3. Higher-Level Synchronization

3.1 Shared Memory Methods

- Monitors
- Protected Types

3.2 Distributed Synchronization/Comm.

- Message-Based Communication
- Procedure-Based Communication
- Distributed Mutual Exclusion

3.3 Other Classical Problems

- The Readers/Writers Problem
- The Dining Philosophers Problem
- The Elevator Algorithm
- Event Ordering with Logical Clocks

3.1 Shared Memory Methods

- Monitors
- Protected Types

Motivation

- Semaphores and Events are:
  - Powerful but low-level abstractions
    - Programming with them is highly error prone
    - Such programs are difficult to design, debug, and maintain
  - Not usable in distributed memory systems
- Need higher-level primitives
  - Based on semaphores or messages

Monitors

- Follow principles of *abstract data types* (object-oriented programming):
  - A data type is manipulated only by a set of predefined operations
- A monitor is
  1. A *collection of data* representing the state of the resource controlled by the monitor, and
  2. *Procedures* to manipulate the resource data

Monitors

- Implementation must guarantee:
  1. Resource is only accessible by monitor procedures
  2. Monitor procedures are mutually exclusive
- For coordination, monitors provide:

c.wait

- Calling process is blocked and placed on waiting queue associated with condition variable c

c.signal

- Calling process wakes up first process on queue associated with c

Monitors

- “condition variable” `c` is *not a conventional variable*
  - `c` has no value
  - `c` is an arbitrary name chosen by programmer
    - By convention, the name is chosen to reflect the an event, state, or condition that the condition variable represents
  - Each `c` has a waiting queue associated
  - A process may “block” itself on `c` -- it *waits* until another process issues a *signal* on `c`

Monitors

- Design Issue:
  - After c.signal, there are 2 ready processes:
    - The calling process which did the c.signal
    - The blocked process which the c.signal "woke up"
  - Which should continue?

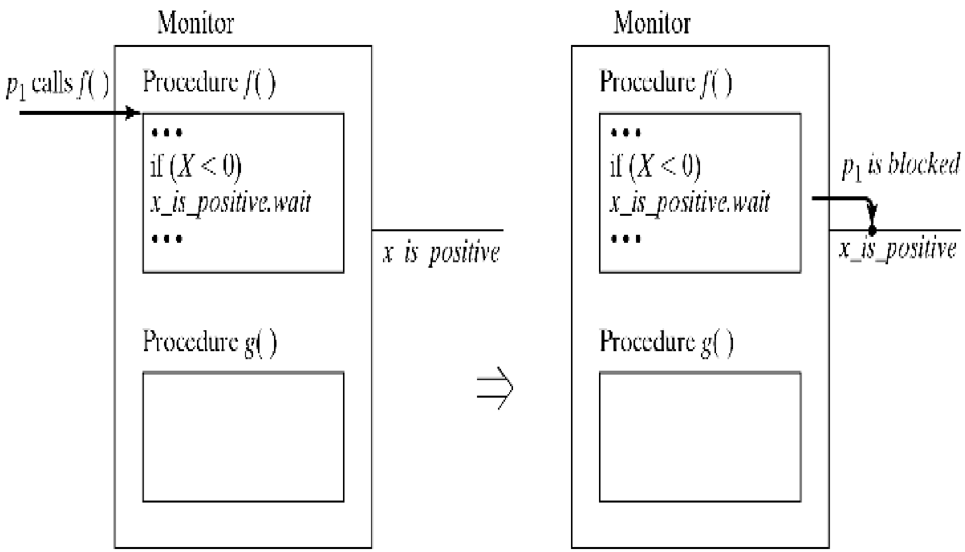
    (Only one can be executing inside the monitor!)

