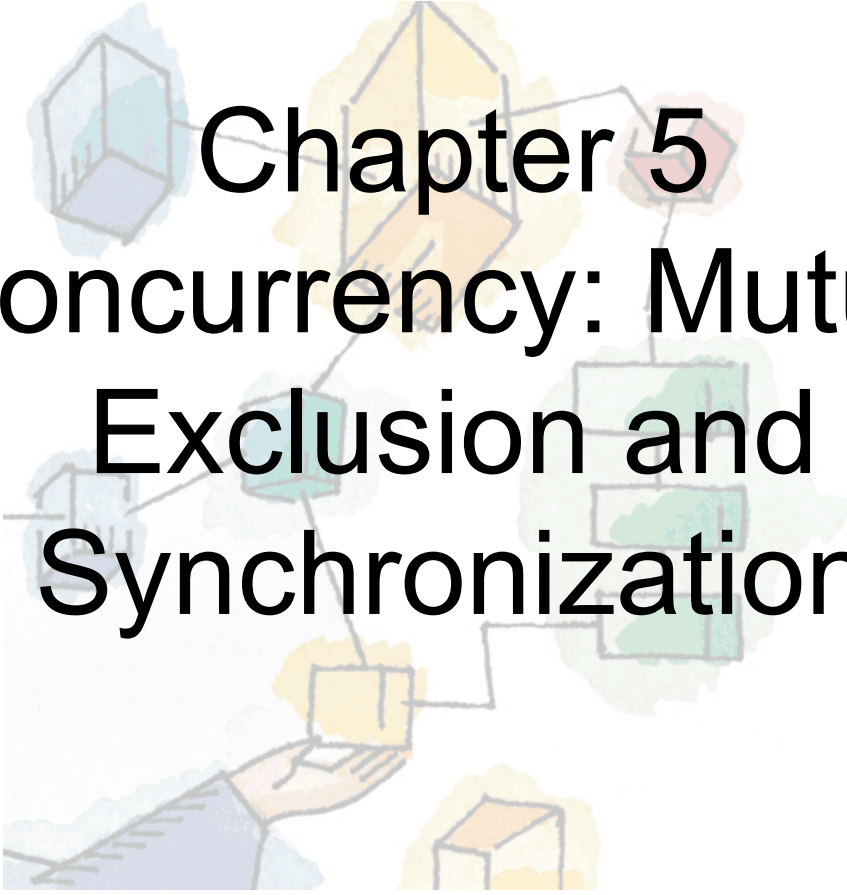


*Operating Systems:
Internals and Design Principles, 6/E*
William Stallings



Chapter 5

Concurrency: Mutual Exclusion and Synchronization

Dave Bremer
Otago Polytechnic, N.Z.
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Roadmap

→ Principals of Concurrency

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





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

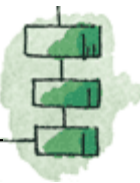




Concurrency

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





Key Terms

Table 5.1 Some Key Terms Related to Concurrency

atomic operation	A sequence of one or more statements that appears to be indivisible; that is, no other process can see an intermediate state or interrupt the operation.
critical section	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.
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 states in response to changes in the other <u>process(es)</u> 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.





Interleaving and Overlapping Processes

- Earlier (Ch2) we saw that processes may be interleaved on uniprocessors

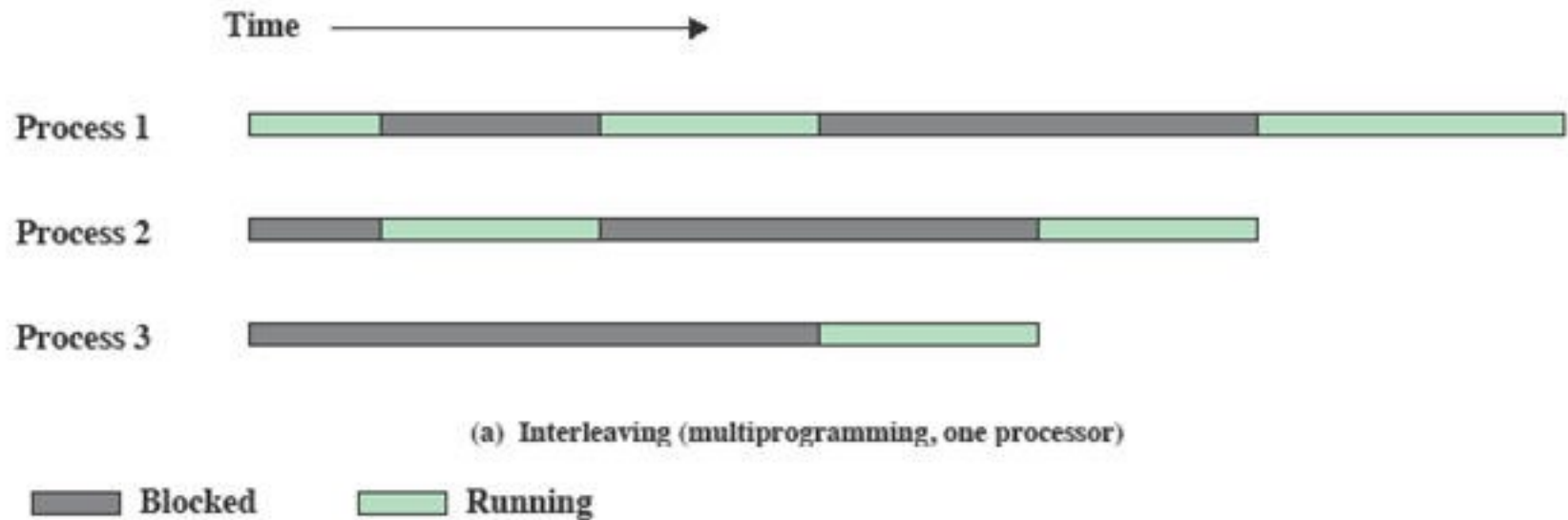


Figure 2.12 Multiprogramming and Multiprocessing





Interleaving and Overlapping Processes

- And not only interleaved but overlapped on multi-processors



(b) Interleaving and overlapping (multiprocessing; two processors)

