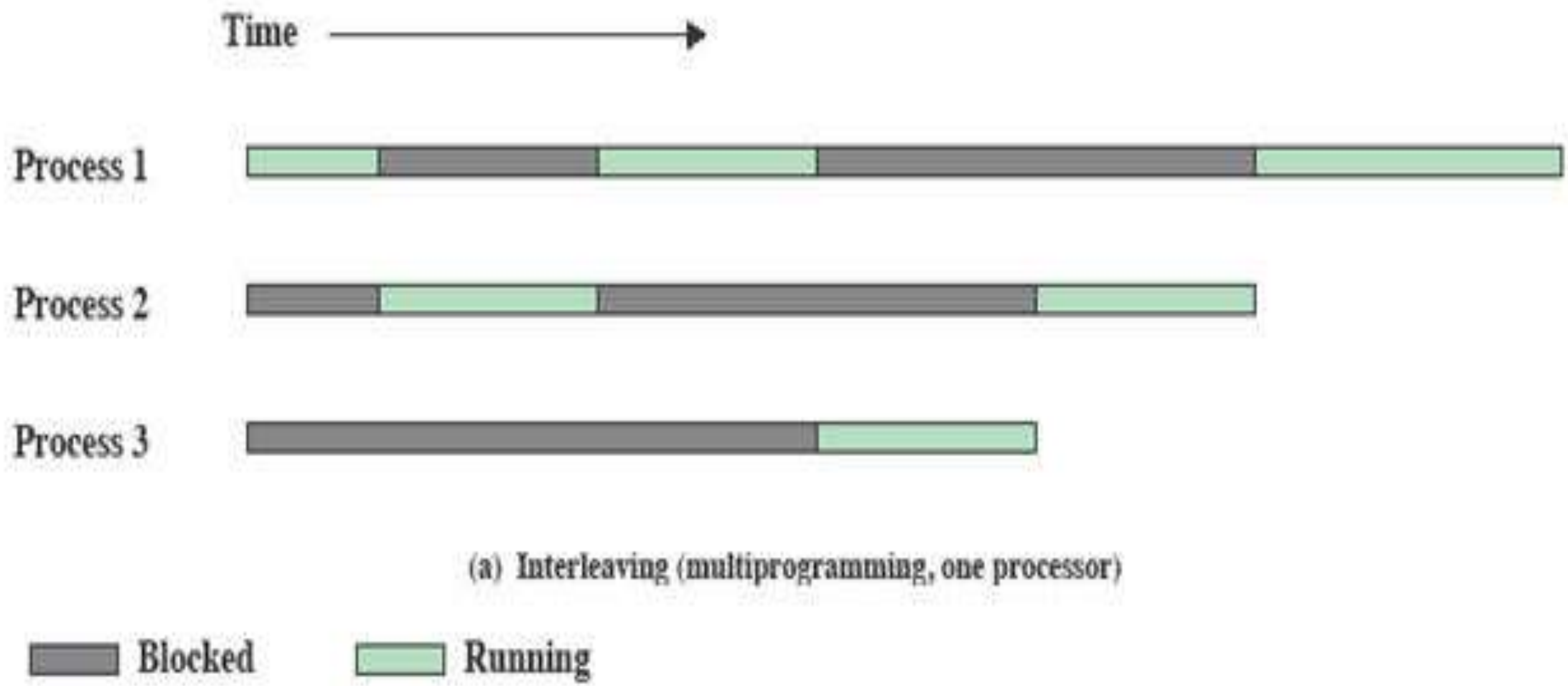


Figure 2.12 Multiprogramming and Multiprocessing

Interleaving and Overlapping Processes

- And not only interleaved but overlapped on multi-processors

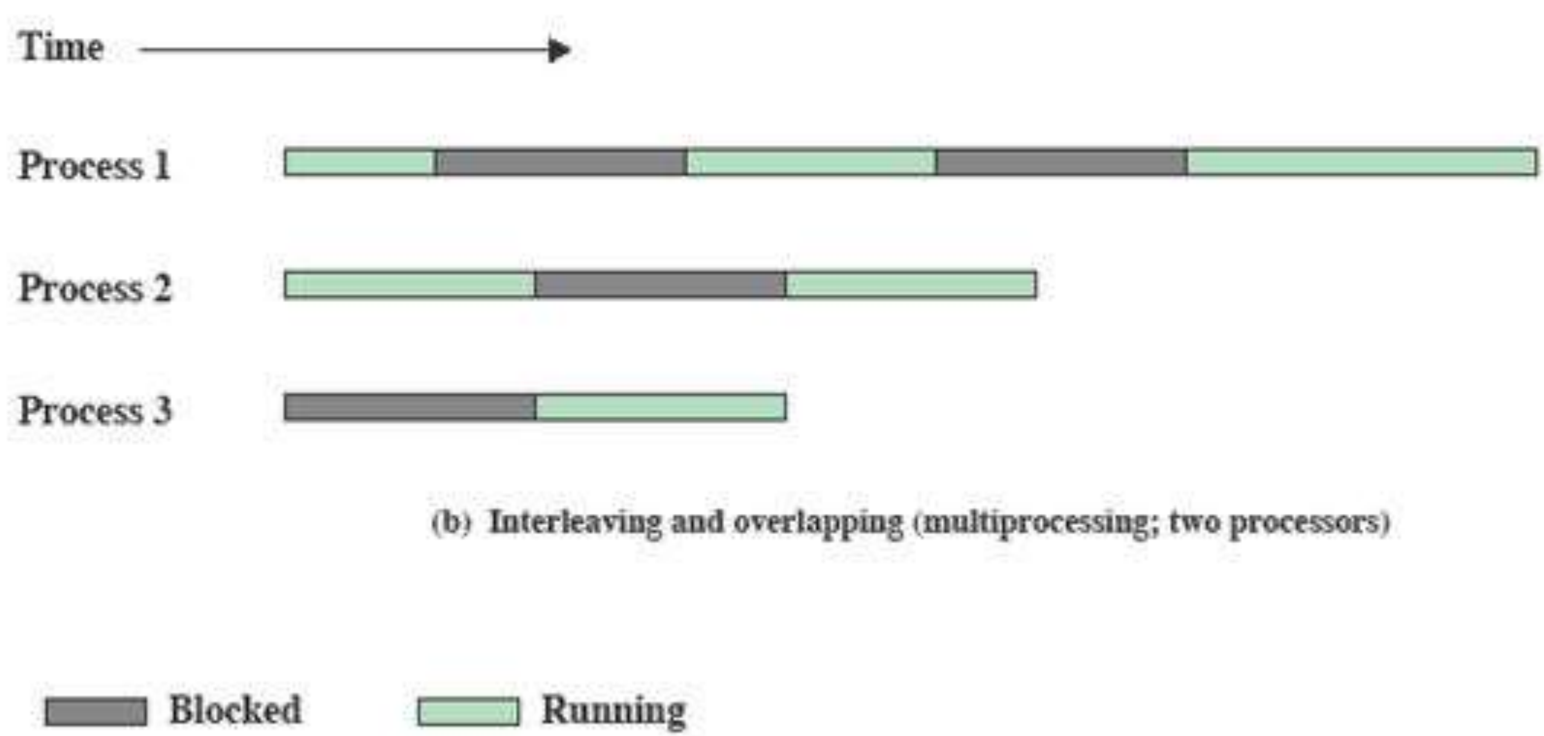


Figure 2.12 Multiprogramming and Multiprocessing

3. Difficulties of Concurrency

- Sharing of global resources (maintain the consistency)
- Optimally managing the allocation of resources (resource blocked)
- Difficult to locate programming errors (running infinite loop)

A Simple Example : Concurrency

```
void echo()
{
  chin = getchar();
  chout = chin;
  putchar(chout);
}
```

An example : Call of a function by two Processes

Process P1	Process P2
{	{
.	.
.	.
echo(); // critical section	echo(); // critical section
.	.
.	.
}	}