  Two different approaches
  - Hoare monitors
  - Mesa-style monitors

Hoare Monitors

- Introduced by Hoare in a 1974 CACM paper
- First implemented by Per Brinch Hansen in Concurrent Pascal
- Approach taken by Hoare monitor:
  - After c.signal,
    - Awakened process continues
    - Calling process is suspended, and placed on high-priority queue

Hoare Monitors



Effect of **wait**

Effect of **signal**

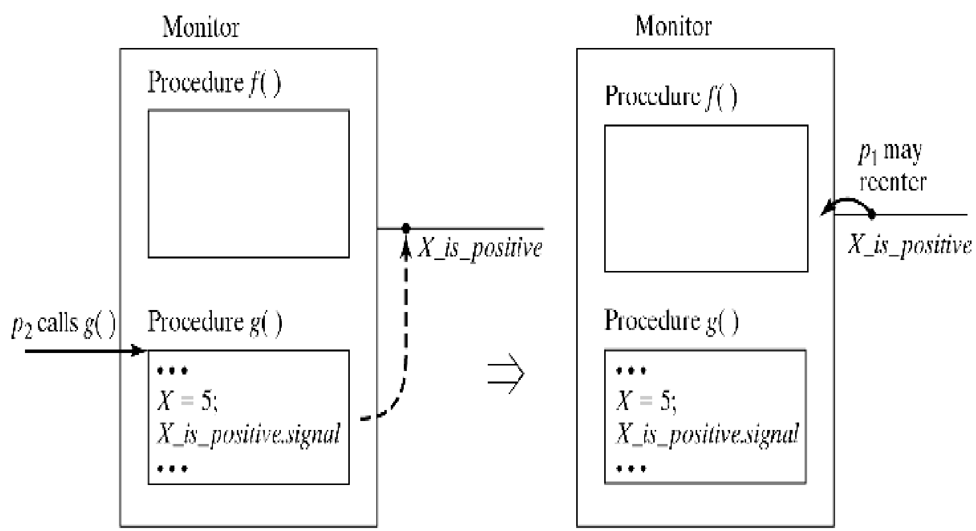


Figure 3-2

Bounded buffer problem

```
monitor BoundedBuffer
{
    char buffer[n];
    int nextin=0, nextout=0, fullCount=0;
    condition notempty, notfull;

    deposit(char data)
    {
      ...
    }

    remove(char data)
    {
      ...
    }
}
```

Bounded buffer problem

```
deposit(char data)
{
   if (fullCount==n) notfull.wait;
   buffer[nextin] = data;
   nextin = (nextin+1) % n;
   fullCount = fullCount+1;
   notempty.signal;
}

remove(char data)
{
   if (fullCount==0) notempty.wait;
   data = buffer[nextout];
   nextout = (nextout+1) % n;
   fullCount = fullCount - 1;
   notfull.signal;
}
```

Priority waits

- Hoare monitor signal resumes longest waiting process (i.e., queue is a FIFO queue)
- Hoare also introduced “Priority Waits” (aka “conditional” or “scheduled”):
  - c.wait(p)
    - p is an integer (priority)
    - Blocked processes are kept sorted by p
  - c.signal
    - Wakes up process with *lowest* (!) p

Example: alarm clock

- Processes can call wakeMe(n) to sleep for n clock ticks
- After the time has expired, call to wakeMe returns
- Implemented using Hoare monitor with priorities

Example: alarm clock

```
monitor AlarmClock {
  int now=0;
  condition wakeup;

  wakeMe(int n) {
    int alarm;
    alarm = now + n;
    while (now<alarm)wakeup.wait(alarm);
    wakeup.signal;
  }
  tick() {
  /*invoked by hardware*/
    now = now + 1;
    wakeup.signal;
  }
}
```

Example: alarm clock

- tick only wakes up one process
- Multiple processes with same alarm time awaken in a chain:
  - tick wakes up the first process
  - the first process wakes up the second process via the wakeup.signal in wakeme
  - etc.
- Without priority waits, all processes would need to wake up to check their alarm settings

Mesa-style monitors

- Variant defined for the programming language Mesa
- notify is a variant of signal
- After c.notify:
  - Calling process continues
  - Awakened process continues when caller exits
- Problem
  - Caller may wake up multiple processes P_1,P_2,P_3, …
  - P_1 could change condition on which P_2 was blocked.