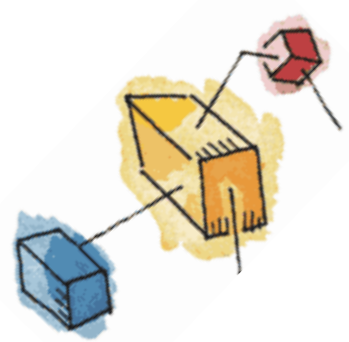
Blocked Running

Figure 2.12 Multiprogramming and Multiprocessing



Difficulties of Concurrency

- Sharing of global resources
- Optimally managing the allocation of resources
- Difficult to locate programming errors as results are not deterministic and reproducible.





A Simple Example

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





A Simple Example: On a Multiprocessor

Process P1

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

Process P2

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





Enforce Single Access

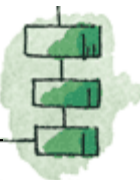
- If we enforce a rule that only one process may enter the function at a time then:
- P1 & P2 run on separate processors
- P1 enters echo first,
 - P2 tries to enter but is blocked – P2 suspends
- P1 completes execution
 - P2 resumes and executes echo





Race Condition

- A race condition occurs when
 - Multiple processes or threads read and write data items
 - They do so in a way where the final result depends on the order of execution of the processes.
- The output depends on who finishes the race last.





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



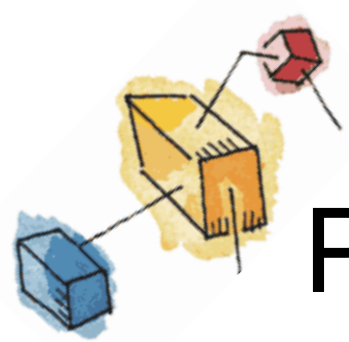


Process Interaction

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	<ul style="list-style-type: none">• Results of one process independent of the action of others• Timing of process may be affected	<ul style="list-style-type: none">• Mutual exclusion• Deadlock (renewable resource)• Starvation
Processes indirectly aware of each other (e.g., shared object)	Cooperation by sharing	<ul style="list-style-type: none">• Results of one process may depend on information obtained from others• Timing of process may be affected	<ul style="list-style-type: none">• Mutual exclusion• Deadlock (renewable resource)• Starvation• Data coherence
Processes directly aware of each other (have communication primitives available to them)	Cooperation by communication	<ul style="list-style-type: none">• Results of one process may depend on information obtained from others• Timing of process may be affected	<ul style="list-style-type: none">• Deadlock (consumable resource)• Starvation





Competition among Processes for Resources

Three main control problems:

- Need for Mutual Exclusion
 - Critical sections
- Deadlock
- Starvation





Requirements for Mutual Exclusion

- Only one process at a time is allowed in the critical section for a resource
- A process that halts in its noncritical section must do so without interfering with other processes
- No deadlock or starvation





Requirements for Mutual Exclusion

- 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



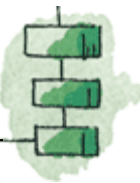


Roadmap

- Principals of Concurrency

→ Mutual Exclusion: Hardware Support

- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem





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 */;  
}
```



Special Machine Instructions

- Compare&Swap Instruction
 - also called a “compare and exchange instruction”
- Exchange Instruction





Compare&Swap Instruction

```
int compare_and_swap (int *word,  
    int testval, int newval)  
{  
    int oldval;  
    oldval = *word;  
    if (oldval == testval) *word = newval;  
    return oldval;  
}
```







Mutual Exclusion (fig 5.2)

```
/* program mutualexclusion */
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));
}
```

(a) Compare and swap instruction

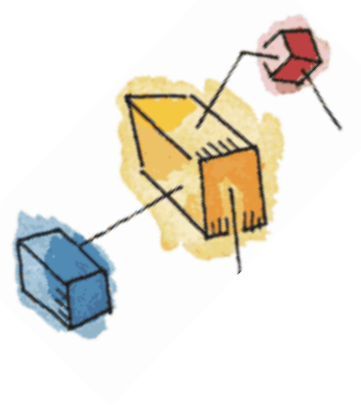




Exchange instruction

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



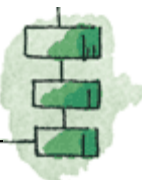


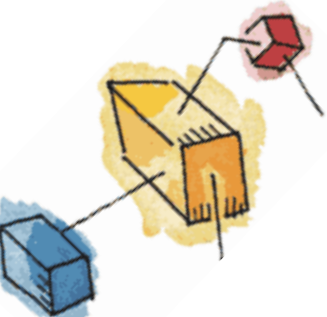
Exchange Instruction

(fig 5.2)

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

(b) Exchange instruction

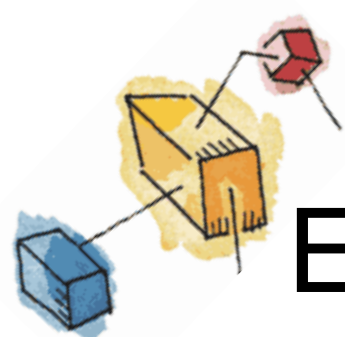




Hardware Mutual Exclusion: Advantages

- 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





Hardware Mutual Exclusion: Disadvantages

- Busy-waiting consumes processor time
- Starvation is possible when a process leaves a critical section and more than one process is waiting.
 - Some process could indefinitely be denied access.
- Deadlock is possible





Roadmap

- 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 */;
    }
}
```