An example : On a Multiprocessor system

Process P1

```
.
chin = getchar();
.
chout = chin;
putchar(chout);
.
.
```

Process P2

```
.
.
chin = getchar();
chout = chin;
.
putchar(chout);
.
```

Solution: Enforce Single Access

- If we enforce a rule that only one process may enter the function at a time then :

Scenario

- P1 & P2 run on separate processors
- P1 enters echo first,
  - P2 tries to enter but is blocked – P2 suspends
- P1 completes execution
  - P2 resumes and executes echo

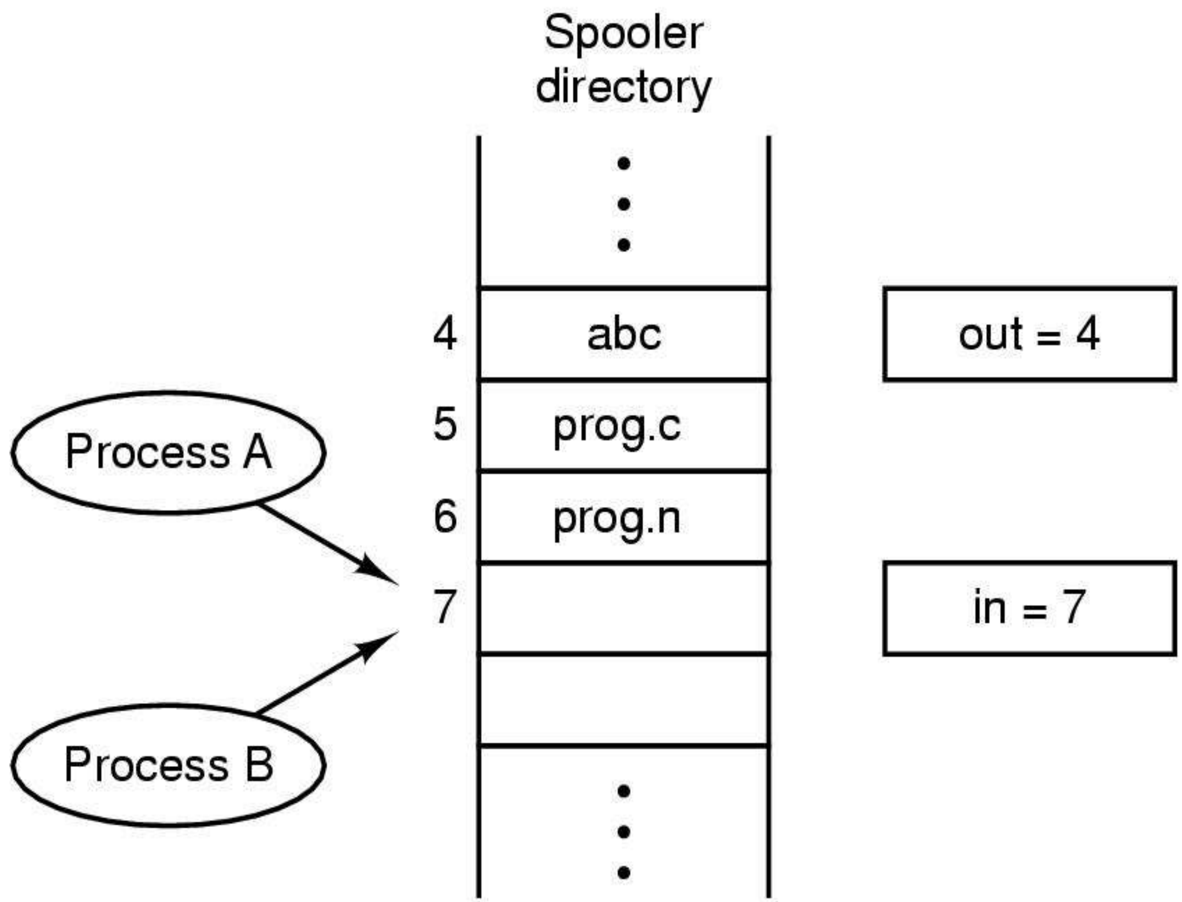
Race Condition

- A race condition occurs when
  - Multiple processes or threads read and write data items (Global resources)
  - Final result depends on the order of execution of the processes.
- The output depends on who finishes the race last.

