Concurrency: Mutual Exclusion and Synchronization

Chapter 5

Concurrency

- Multiple applications
  - Multiprogramming
- Structured application
  - Application can be a set of concurrent processes
- Operating-system structure
  - Operating system is a set of processes or threads

Concurrency

Table 5.1 Some Key Terms Related to Concurrency

critical section	A section of code within a process that requires access to shared resources and which may not be executed while another process is in a corresponding section of code.
deadlock	A situation in which two or more processes are unable to proceed because each is waiting for one of the others to do something.
livelock	A situation in which two or more processes continuously change their state in response to changes in the other process(es) without doing any useful work.
mutual exclusion	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.
race condition	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.
starvation	A situation in which a runnable process is overlooked indefinitely by the scheduler; although it is able to proceed, it is never chosen.

Difficulties of Concurrency

- Sharing of global resources
- Operating system managing the allocation of resources optimally
- Difficult to locate programming errors

A Simple Example

Setup: two processes/two threads

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

A Simple Example

Setup: two processes/two threads, multiprocessor

Hint: chin, chout are global variables, getchar echoes characters.

```
  Process P1          Process P2
.                        .
chin = getchar();        .
.                  chin = getchar();
chout = chin;          chout = chin;
putchar(chout);          .
     .                   putchar(chout);
     .                        .
```

Operating System Concerns

- Keep track of various processes
- Allocate and deallocate resources
  - Processor time
  - Memory
  - Files
  - I/O devices
- Protect data and resources
- Functions of process must be independent of the speed of execution of other concurrent processes

Interaction Among Processes

- Processes unaware of each other
- Processes indirectly aware of each other
- Process directly aware of each other

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

Competition Among Processes for Resources

- Mutual Exclusion
  - Critical sections
    - Only one program at a time is allowed in its critical section
    - Example only one process at a time is allowed to send command to the printer
- Deadlock
- Starvation

Requirements for Mutual Exclusion

1. Only one process at a time is allowed in the critical section for a resource
2. A process that halts in its noncritical section must do so without interfering with other processes
3. No deadlock or starvation
4. A process must not be delayed access to a critical section when there is no other process using it
5. No assumptions are made about relative process speeds or number of processes
6. A process remains inside its critical section for a finite time only

Mutual Exclusion: Hardware Support

- Interrupt Disabling
  - A process runs until it invokes an operating system service or until it is interrupted
  - Disabling interrupts guarantees mutual exclusion in a uniprocessor system
  - Processor is limited in its ability to interleave programs
  - Multiprocessing
    - disabling interrupts on one processor will not guarantee mutual exclusion
  - NOC: open question

Mutual Exclusion: Hardware Support

- Special Machine Instructions
  - Performed in a single instruction cycle
  - Access to the memory location is blocked for any other instructions

Mutual Exclusion: Hardware Support

- Test and Set Instruction

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

Mutual Exclusion: Hardware Support

- Exchange Instruction

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

Mutual Exclusion

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

}
```

(a) Test and set instruction

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

(b) Exchange instruction

Figure 5.2 Hardware Support for Mutual Exclusion

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 process is 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
  - Pipeline stalls

Semaphores

- Special variable called a semaphore is used for signaling
- If a process is waiting for a signal, it is suspended until that signal is sent

Semaphores

- Semaphore is a variable that has an integer value
  - May be initialized to a nonnegative number
  - Wait operation decrements the semaphore value
  - Signal operation increments semaphore value

Semaphore Operations

- Initialize with a non-negative value
- semWait() decrements the semaphore value
- semSignal() increments the value

- No other way to access the semaphore (!!)

- In general, anyone can call semWait() and semSignal()
- For a mutex, only the process with the lock can release the lock.

Properties of Semaphore Use

- No way to know whether a semWait() will block or not.
- semSignal() may wake up a process. The signaling and unblocked process continue concurrently → you don't know which is next on a uniprocessor system.
- On semSignal(), you don't know whether it wakes up a process.

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 ==  1)
          s.value = 0;
     else
          {
               place this process in s.queue;
               block this process;
          }
}
void semSignalB(semaphore s)
{
     if (s.queue.is_empty())
          s.value = 1;
     else
     {
          remove a process P from s.queue;
          place process P on ready list;
     }
}
```