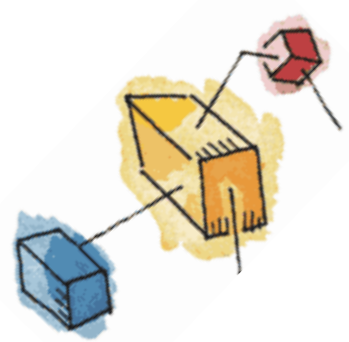


Figure 5.4 A Definition of Binary Semaphore Primitives

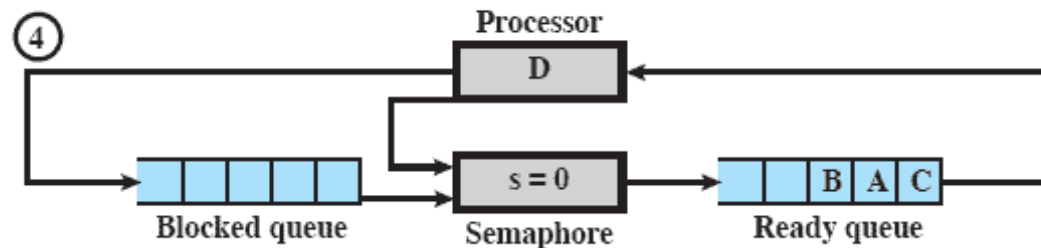
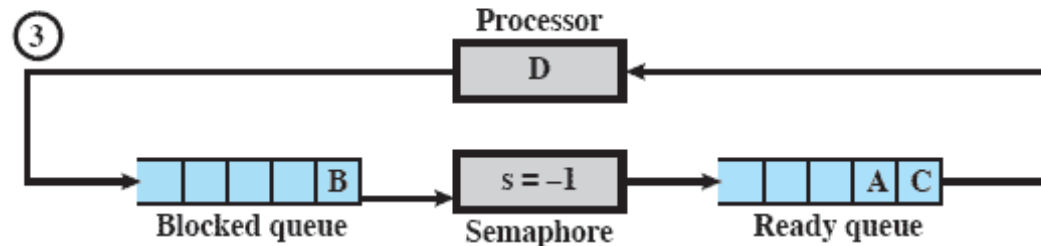
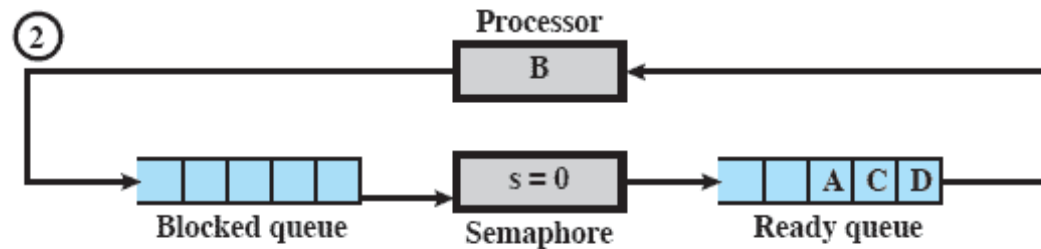
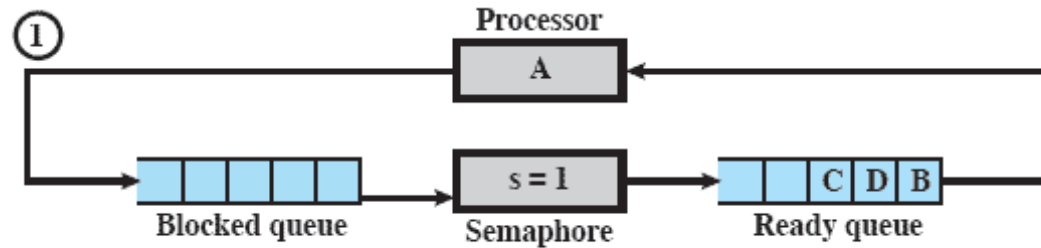