IPC: Race Condition

Race Condition

The situation where 2 or more processes are reading or writing some shared data is called race condition



Two processes want to access shared memory at same time

4. Operating System Concerns

- What design and management issues are raised by the existence of concurrency?
- The OS must
  - Keep track of various processes
  - Allocate and de-allocate resources
  - Protect the data and resources against interference by other processes.
  - Ensure that the processes and outputs are independent of the processing speed

Process Interaction

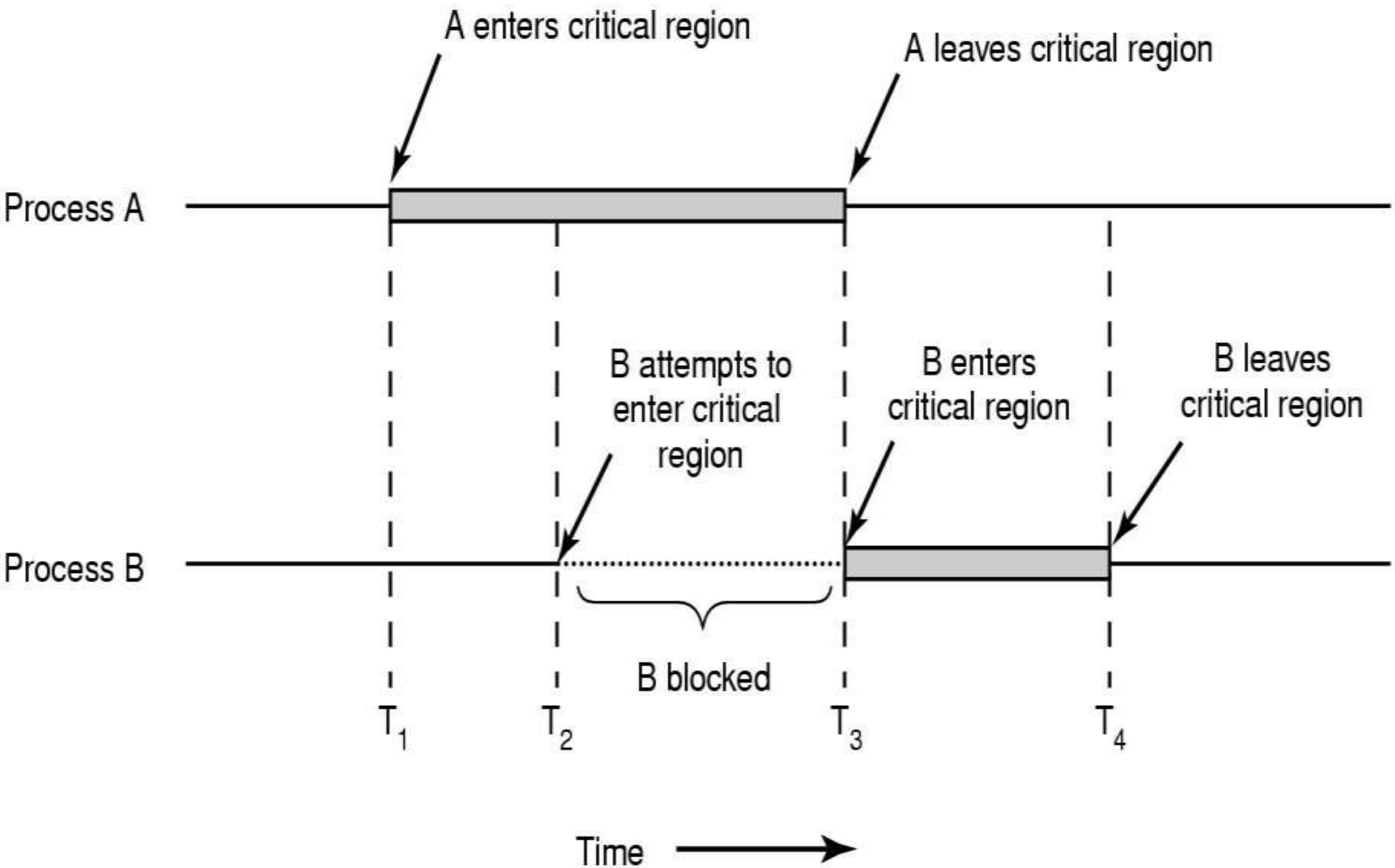
Table 5.2 Process Interaction

Degree of Awareness	Relationship	Influence That One Process Has on the Other	Potential Control Problems
Processes unaware of each other	Competition	• Results of one process independent of the action of others • Timing of process may be affected	• Mutual exclusion • Deadlock (renewable resource) • Starvation
Processes indirectly aware of each other (e.g., shared object)	Cooperation by sharing	• Results of one process may depend on information obtained from others • Timing of process may be affected	• Mutual exclusion • Deadlock (renewable resource) • Starvation • Data coherence
Processes directly aware of each other (have communication primitives available to them)	Cooperation by communication	• Results of one process may depend on information obtained from others • Timing of process may be affected	• Deadlock (consumable resource) • Starvation

5. Mutual Exclusion : Requirements

- Only one process at a time is allowed in the critical section for a resource
- A process that executes in its noncritical section must not interfere with other processes
- No deadlock or starvation
- A process must not be delayed 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 using Critical Regions



Outline

- Principles of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem

1. Disabling Interrupts

- Uniprocessors only allow interleaving
- Interrupt Disabling
  - A process runs until it invokes an operating system service or until it is interrupted
  - Disabling interrupts guarantees mutual exclusion
  - Will not work in multiprocessor architecture

Pseudo-Code

```
while (true)
{
  /* disable interrupts */;
  /* critical section */;
  /* enable interrupts */;
  /* remainder */;
}
```

Synchronization Hardware : Problems

- Many systems provide hardware support for critical section code
- Uniprocessor – could disable interrupts
  - Currently running code would execute without preemption
  - Not supporting in multiprogramming environment
- Multiprocessors -
  - Generally too inefficient on multiprocessor systems
  - Operating systems using this not broadly scalable

Machine Instructions

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

Mutual Exclusion: Hardware Support

- Test and Set Instruction

```
boolean TestAndSet (int lock)
{
    if (lock == 0)
    {
        lock = 1;
        return true;
    }
    else
    {
        return false;
    }
}
```

Mutual Exclusion: Hardware Support

- Exchange Instruction

```
void Swap(int register,
          int memory)
{
   int temp;
   temp = memory;
   memory = register;
   register = temp;
}
```

Solution using TestAndSet

- Shared boolean variable lock., initialized to false.
- Solution:

```
boolean TestAndSet (int lock) {
if (lock == 0)
{
        lock = 1;
        return true;
}
else
{
return false;
}
}
```