Figure 5.4 A Definition of Binary Semaphore Primitives

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

- Processes A,B,C read data from Process D

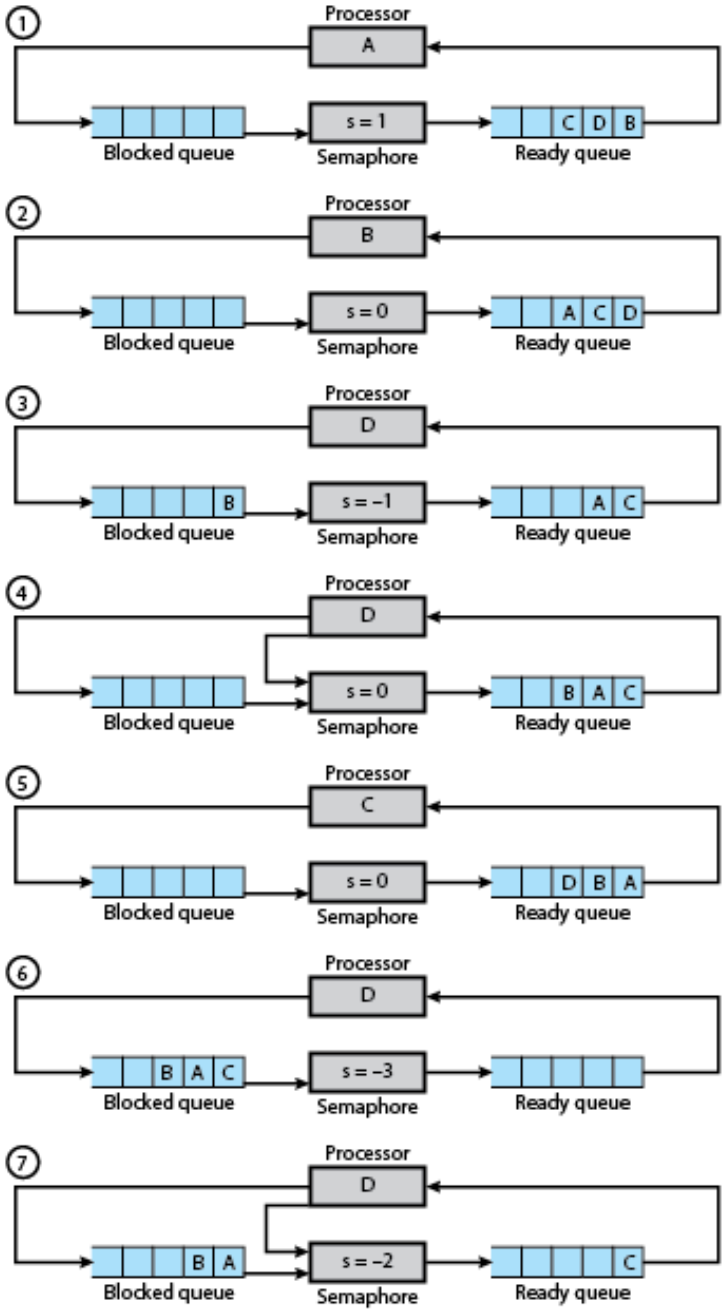


Figure 5.5 Example of Semaphore Mechanism

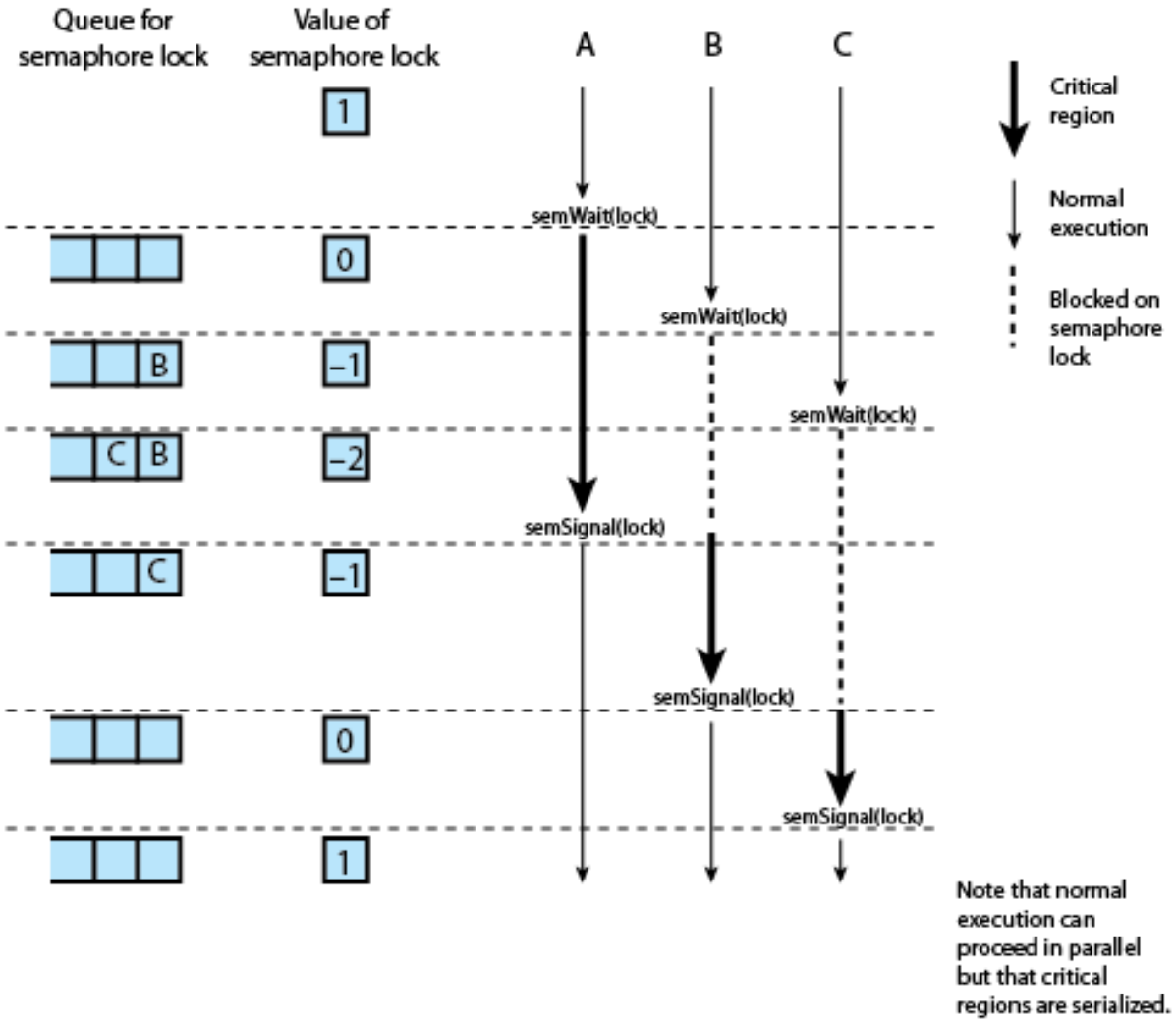


Figure 5.7 Processes Accessing Shared Data Protected by a Semaphore

Review

- What do we need to implement Semaphores?
- What are the components of Semaphores?
- When do Semaphores block?
- Can Semaphores become negative?
- If Semaphores are used to protect code sections: what does the initial number control?
- … what does the current value indicate?