Strong/Weak Semaphore

- 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



Example of Semaphore Mechanism

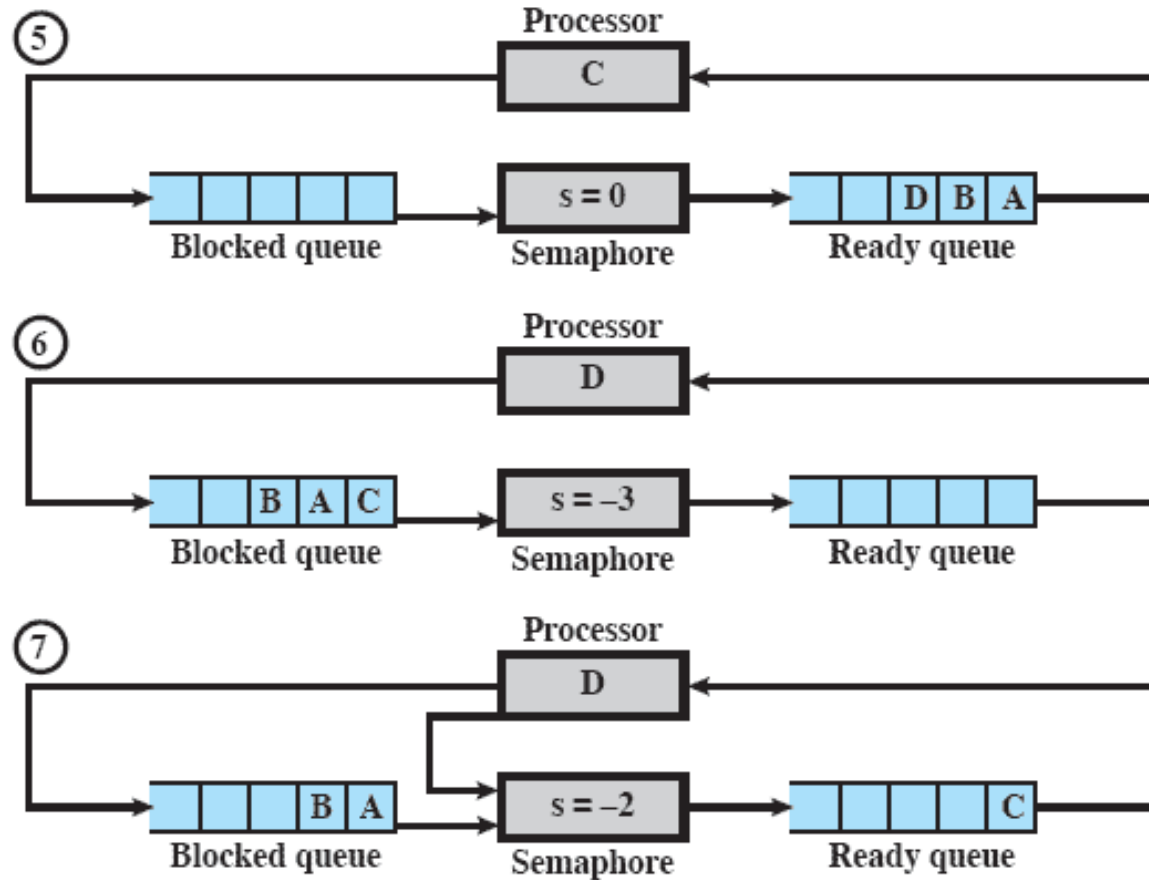
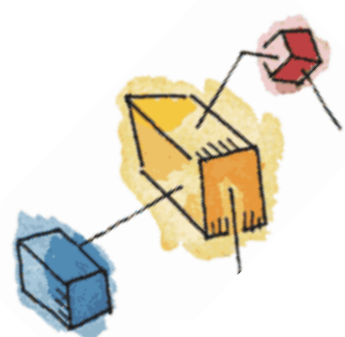