Process - 1

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

                 //    critical section

            lock = FALSE;

                 //      remainder section

     } while (TRUE);
```

Process - 2

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

                 //    critical section

            lock = FALSE;

                 //      remainder section

     } while (TRUE);
```

Solution using Swap

```
void Swap(int register,
int memory)
{
int temp;
temp = memory;
memory = register;
register = temp;
}
```

- Method:

1. Shared Boolean variable lock initialized to FALSE;
2. Each process has a local Boolean variable key

Solution:

```
Process - I
do {
      key = TRUE;
       while ( key == TRUE && lock == FALSE)
            Swap (&lock, &key );

            //    critical section

            lock = FALSE;

           //     remainder section

     } while (TRUE);
```

Mutual Exclusion Machine Instructions

- Advantages
  - Applicable to any number of processes on either a single processor or multiple processors sharing main memory
  - It is simple and therefore easy to verify
  - It can be used to support multiple critical sections

Mutual Exclusion Machine Instructions

- Disadvantages
  - Busy-waiting consumes processor time
  - Starvation is possible when a process leaves a critical section and more than one processes are waiting.
  - Deadlock
    - If a low priority process has the critical region and a higher priority process needs, the higher priority process will obtain the processor to wait for the critical region

Outline

- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem

Semaphore

- Semaphore:
  - An integer value used for signalling among processes.
- Only three operations may be performed on a semaphore, all of which are atomic:
  - Initialize,
  - Decrement (`semWait`)
  - Increment. (`semSignal`)

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 */;
     }
}
```

Figure 5.3 A Definition of Semaphore Primitives

Binary Semaphore Primitives

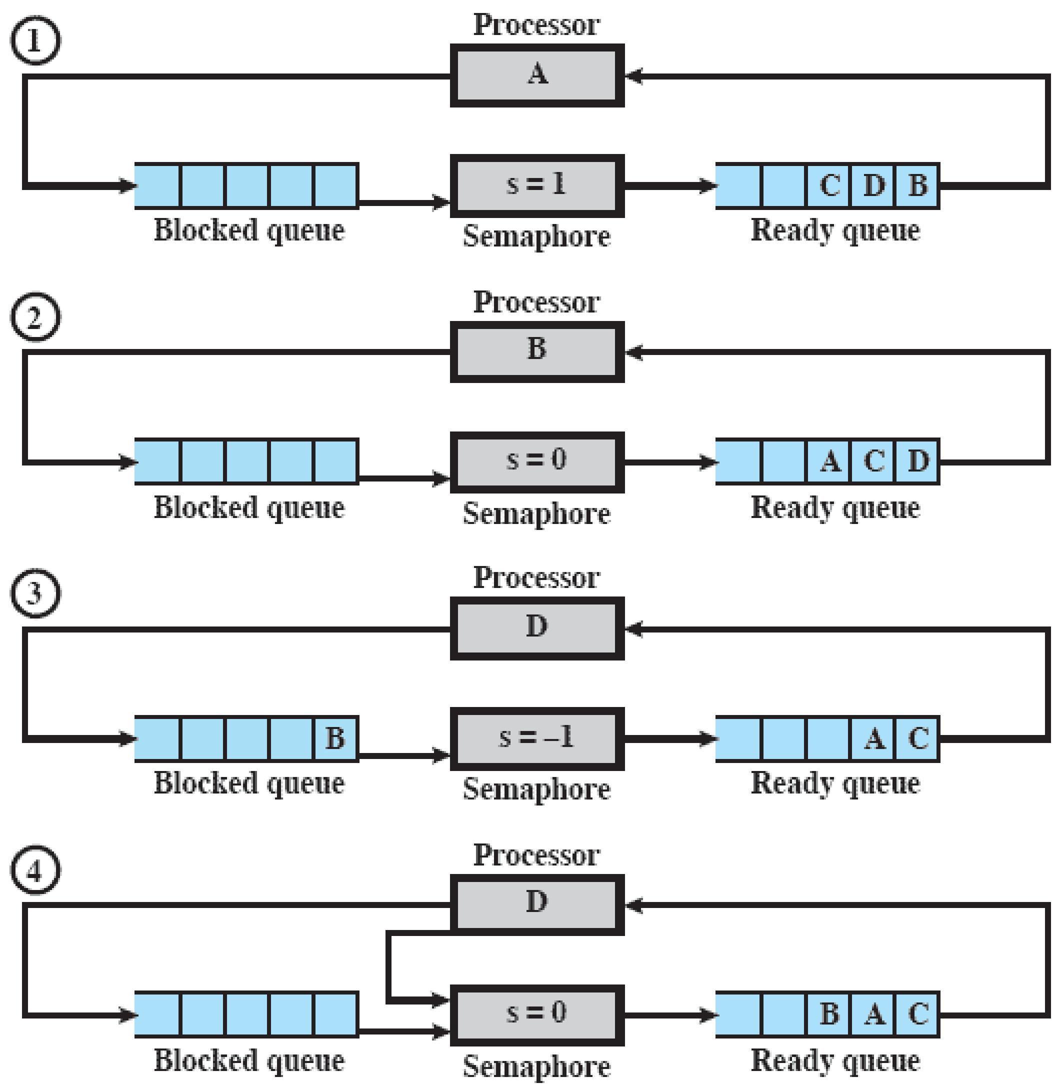
```
struct binary_semaphore {
     enum {zero, one} value;
     queueType queue;
};
void semWaitB(binary_semaphore s)
{
     if (s.value == one)
          s.value = zero;
     else {
               /* place this process in s.queue */;
               /* block this process */;
     }
}
void semSignalB(semaphore 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 Semaphore

- A queue is used to hold processes waiting on the semaphore
  - In what order are processes removed from the queue?
- ***Strong Semaphores*** use FIFO
- ***Weak Semaphores*** don't specify the order of removal from the queue

Example of Strong Semaphore Mechanism



Semaphore Primitives (Repeated)

```
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 */;
     }
}
```