Mesa monitors

- Solution

  instead of: `if (!condition) c.wait`

  use: `while (!condition) c.wait`

- *signal vs notify*
  - ***(Beware: There is no universal terminology)***
  - signal may involve caller "stepping aside"
  - notify usually has caller continuing
  - signal "simpler to use" but notify may be more efficiently implemented

Monitors in Java

- Java supports synchronized methods, which permit Java objects to be used somewhat similarly to Mesa monitors
  - Every object has an implicit lock, with a single associated condition
  - If a method is declare synchronized, the object's lock protects the entire method
  - wait() causes a thread to wait until it is notified
  - notifyAll() awakens all threads waiting on the object's lock
  - notify () awakens a single randomly chosen thread waiting on the object's lock
- But there are differences…

Differences between Java objects and monitors

- Monitors
  1. Resource is only accessible by monitor procedures
  2. Monitor procedures are mutually exclusive

- Java objects
  1. Fields are not required to be private
  2. Methods are not required to be synchronized

Per Brinch Hansen: "It is astounding to me that Java's insecure parallelism is taken seriously by the programming community, a quarter of a century after the invention of monitors and Concurrent Pascal. It has no merit." [Java's Insecure Parallelism, ACM SIGPLAN Notices 34: 38-45, April 1999].

Protected types (Ada 95)

- Encapsulated objects with public access procedures called *entries* .
- Equivalent to special case of monitor where
  - c.wait is the *first* operation of a procedure
  - c.signal is the *last* operation
- wait/signal combined into a when clause
  - The when c construct forms a *barrier*
  - Procedure continues only when the condition c is true

Example

```
entry deposit(char c)
    when (fullCount < n)
    {
        buffer[nextin] = c;
        nextin = (nextin + 1) % n;
        fullCount = fullCount + 1;
    }

entry remove(char c)
    when (fullCount > 0)
    {
        c = buffer[nextout];
        nextout = (nextout + 1) % n;
        fullCount = fullCount - 1;
    }
```

3.2 Distributed Synchronization and Communication

- Message-based Communication
  - Direct message passing
  - Indirect message passing: channels, ports, mailboxes
- Procedure-based Communication
  - Remote Procedure Calls (RPC)
  - Rendezvous
- Distributed Mutual Exclusion

Distributed Synchronization

- Semaphore-based primitive requires shared memory
- For distributed memory:
  - send(p,m)
    - Send message m to process p
  - receive(q,m)
    - Receive message from process q in variable ***m***
- Semantics of send and receive vary significantally in different systems.

Distributed Synchronization

- Types of send/receive:
  - Does sender wait for message to be accepted?
  - Does receiver wait if there is no message?
  - Does sender name exactly one receiver?
  - Does receiver name exactly one sender?

Types of send/receive

send	blocking	nonblocking
explicit naming	send m to r wait until accepted	send m to r
implicit naming	broadcast m wait until accepted	broadcast m

receive	blocking	nonblocking
explicit naming	wait for message from s	if there is a message from s, receive it; else proceed
implicit naming	wait for message from any sender	if there is a message from any sender, receive it; else proceed

Channels, Ports, and Mailboxes

- Allow indirect communication
- Senders/Receivers name channel/port/mailbox instead of processes
- Senders/Receivers determined at runtime
  - Sender does not need to know who receives the message
  - Receiver does not need to know who sent the message

Named Message Channels

- Named channel, ch1, connects processes p1 and p2
- p1 sends to p2 using send(ch1,"a")
- p2 receives from p1 using: receive(ch1,x)
- Used in CSP/Occam: Communicating Sequential Processes in the Occam Programming Language (Hoare, 1978)

Named Message Channels in CSP/Occam

- Receive statements may be implemented as *guarded commands*
  - Syntax: `when (c1) s1`
  - `s` is *enabled* (able to be executed) only when `c` is true
  - If more than one guarded command is enabled, one of them is selected for execution
  - The condition `c` may contain receive statements, which evaluate to true if and only if the sending process is ready to send on the specified channel.
  - Allow processes to receive messages selectively based on arbitrary conditions