Figure 5.5 Example of Semaphore Mechanism



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



Processes Using Semaphore

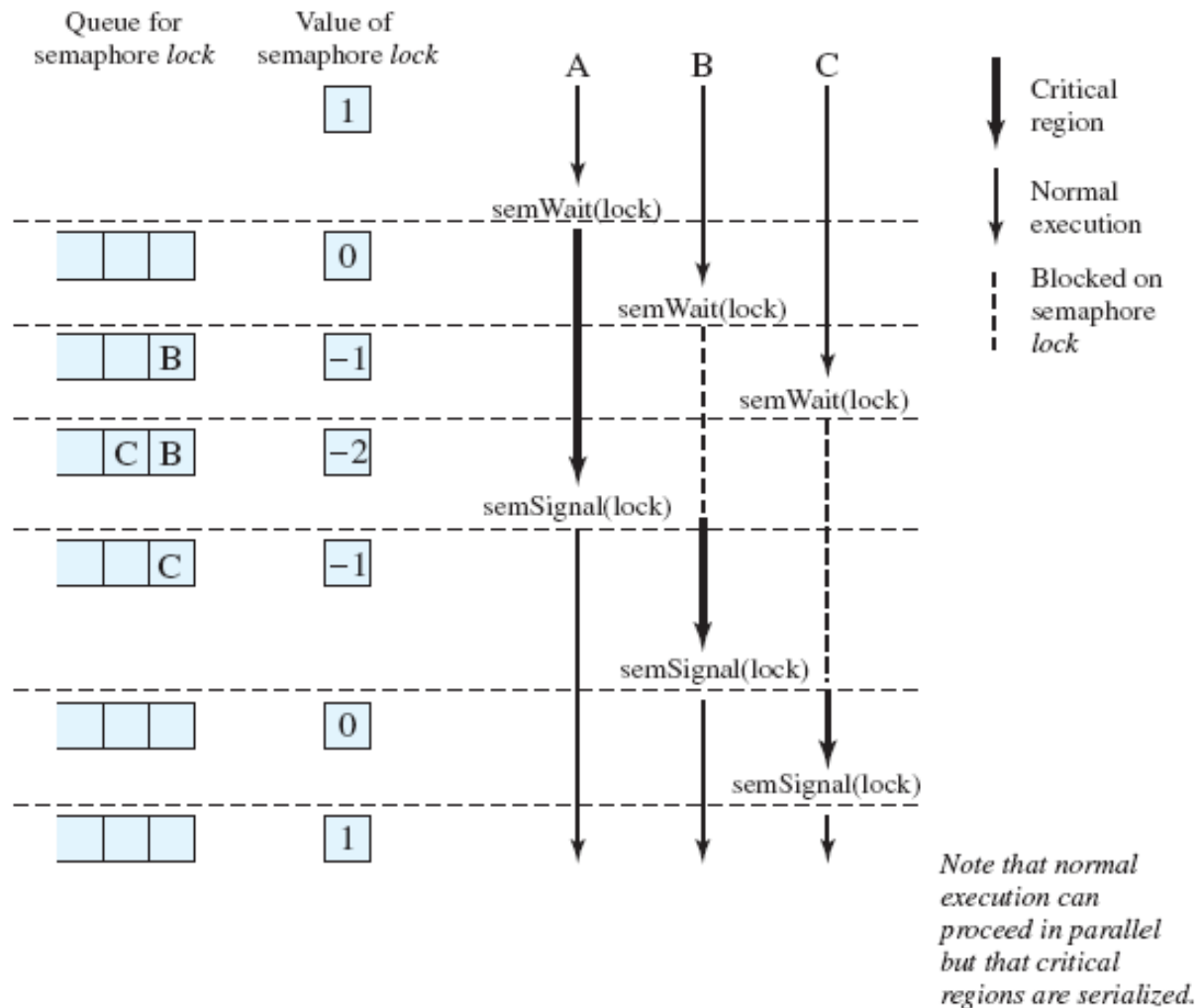


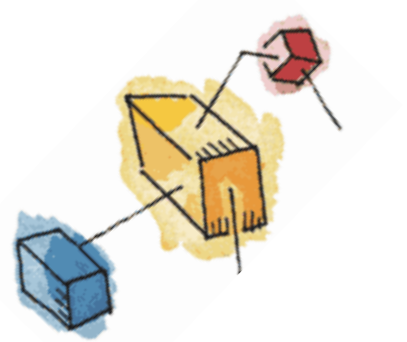
Figure 5.7 Processes Accessing Shared Data Protected by a Semaphore



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 empty buffer





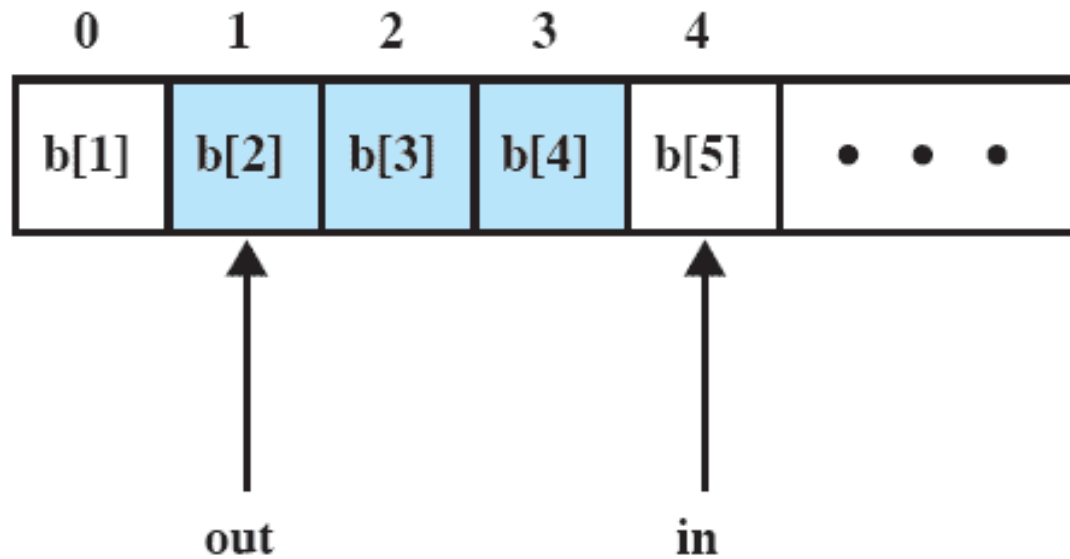
Functions

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

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



Buffer



Note: shaded area indicates portion of buffer that is occupied

Figure 5.8 Infinite Buffer for the Producer/Consumer Problem



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



Bounded Buffer

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


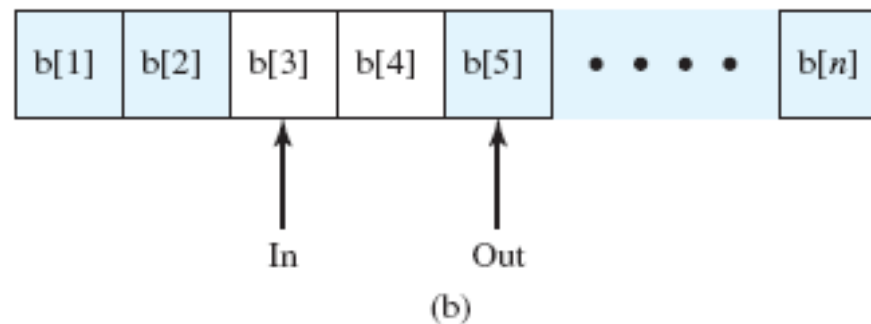
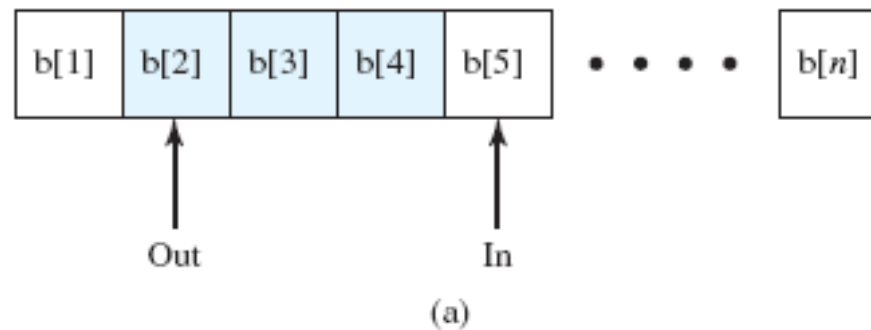