Figure 5.3 A Definition of Semaphore Primitives

Example of Semaphore Mechanism

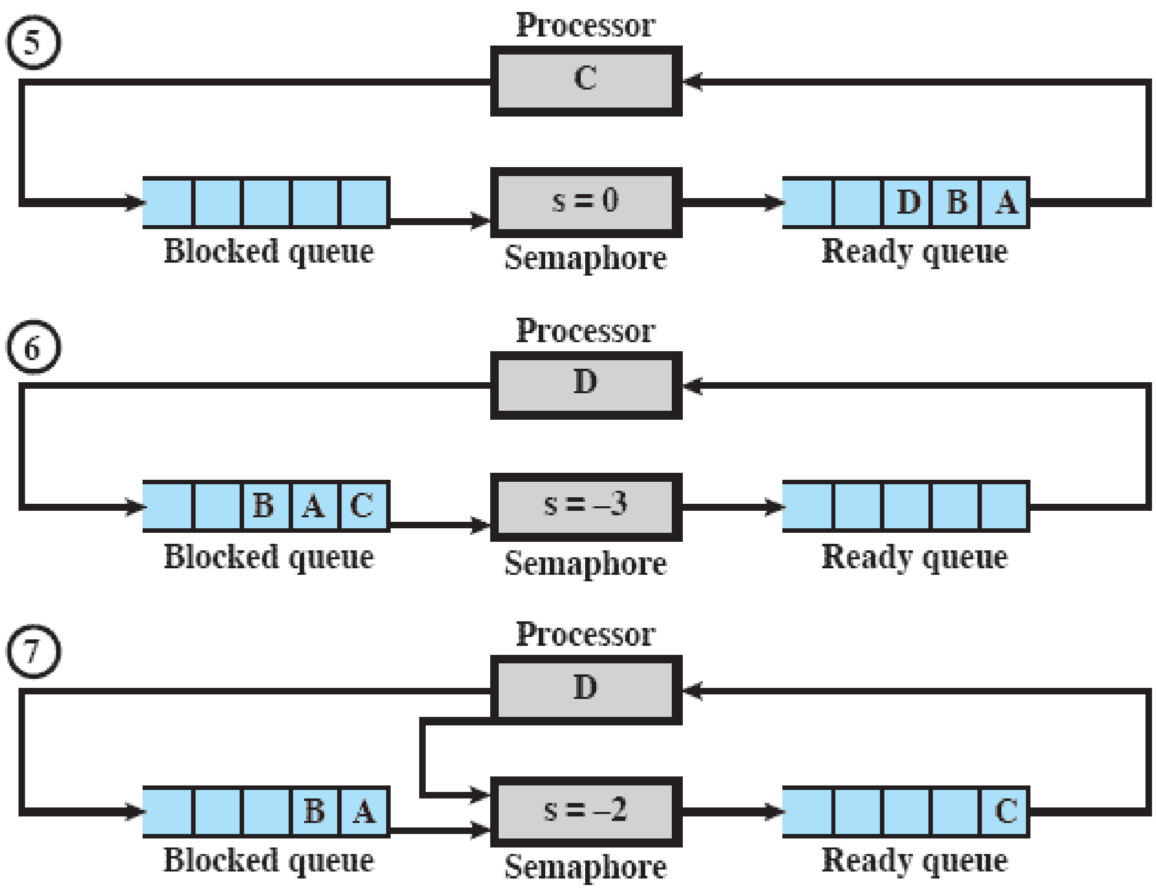


Figure 5.5 Example of Semaphore Mechanism

Mutual Exclusion Using Semaphores

```
/* 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

Semaphore Primitives (Repeated)