Producer/Consumer Problem

- 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

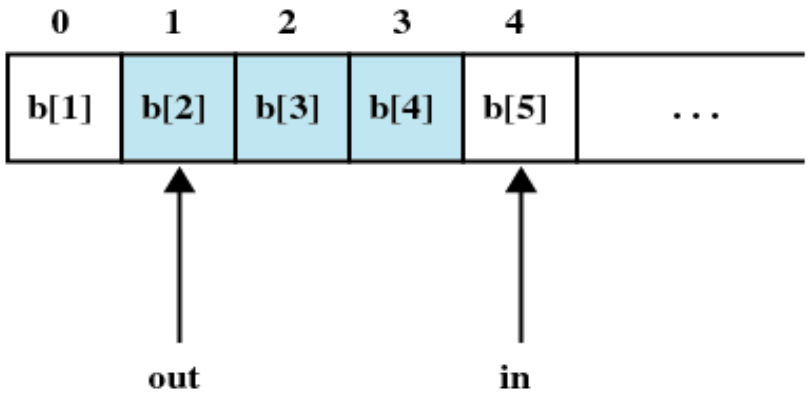
Producer

```
producer:
while (true) {
  /* produce item v */
  b[in] = v;
  in++;
}
```

Consumer

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

Producer/Consumer Problem



Note: shaded area indicates portion of buffer that is occupied

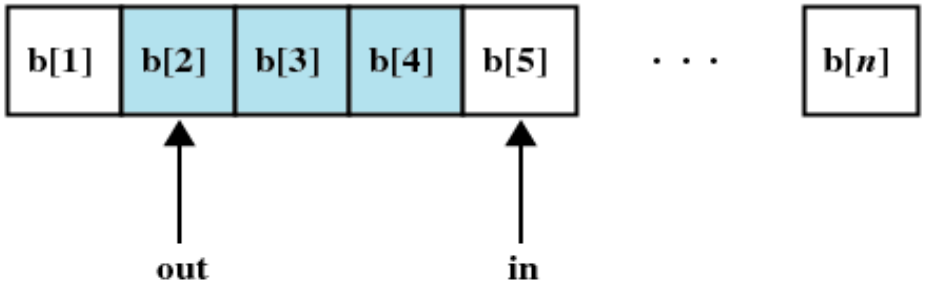
Figure 5.8 Infinite Buffer for the Producer/Consumer Problem

Producer with Circular Buffer

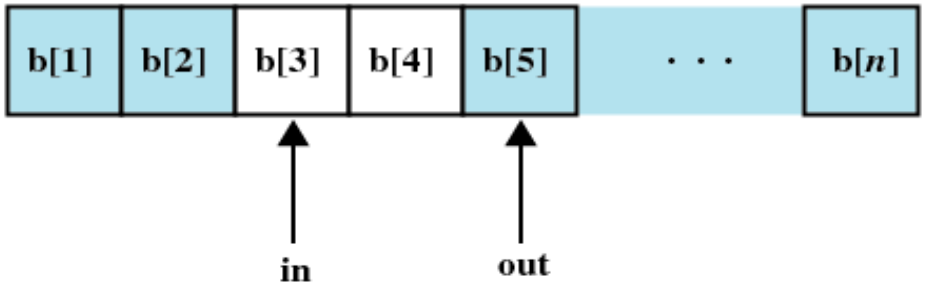
```
producer:
while (true) {
  /* produce item v */
  while ((in + 1) % n == out)  /*
  do nothing */;
  b[in] = v;
  in = (in + 1) % n
}
```

Consumer with Circular Buffer

```
consumer:
while (true) {
  while (in == out)
   /* do nothing */;
  w = b[out];
  out = (out + 1) % n;
  /* consume item w */
}
```



(a)



(b)

Figure 5.12 Finite Circular Buffer for the Producer/Consumer Problem

```
/* program producerconsumer */
int n;
binary_semaphore s = 1;
binary_semaphore 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);
}
```