Figure 5.12 Finite Circular Buffer for the Producer/Consumer Problem





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);
}
```





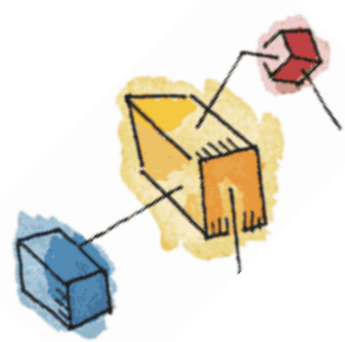
Functions in a Bounded Buffer

- .

Producer	Consumer
<pre>while (true) { /* produce item v */ while ((in + 1) % n == out) /* do nothing */; b[in] = v; in = (in + 1) % n }</pre>	<pre>while (true) { while (in == out) /* do nothing */; w = b[out]; out = (out + 1) % n; /* consume item w */ }</pre>

Demonstration Animations

- [Producer/Consumer](#)
 - Illustrates the operation of a producer-consumer buffer.
- [Bounded-Buffer Problem Using Semaphores](#)
 - Demonstrates the bounded-buffer consumer/producer problem using semaphores.





Roadmap

- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores

→ Monitors

- Message Passing
- Readers/Writers Problem





Monitors

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





Chief 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



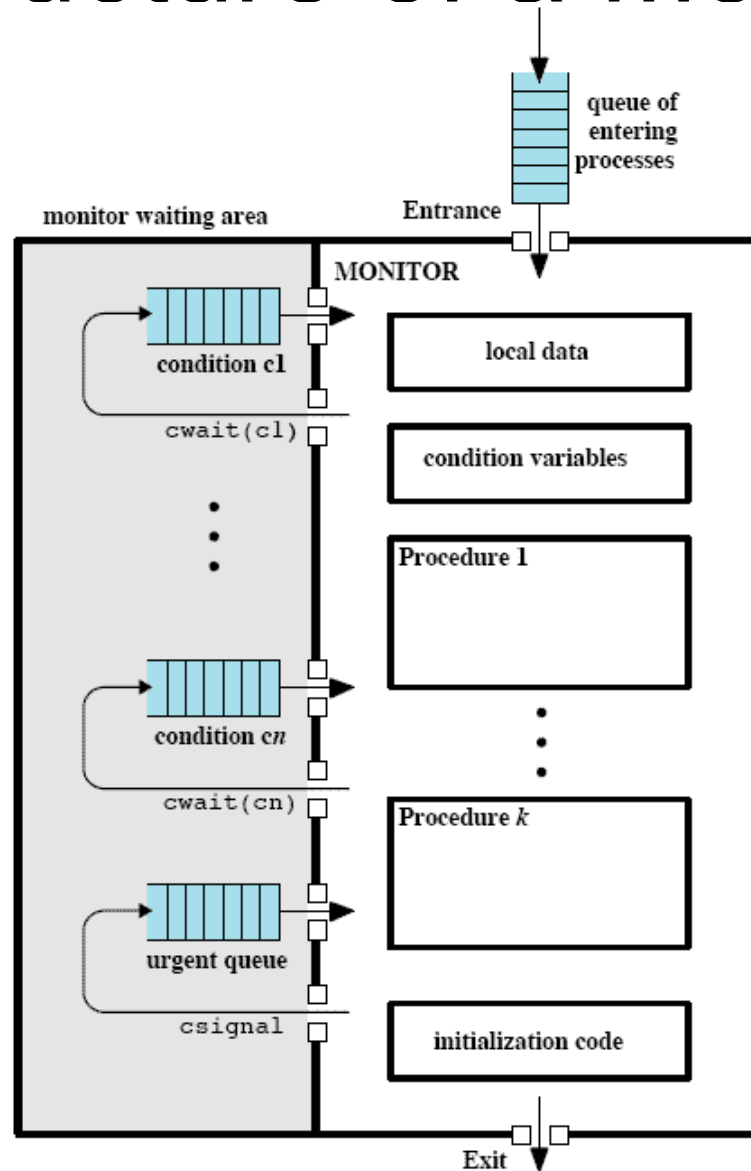


Synchronization

- 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





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 */
}
```





Solution Using Monitor

```
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);
}
```





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





Roadmap

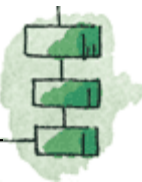
- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing
- Readers/Writers Problem





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

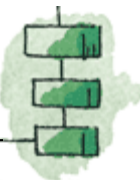
- The actual function of message passing is normally provided in the form of a pair of primitives:
 - send (destination, message)
 - receive (source, message)





Synchronization

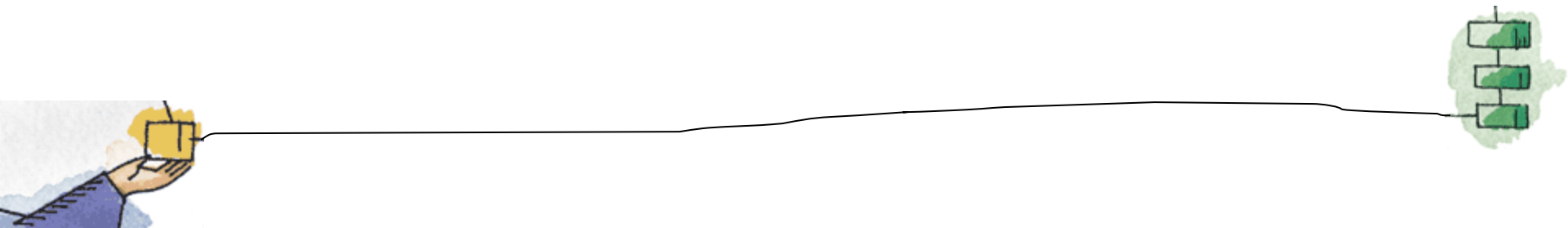
- Communication requires synchronization
 - Sender must send before receiver can receive
- What happens to a process after it issues a send or receive primitive?
 - Sender and receiver may or may not be blocking (waiting for message)





Blocking send, Blocking receive

- Both sender and receiver are blocked until message is delivered
- Known as a *rendezvous*
- Allows for tight synchronization between processes.