Example: Bounded buffer with CSP

- Producer P, Consumer C, and Buffer B are Communicating Sequential Processes
- Problem statement:
  - When Buffer full: B can only send to C
  - When Buffer empty: B can only receive from P
  - When Buffer partially filled: B must know whether C or P is ready to act
- Solution:
  - C sends request to B first; B then sends data
  - Inputs to B from P and C are guarded with when clause

Bounded Buffer with CSP

- Define 3 named channels
  - *deposit:* P $\rightarrow$ B
  - *request:* B $\leftarrow$ C
  - *remove:* B $\rightarrow$ C

- P does:
  - send(deposit, data);

- C does:
  - send(request)
  - receive(remove, data)

- Code for B on next slide

Bounded buffer with CSP

```
process BoundedBuffer
{
 ...
   while (1) {
   when ((fullCount<n) && receive(deposit, buf[nextin]))
   {
      nextin = (nextin + 1) % n;
      fullCount = fullCount + 1;
   }  or
   when ((fullCount>0) && receive(request))
   {
      send(remove, buf[nextout]);
      nextout = (nextout + 1) % n;
      fullCount = fullCount - 1;
    }
}
```

Ports and Mailboxes

- Indirect communication (named message channels) allows a receiver to receive from multiple senders (nondeterministically)
- When channel is a queue, send can be nonblocking
- Such a queue is called *mailbox* or *port*, depending on number of receivers:
  - A mailbox can have multiple receivers
    - This can be expensive because receivers referring to the same mailbox may reside on different computers
  - A port can have only one receiver
    - So all messages addressed to the same port can be sent to one central place.