```
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 */;
     }
}
```

Figure 5.3 A Definition of Semaphore Primitives

Processes Using Semaphore

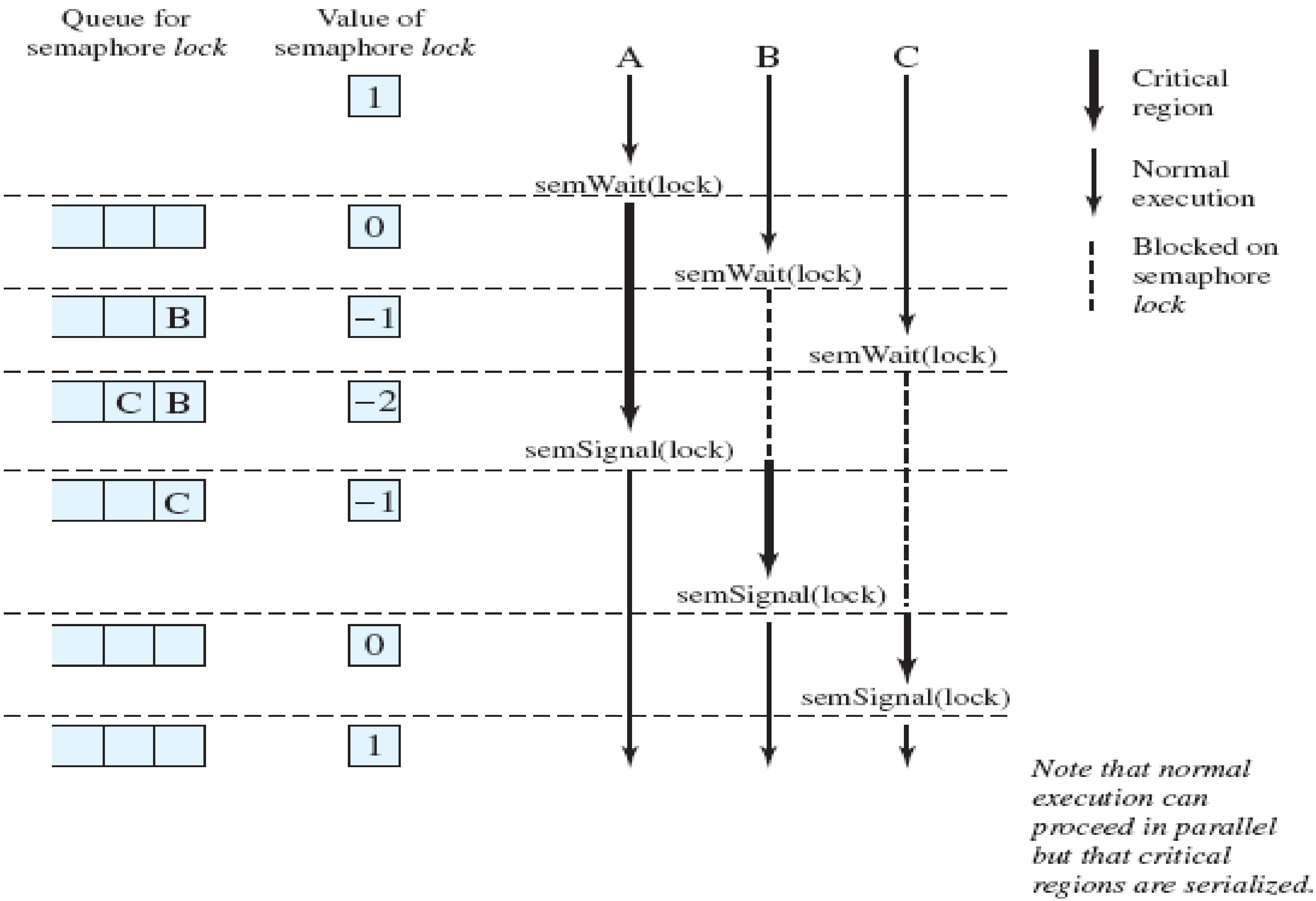


Figure 5.7 **Processes Accessing Shared Data Protected by a Semaphore**

Producer/Consumer Problem

- General Situation:

1. One or more producers are generating data and placing these in a buffer
2. A single consumer is taking items out of the buffer one at time
3. 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 empty buffer

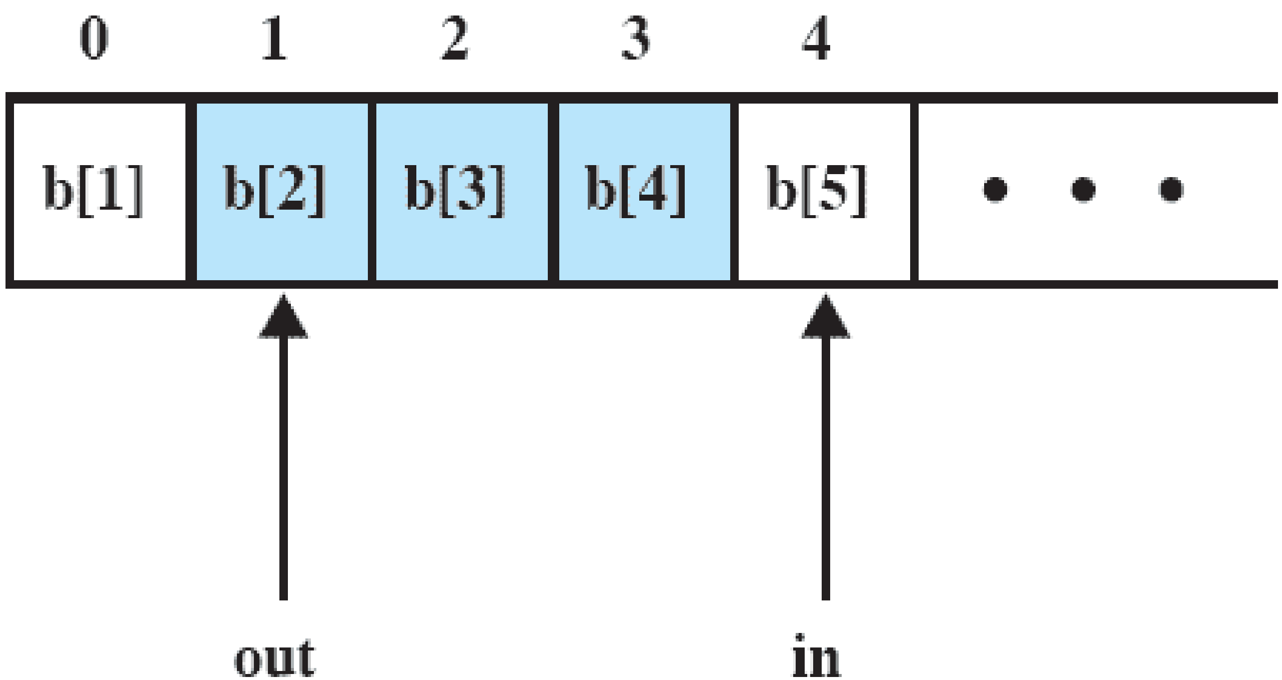
Functions

- Assume an infinite buffer ***b*** with a linear array of elements

Producer	Consumer

while (true) {
/* produce item v */
b[in] = v;
in++;
}
	while (true) {
	while (in <= out)
	/*do nothing */;
	w = b[out];
	out++;
	/* consume item w */
	}

Buffer



Note: shaded area indicates portion of buffer that is occupied

Figure 5.8 Infinite Buffer for the Producer/Consumer Problem

Incorrect Solution

```
/* 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);
}
```

Possible Scenario

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	**if** (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	**if** (n==1) (semSignalB(delay))		0	1	1
13	semSignalB(s)		1	1	1
14		**if** (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		**if** (n==0) (semWaitB(delay))	1	0	0
19		semWaitB(s)	0	0	0
20		n--	0	–1	0
21		semiSignlaB(s)	1	–1	0

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

Correct Solution

```
/* 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);
}
```

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);
}
```

Figure 5.11 A Solution to the Infinite-Buffer Producer/Consumer Problem Using Semaphores

outline

- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem

Monitors

- The monitor is a programming-language construct
- It provides equivalent functionality to that of semaphores
- It is easier to control.
- Implemented in a number of programming languages, including
  - Concurrent Pascal, Pascal-Plus,
  - Modula-2, Modula-3, and Java.