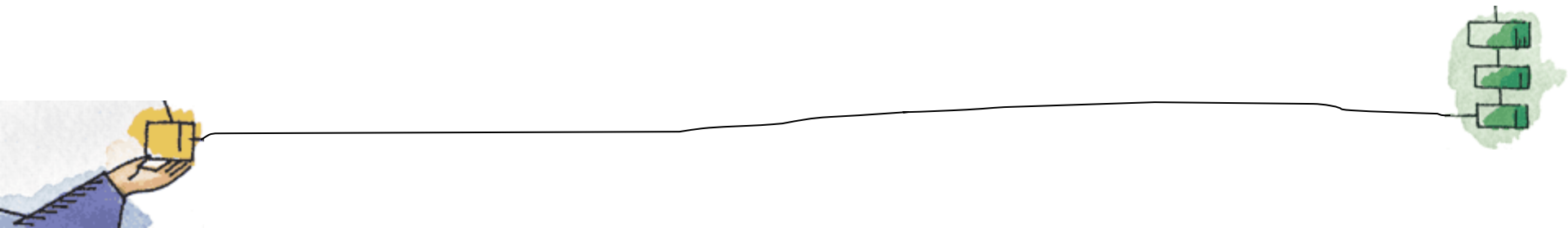
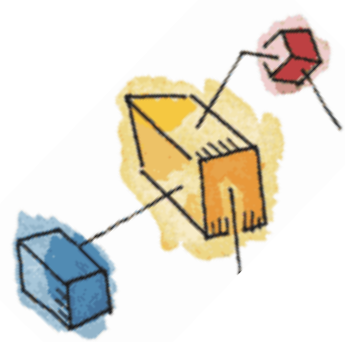
Non-blocking Send

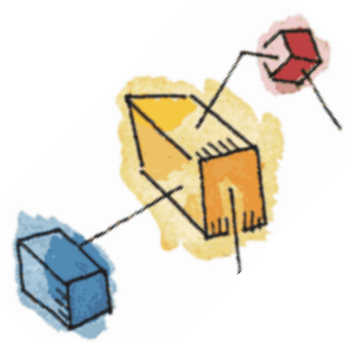
- More natural for many concurrent programming tasks.
- Nonblocking send, blocking receive
 - Sender continues on
 - Receiver is blocked until the requested message arrives
- Nonblocking send, nonblocking receive
 - Neither party is required to wait