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.

```
/* program producerconsumer */
int n;
binary_semaphore s = 1;
binary_semaphore 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 5.10 A Correct Solution to the Infinite-Buffer Producer/Consumer Problem Using Binary Semaphores

```
/* program  producerconsumer */
semaphore n = 0;
semaphore 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

```
/* program boundedbuffer */
const int sizeofbuffer = /* buffer size */;
semaphore s = 1;
semaphore n= 0;
semaphore 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);
}
```

Figure 5.13 A Solution to the Bounded-Buffer Producer/Consumer Problem Using Semaphores

Monitors

- Monitor is a software module
- Chief characteristics
  - Local data variables are accessible only by the monitor (=> shared data in monitor is “safe”)
  - Process enters monitor by invoking one of its procedures (=> controlled entry)
  - Only one process may be executing in the monitor at a time (=> mutex)
- Uses condition variables for signaling
- Unused signals are lost (!= semaphores)

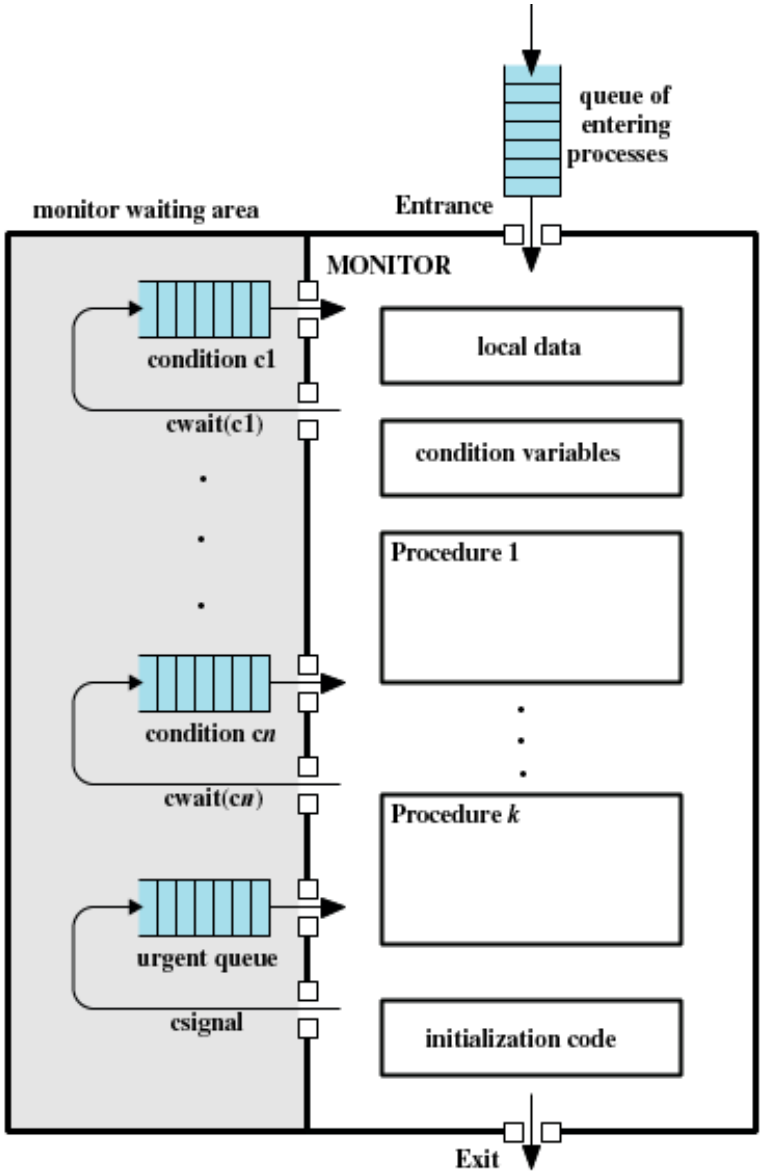


Figure 5.15 Structure of a Monitor

```
/* 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 */
}
```

```
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

- Enforce mutual exclusion
- Exchange information