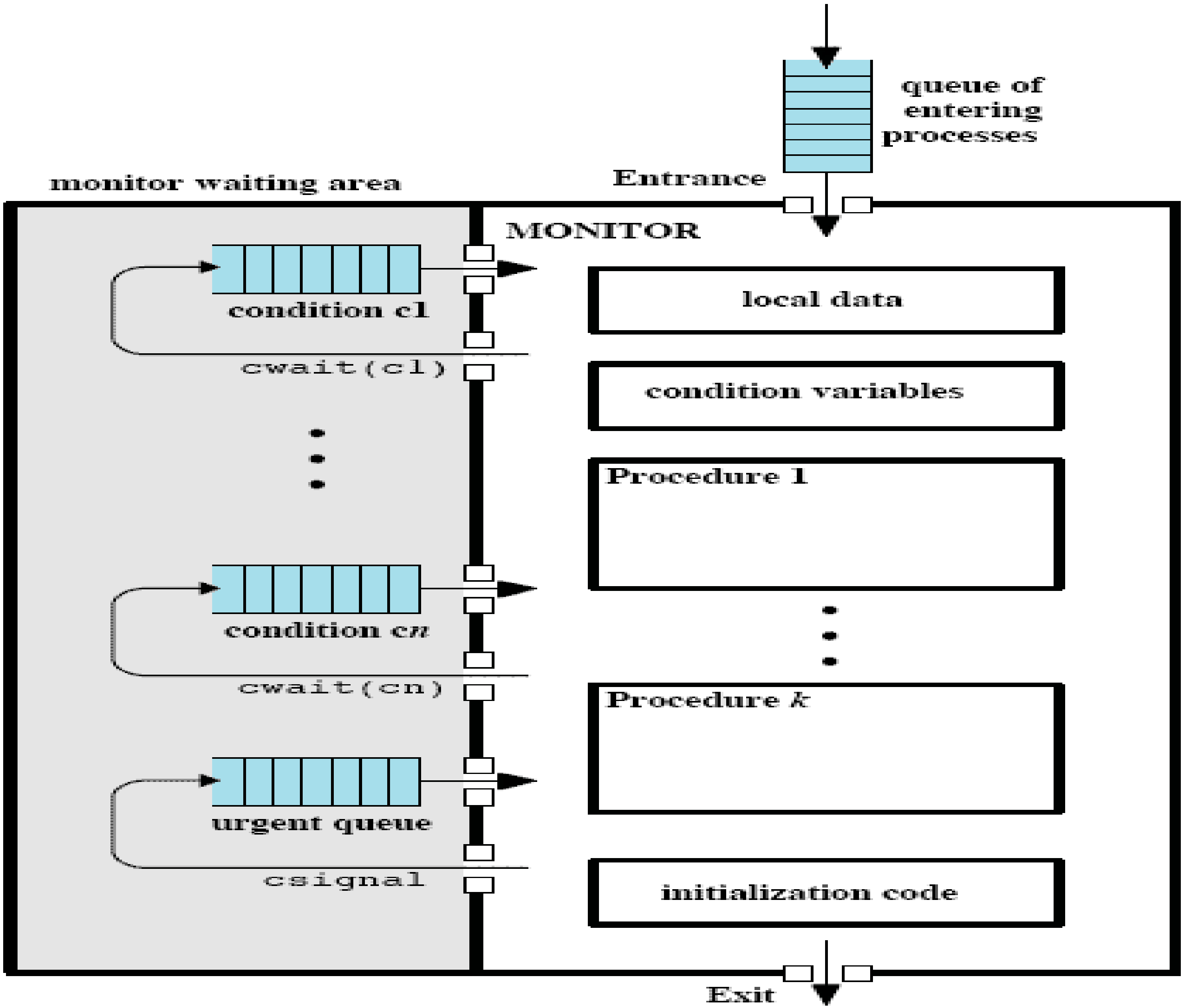
Main characteristics

- Local data variables are accessible only by the monitor
- Process enters monitor by invoking one of its procedures
- Only one process may be executing in the monitor at a time

Synchronization

- Synchronisation achieved by **condition variables** within a monitor
  - only accessible by the monitor.
- Monitor 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



Monitors

- One have to be very careful while using semaphore

- Monitor is like class where only one procedure is active at one time

It is sufficient to put only the critical regions into monitor procedures as no two processes will ever execute their critical regions at the same time

```
monitor example
        integer i;
        condition c;

        procedure producer( );
        .
        .
        .
        end;

        procedure consumer( );
        .
        .
        .
        end;
end monitor;
```

Bounded Buffer Solution Using Monitor

```
/* program producerconsumer */
monitor boundedbuffer;
char buffer [N];                                        /* space for N items */
int nextin, nextout;                                    /* 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 */
}
{                                                          /* monitor body */
     nextin = 0; nextout = 0; count = 0;           /* buffer initially empty */
}
```

Bounded Buffer 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

outline

- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem

Process Interaction

- When processes interact with one another, two fundamental requirements must be satisfied:
  - synchronization and
  - communication.
- Message Passing is one solution to the second requirement
  - Added bonus: It works with shared memory *and* with distributed systems

Message Passing

- The actual function of message passing is normally provided in the form of a pair of primitives:
- send (destination, message)
- receive (source, message)

Synchronization

- Communication requires synchronization
  - Sender must send before receiver can receive
- What happens to a process after it issues a send or receive primitive?
  - Sender and receiver may or may not be blocking (waiting for message)

Blocking send,
Blocking receive

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

Non-blocking Send

- More natural for many concurrent programming tasks.
- Nonblocking send, blocking receive
  - Sender continues on
  - Receiver is blocked until the requested message arrives
- Nonblocking send, nonblocking receive
  - Neither party is required to wait

Addressing

- Sendin process need to be able to specify which process should receive the message
  - Direct addressing
  - Indirect Addressing

Direct Addressing

- Send primitive includes a specific identifier of the destination process
- Receive primitive could know ahead of time which process a message is expected
- Receive primitive could use source parameter to return a value when the receive operation has been performed

Indirect addressing

- Messages are sent to a shared data structure consisting of queues
- Queues are called *mailboxes*
- One process sends a message to the mailbox and the other process picks up the message from the mailbox