Addressing

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

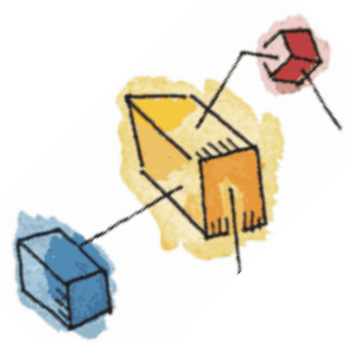




Direct Addressing

- 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

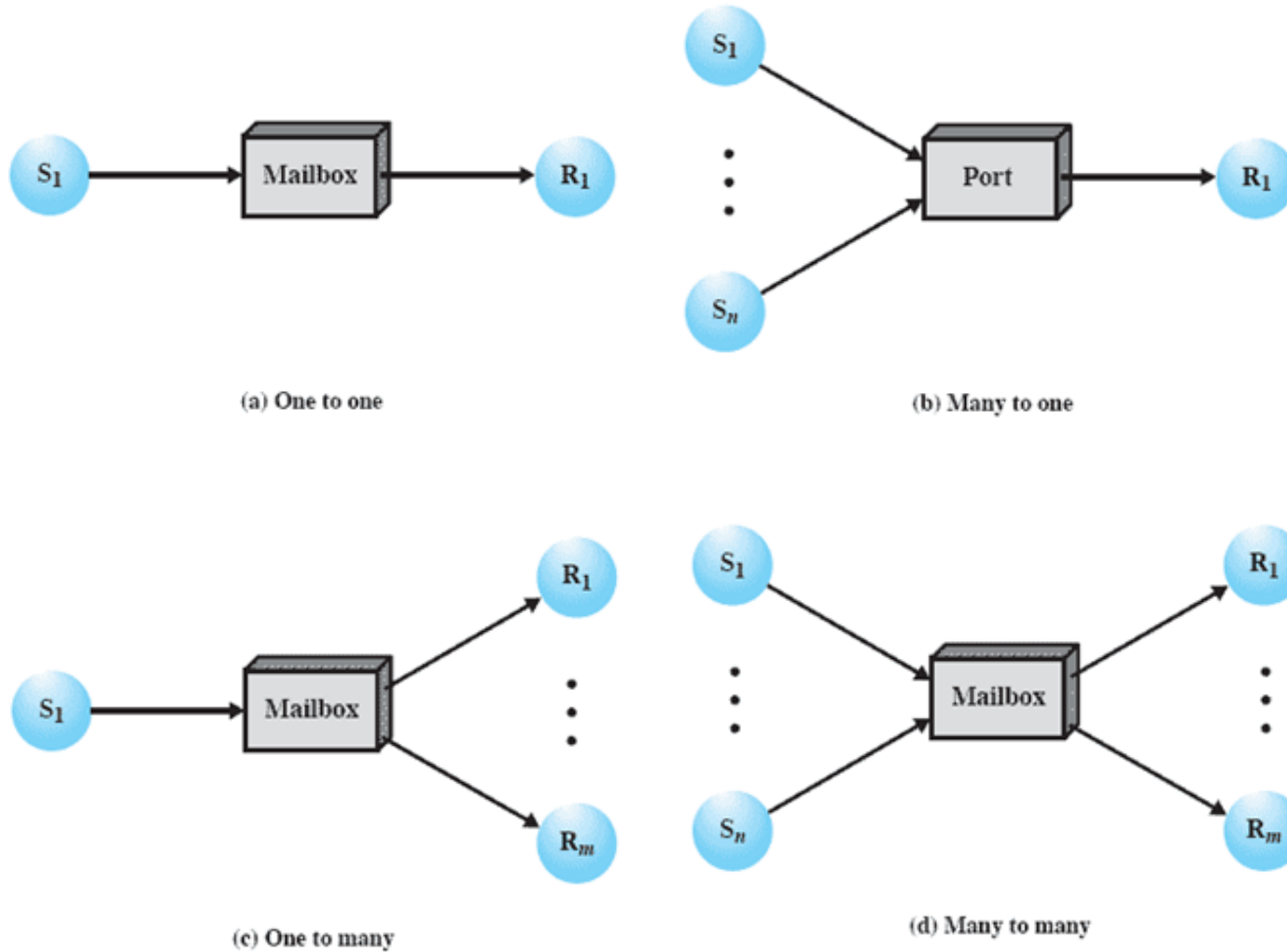


Figure 5.18 Indirect Process Communication



General Message Format

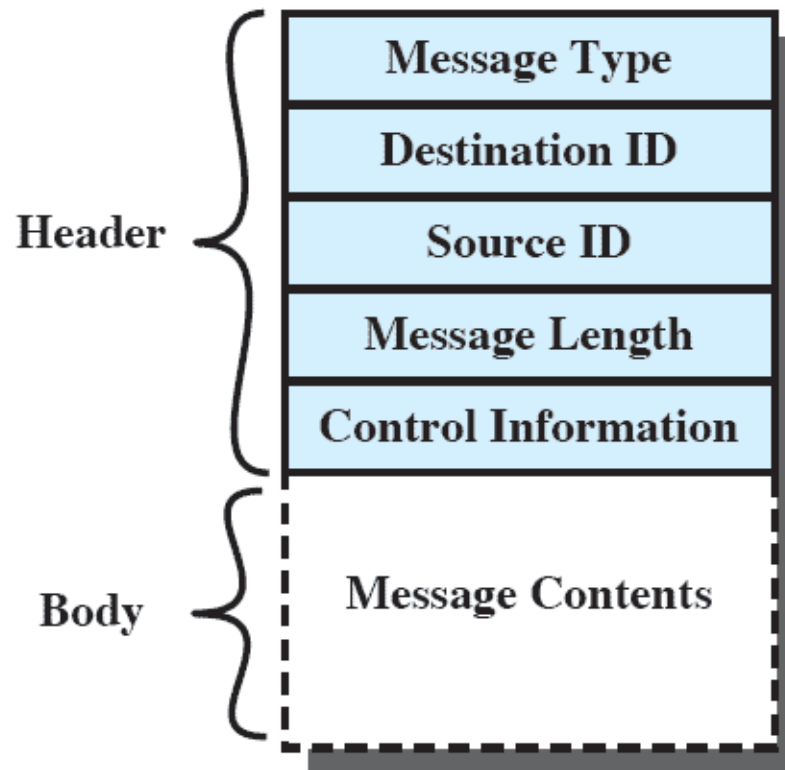


Figure 5.19 General Message Format





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







Producer/Consumer 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);
}
```



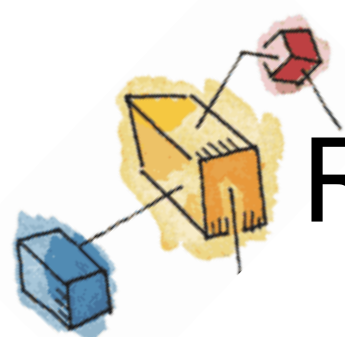


Roadmap

- Principals of Concurrency
- Mutual Exclusion: Hardware Support
- Semaphores
- Monitors
- Message Passing

→ Readers/Writers Problem



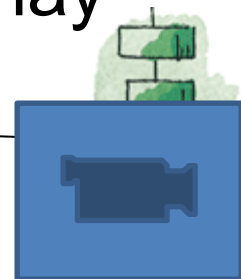


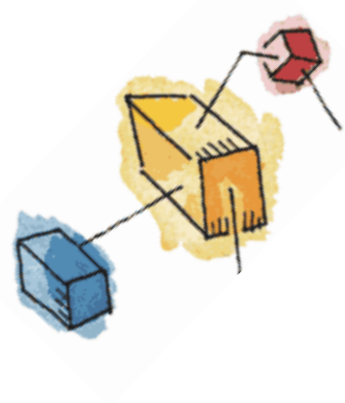
Readers/Writers Problem

- 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.



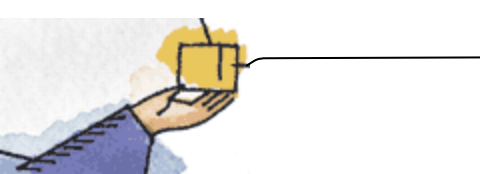
interaction of readers and writers.





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);
}
```





Message Passing

```
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++;
        }
    }
}
```