Ports and Mailboxes

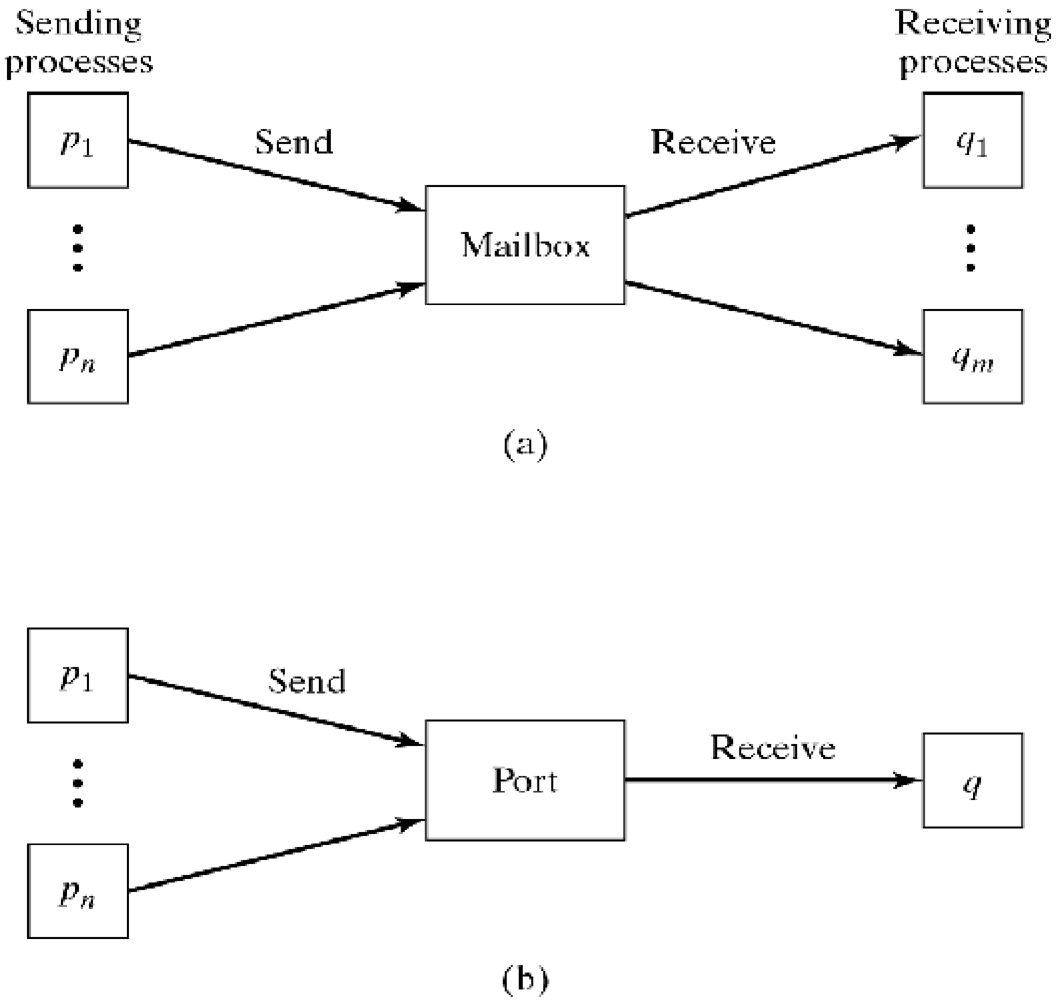


Figure 3-2

UNIX implements of interprocess communication

2 mechanisms: pipes and sockets

- Pipes: Sender's standard output is receiver's standard input

  p1 | p2 | … | pn

- Sockets are named endpoints of a 2-way channel between 2 processes. Processes may be on different machines. To establish the channel:
  - One process acts as a server, the other a client
  - Server binds it socket to IP address of its machine and a port number
  - Server issues an accept statement and blocks until client issues a corresponding connect statement
  - The connect statement supplies the client's IP address and port number to complete the connection.

Procedure-Based Communication

- Send/Receive are low level (like P/V)
- Typical interaction:

  Send Request and then Receive Result

  Make this into a single higher-level primitive
- Use *RPC (Remote Procedure Call)* or *Rendezvous*
  - Caller invokes procedure on remote machine
  - Remote machine performs operation and returns result
  - Similar to regular procedure call, but parameters cannot contain pointers or shared references, because caller and server do not share any memory

RPC

- Caller issues:

  result = f(params)

- This is translated into:

Calling Process

```
...
send(server,f,params);
receive(server,result);
...
```

Server Process

```
process RP_server
{
   while (1)
   {
      receive(caller,f,params);
      result=f(params);
      send(caller,result);
   }
}
```

Rendezvous

– With RPC: Called process p is part of a dedicated server
– With Rendezvous:
  - p is part of an arbitrary process
  - p maintains state between calls
  - p may accept/delay/reject call
  - Setup is symmetrical:
    Any process may be a client or a server

Rendezvous (Ada 95)

- Caller: Similar syntax/semantics to RPC

  q.f(param)

  where q is the called process (server)
- Server: Must indicate willingness to accept:

  accept f(param) S
- Rendezvous:
  Caller (calling process) or Server (called process) waits for the other,
  Then they execute in parallel.
- ("Rendezvous" is French for "meeting.")

