Chapter 5
Concurrency: Mutual Exclusion and Synchronization
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

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>atomic operation</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>critical section</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>deadlock</strong></td>
<td>A situation in which two or more processes are unable to proceed because each is waiting for one of the others to do something.</td>
</tr>
<tr>
<td><strong>livelock</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>mutual exclusion</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>race condition</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>starvation</strong></td>
<td>A situation in which a runnable process is overlooked indefinitely by the scheduler; although it is able to proceed, it is never chosen.</td>
</tr>
</tbody>
</table>
Interleaving and Overlapping Processes

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

![Diagram showing interleaving and overlapping processes over time with blocks for blocked and running states.](image-url)
Interleaving and Overlapping Processes

• And not only interleaved but overlapped on multi-processors

![Diagram showing time and overlapping processes]
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

\[
\text{chin} = \text{getchar}();
\]

\[
\text{chout} = \text{chin};
\]

\[
\text{putchar(chout)};
\]

Process P2

\[
\text{chin} = \text{getchar}();
\]

\[
\text{chout} = \text{chin};
\]

\[
\text{putchar(chout)};
\]
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
### Table 5.2 Process Interaction

<table>
<thead>
<tr>
<th>Degree of Awareness</th>
<th>Relationship</th>
<th>Influence That One Process Has on the Other</th>
<th>Potential Control Problems</th>
</tr>
</thead>
</table>
| 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

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
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)

```c
/* 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

```c
void exchange (int register, int memory)
{
    int temp;
    temp = memory;
    memory = register;
    register = temp;
}
```
Exchange Instruction
(fig 5.2)

```c
/* 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 \( \text{semWait} \)
  – increment. \( \text{semSignal} \)
Semaphore Primitives

```c
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

```c
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

1. Processor A
   - Blocked queue
   - Semaphore (s = 1)
   - Ready queue (C D B)

2. Processor B
   - Blocked queue
   - Semaphore (s = 0)
   - Ready queue (A C D)

3. Processor D
   - Blocked queue
   - Semaphore (s = -1)
   - Ready queue (A C)

4. Processor D
   - Blocked queue
   - Semaphore (s = 0)
   - Ready queue (B A C)
Example of Semaphore Mechanism

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));
}
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

<table>
<thead>
<tr>
<th>Producer</th>
<th>Consumer</th>
</tr>
</thead>
</table>
| while (true) {
  /* produce item v */
  b[in] = v;
  in++;
} | while (true) {
  while (in <= out) /*do nothing*/;
  w = b[out];
  out++;
  /* consume item w */
} |
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);
}
Possible Scenario

Table 5.4  Possible Scenario for the Program of Figure 5.9

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

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

```c
/* 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);
}
Bounded Buffer

<table>
<thead>
<tr>
<th>Block on:</th>
<th>Unblock on:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Producer: insert in full buffer</td>
<td>Consumer: item inserted</td>
</tr>
<tr>
<td>Consumer: remove from empty buffer</td>
<td>Producer: item removed</td>
</tr>
</tbody>
</table>

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

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

#### Consumer

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

MONITOR

- local data
- condition variables
- Procedure 1
- Procedure k
- initialization code
Bounded Buffer Solution
Using Monitor

```c
/* 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];              /* one fewer item in buffer */
    nextout = (nextout + 1) % N;
    count--;                          /* resume any waiting producer */
    csignal(notfull);
}

void monitor body
{
    nextin = 0; nextout = 0; count = 0; /* buffer initially empty */
}
```
Solution Using Monitor

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

(a) One to one

(b) Many to one

(c) One to many

(d) Many to many

Figure 5.18 Indirect Process Communication
General Message Format

Header
- Message Type
- Destination ID
- Source ID
- Message Length
- Control Information

Body
- Message Contents

Figure 5.19 General Message Format
Mutual Exclusion Using Messages

```c
/* 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);
}
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.
Readers have Priority

```c
/* 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

```c
/* 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

```c
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

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

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

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