```
send (destination, message)
receive (source, message)
```

Synchronization

- 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
  - Called a rendezvous

Synchronization

- 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

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

Addressing

- 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

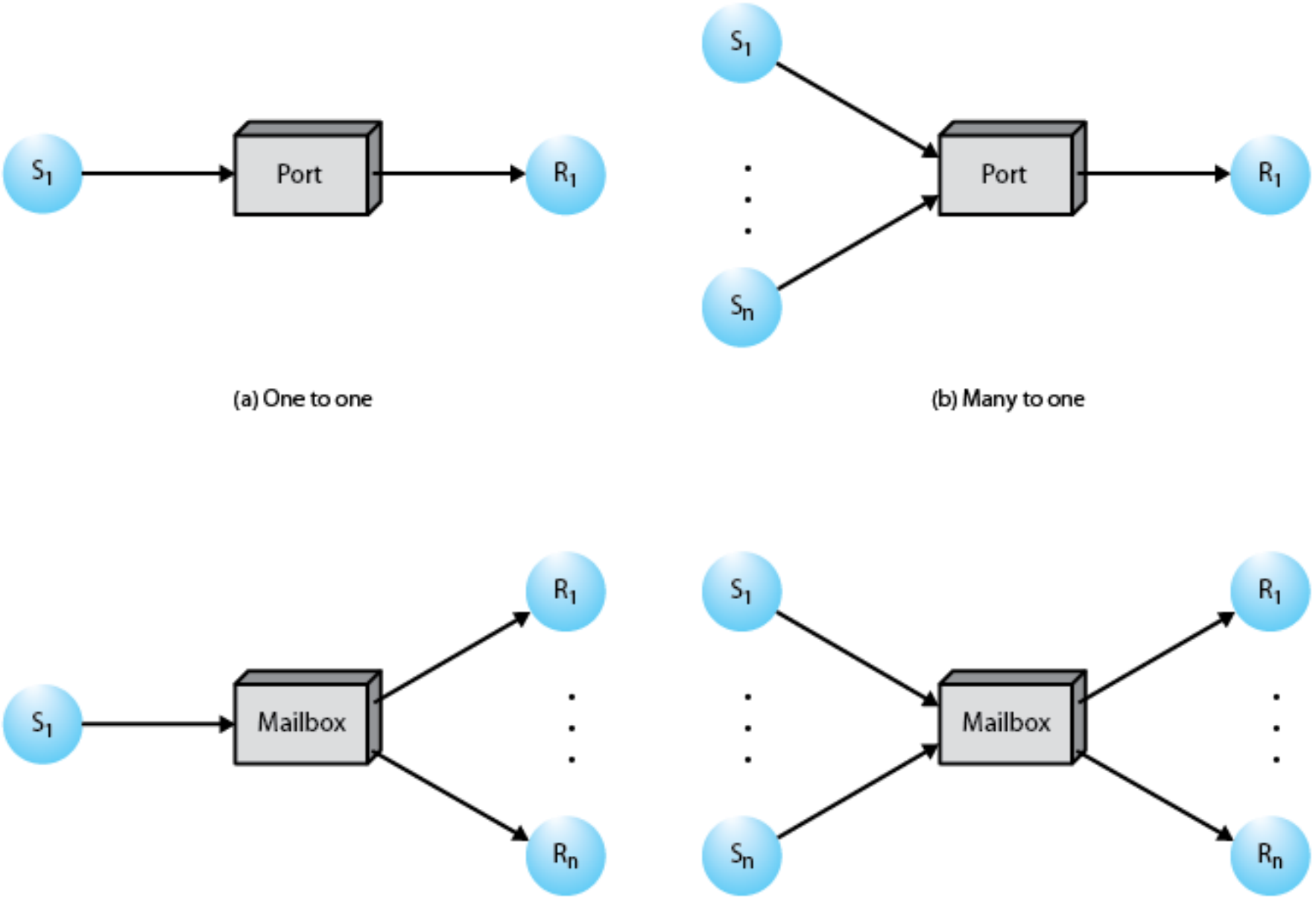
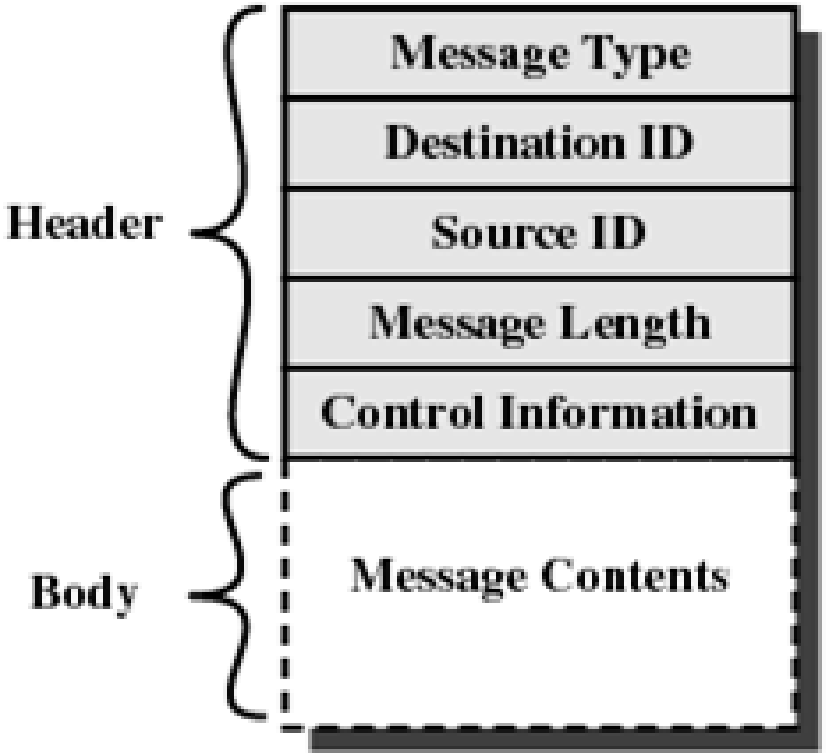


Figure 5.18 Indirect Process Communication

Message Format

… depends on the requirements of the OS (e.g., fixed-length vs. variable length messages)