Rendezvous

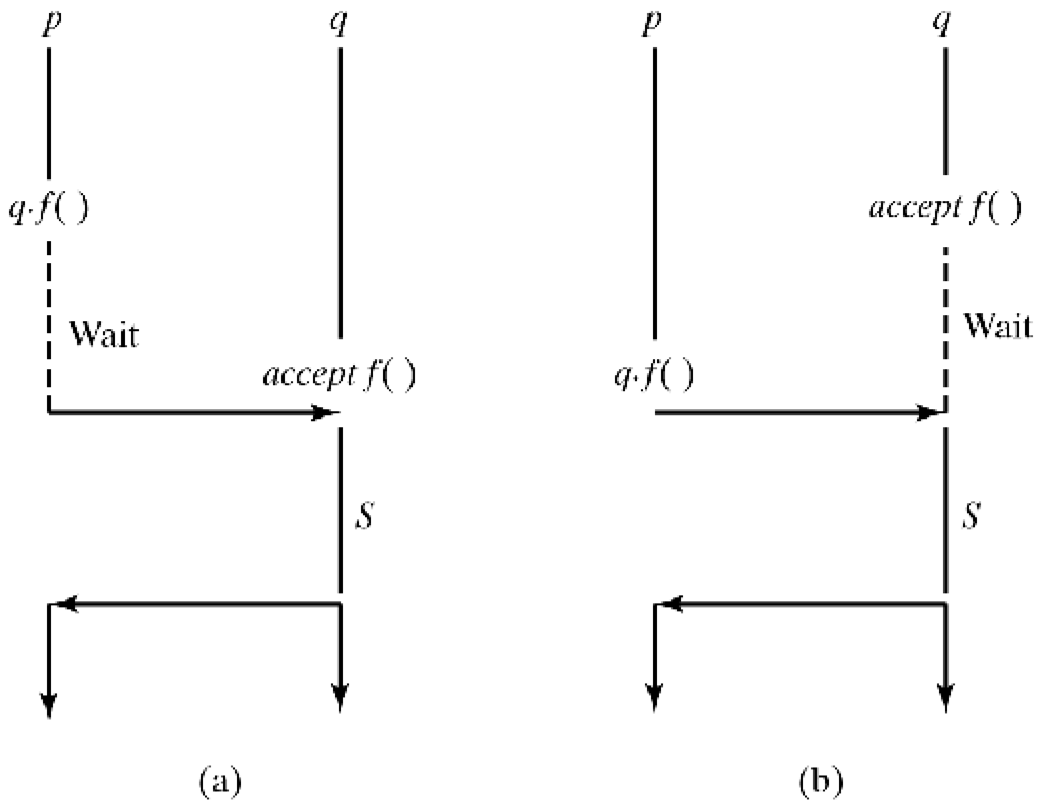


Figure 3-3

Rendezvous

- To permit selective receive, Ada provides *guarded when clauses* (like in CSP/Occam) through the *select* statement
- For an *accept* statement to be selected:
  - the *when* clause guarding it must be true; and
  - there must be at least one pending procedure call to the *accept* statement.

```
select {
  [when B1:] accept E1(…) S1;
  or
  [when B2:] accept E2(…) S2;
  or
  …
  [when Bn:] accept En(…) Sn;
  [else R]
}
```

Example: Bounded Buffer

```
process BoundedBuffer {
while(1) {
  select {
    when (fullCount < n):
      accept deposit(char c) {
        buffer[nextin] = c;
        nextin = (nextin + 1) % n;
        fullCount = fullCount + 1;
      }
    or
    when (fullCount > 0):
      accept remove(char c) {
        c = buffer[nextout];
        nextout = (nextout + 1) % n;
        fullCount = fullCount - 1;
    }
  }}}
```

Distributed Mutual Exclusion

- Critical Section problem in a Distributed Environment
  - Several processes share a resource (a printer, a satellite link, a file…)
  - Only one process can use the resource at a time
- Additional Challenges:
  - No shared memory
  - No shared clock
  - Delays in message transmission.

Distributed Mutual Exclusion

- Central Controller Solution
  - Requesting process sends request to controller
  - Controller grants it to one processes at a time
  - Problems with this approach:
    - Single point of failure,
    - Performance bottleneck
- Fully Distributed Solution:
  - Processes negotiate access among themselves

Distributed Mutual Exclusion

- Token Ring solution
  - Each process has a controller
  - Controllers are arranged in a ring
  - Controllers pass a token around the ring
  - Process whose controller holds token may enter its CS