Indirect Process Communication

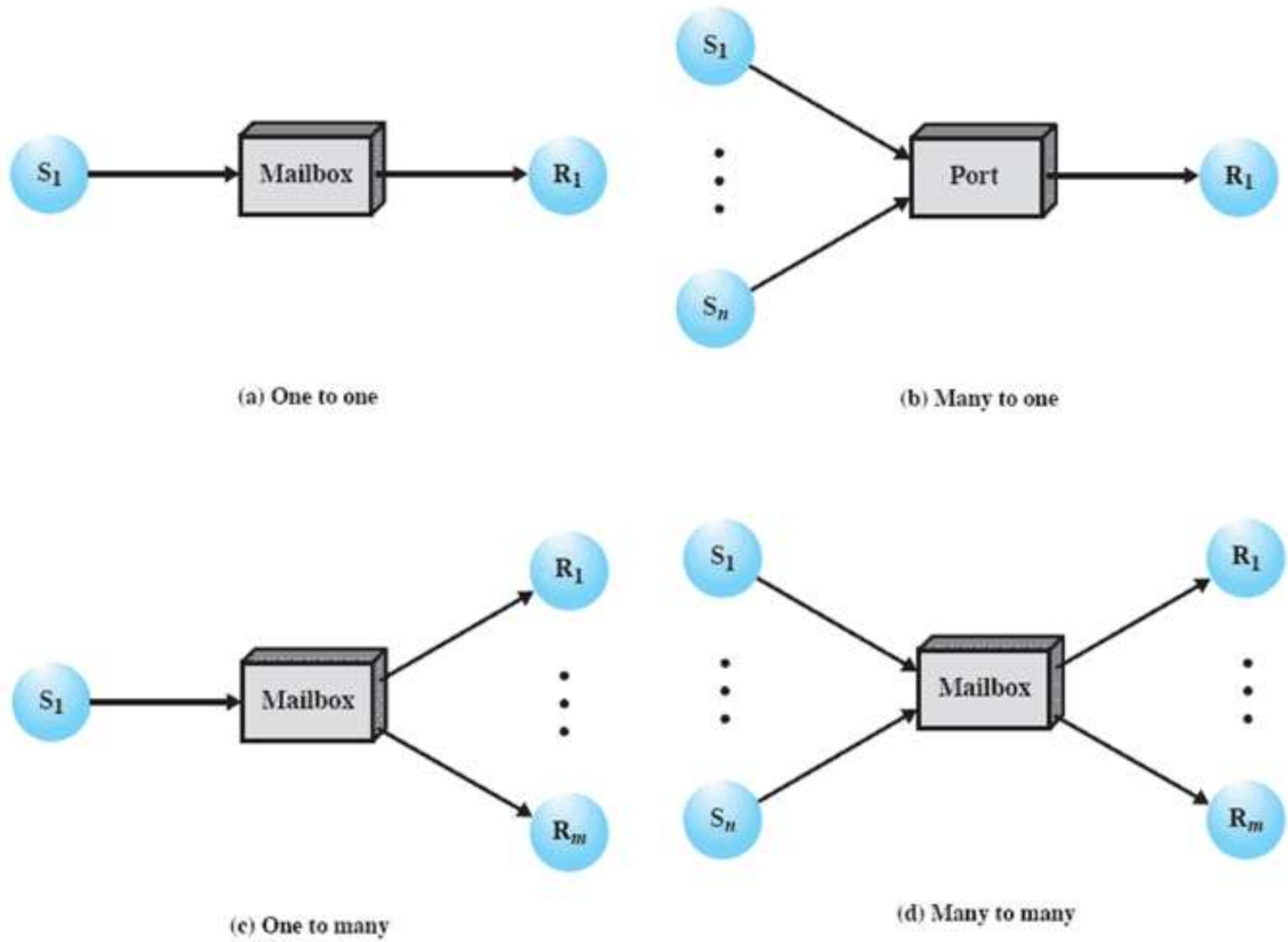


Figure 5.18 Indirect Process Communication

General Message Format

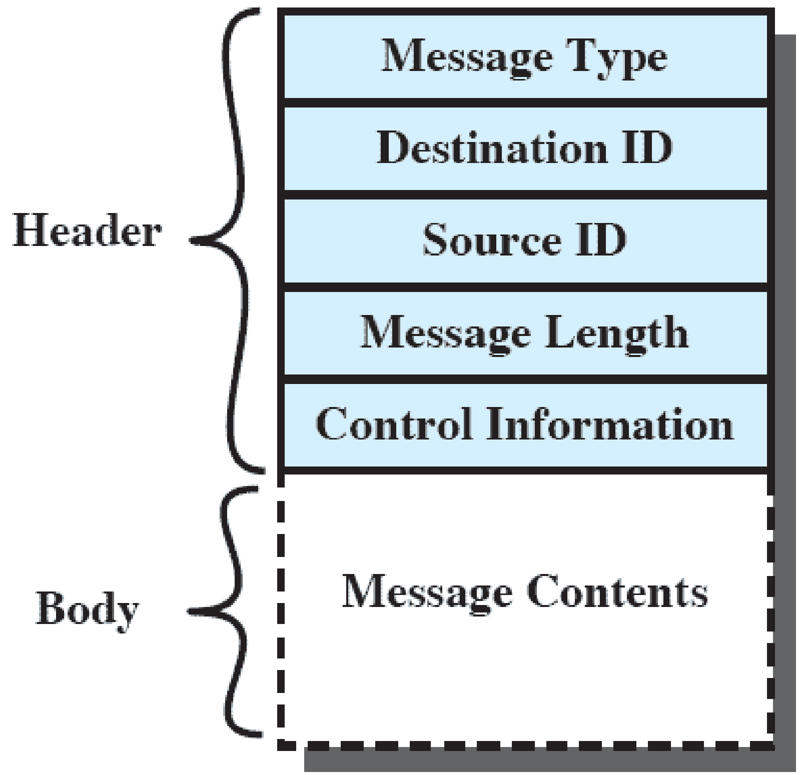


Figure 5.19 General Message Format

Mutual Exclusion Using Messages

```
/* 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

outline

- Principals of Concurrency
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- Readers/Writers Problem

Readers/Writers Problem

- A data area is shared among many processes
  - Some processes only read the data area, some only write to the area
- Conditions to satisfy:
  1. Multiple readers may read the file at once.
  2. Only one writer at a time may write
  3. If a writer is writing to the file, no reader may read it.
- Priority
  1. Readers have priority
  2. Writers have priority

Reader have priority : Regulations

- No reader will be kept waiting unless writer has already obtained the permission to write
- No reader should wait for other reader to finish simply because writer is waiting
- Problem : In this case there is possibility of starvation for the writers

Writer have priority : Regulations

- Once the writer is ready that writer performs its write as soon as possible
- Writer is waiting to write, new reader will not perform read operation.
- Problem : In this case there is a possibility of starvation for readers

Readers have Priority

```
/* 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);
}
```

Writers have Priority

```
/* 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);
    }
}
```

Writers have Priority

```
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);
}
```