```
/* program mutualexclusion */
const int n = /* number of processes  */;
void P(int i)
{
    message msg;
    while (true)
    {
     receive (mutex, msg);
     /* critical section   */;
     send (mutex, msg);
     /* remainder   */;
    }
}
void main()
{
    create_mailbox (mutex);
    send (mutex, 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/Consumer Problem Using Messages

Readers/Writers Problem

- Any number of readers may simultaneously read the file
- Only one writer at a time may write to the file
- 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/Writers Problem Using Semaphores: Readers 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);
    }
}
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

FAQ

- Example, why the order of operations matters. Specifically, why should semaphores for capacity management be outside the atomic buffer access. Example:

`produce()`
`semWait(s)`
`semWait(e)`
`append()`
`semSignal(n)`
`semWait(s)`
	`semWait(n)`
	`semWait(s)`
	`append()`
	`semWait(s)`
	`semSignal(e)`
	`consume()`

Hint: this is the wrong way!

- Now assume, we can only put one item into the buffer, and initially the buffer is full.

	producer	consumer	s	n	e	
			1	1	0	
1	produce()					
2	semWait(s)		0	1	0	
3	semWait(e)		0	0	0	<- producer blocked
4		semWait(n)	0	0	0	
5		semWait(s)	0	0	0	<- consumer blocked!

error was moving capacity mgt. inside critical section

- Tip: force buffer exhaustion to trigger cyclic dependency