Distributed Mutual Exclusion with Token Ring

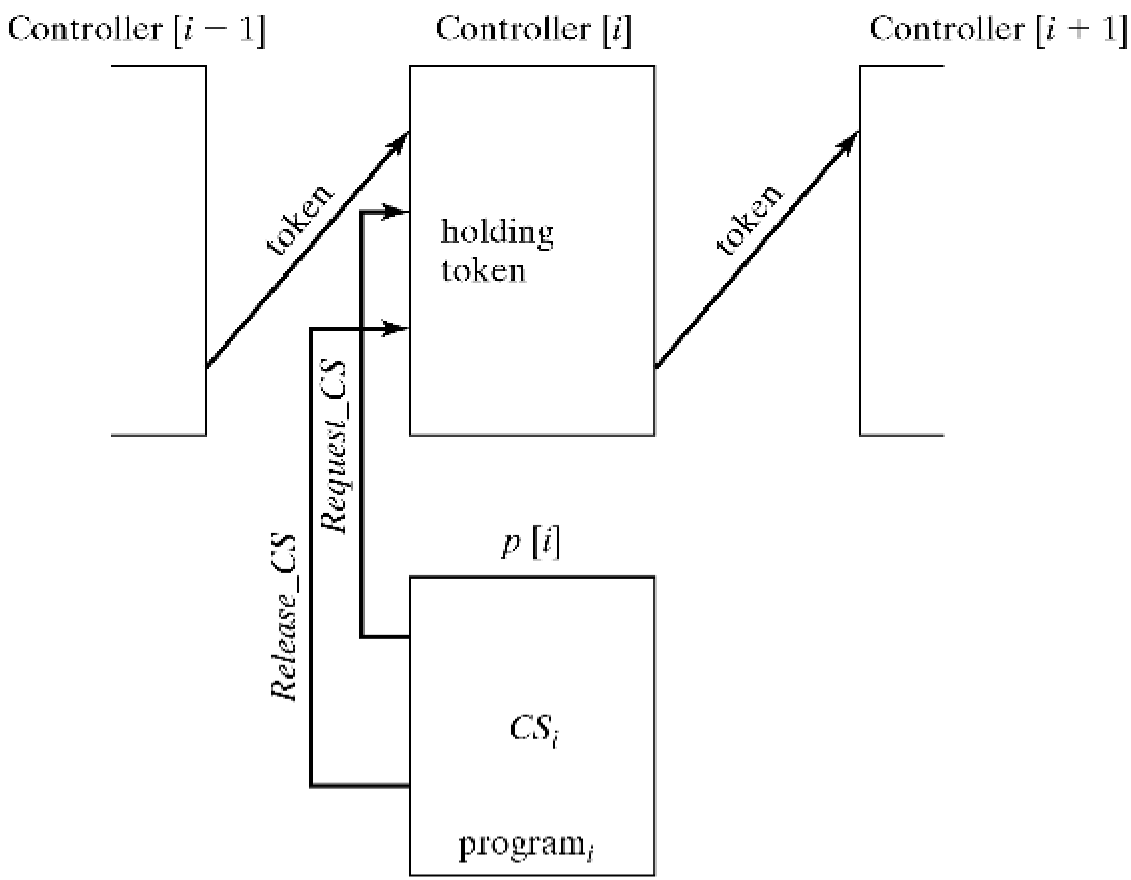


Figure 3-4

Distributed Mutual Exclusion

```
process controller[i] {
    while(1) {
        accept Token;
        select {
             accept Request_CS() {busy=1;}
             else null;
        }
        if (busy) accept Release_CS() {busy=0;}
        controller[(i+1) % n].Token;
    }
}
process p[i] {
    while(1) {
        controller[i].Request_CS();
         CSi;
         controller[i].Release_CS();
         programi;
    }
}
```

3.3
Other Classical SynchronizationProblems

- The Readers/Writers Problem
- The Dining Philosophers Problem
- The Elevator Algorithm
- Event Ordering with Logical Clocks

Readers/Writers Problem

- Extension of basic Critical Section (CS) problem (Courtois, Heymans, and Parnas, 1971)
- Two types of processes entering a CS: *Readers (R)* and *Writers (W)*
- CS may only contain
  - A single W process (and no R processes); or
  - Any number of R processes (and no W processes).
- This is a relaxation of the mutual exclusion condition, because multiple readers are allowed at one.
- A good solution should:
  - Satisfy this relaxed extended mutual exclusion condition
  - Take advantage of the fact that multiple R processes can be in the CS simultaneously
  - Prevent starvation of either process type

Readers/Writers Problem

- Two possible algorithms:
  1. ***R has priority over W:*** No R is kept waiting unless a W has already obtained permission to enter the CS.
  2. ***W has priority over R :*** When a W is waiting, only those R processes already granted permission to read are allowed to continue. All other R processes must wait until the W completes.
- Both of the above algorithms lead to starvation.

Readers/Writers Problem

- Solution that prevents starvation of either process type:
  1. If R processes are in CS, a new R cannot enter if a W is waiting
  2. If a W is in CS, once it leaves, all R processes waiting can enter, *even if they arrived after new W processes that are also waiting.*

Solution using monitor

```
monitor Readers_Writers {
  int readCount=0,writing=0;
  condition OK_R, OK_W;

  start_read()
  {
    if (writing || !empty(OK_W))
      OK_R.wait;
    readCount = readCount + 1;
    OK_R.signal;
  }

  end_read()
  {
    readCount = readCount - 1;
    if (readCount == 0)
      OK_W.signal;
  }

  start_write()
  {
    if ((readCount !=0)||writing)
      OK_W.wait;
    writing = 1;
  }

  end_write()
  {
    writing = 0;
    if (!empty(OK_R))
      OK_R.signal;
    else OK_W.signal;
  }
}
```

Dining philosophers Problem

- Each philosopher needs both forks to eat
- Requirements
  - Prevent deadlock
  - Guarantee fairness: no philosopher must starve
  - Guarantee concurrency: non-neighbors may eat at the same time

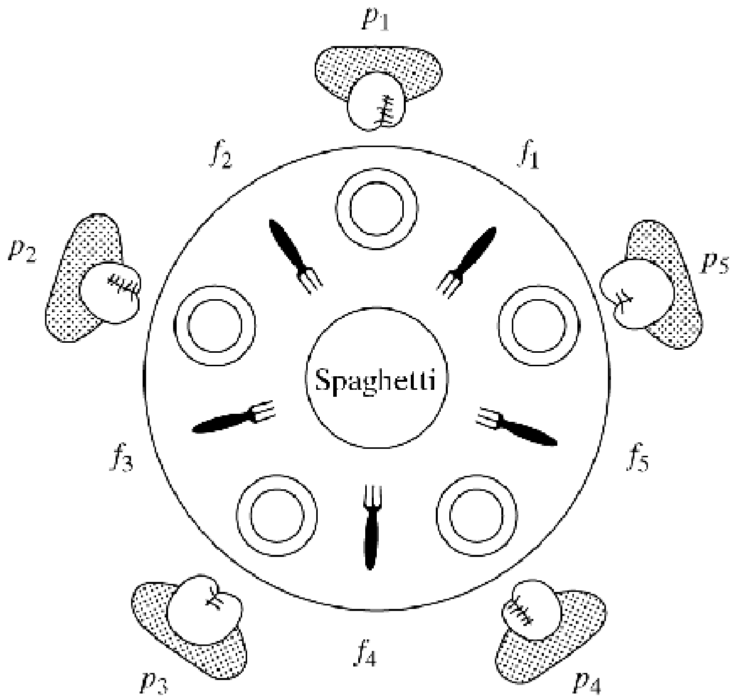


Figure 3-5

Dining philosophers problem

- One obvious solution: each philosopher graps left fork first

```
p(i) : {
    while (1) {
            think(i);
        grab_forks(i);
        eat(i);
        return_forks(i);
    } }

grab_forks(i):   { P(f[i]); P(f[i%5 + 1]) }

return_forks(i): { V(f[i]); V(f[i%5 + 1]) }
```

- May lead to deadlock (each philosopher has left fork, is waiting for right fork)

Dining Philosophers

- Two possible solutions to deadlock
  1. Use a counter:
     At most n–1 philosophers may attempt to grab forks
  2. One philosopher requests forks in reverse order, e.g.,

     `grab_forks(1): { P(f [2]); P(f [1]) }`
- Both violate concurrency requirement:
  – While P(1) is eating the others could be blocked in a chain.

    (Exercise: Construct a sequence of requests/releases where this happens.)

Dining Philosophers

Solution that avoids deadlock and provides concurrency:

- Divide philosophers into two groups
  - Odd-numberered philosophers (1,3,5) grab left fork first
  - Even-numberered philosophers (2,4) grab right fork first

Elevator Algorithm

- Loosely simulates an elevator
- Same algorithm can be used for disk scheduling
- Organization of elevator
  - *n* floors
  - Inside elevator, one button for each floor
  - At each floor, outside the door, there is a single (!) call button
- Elevator scheduling policy
  - When elevator is moving up, it services all requests at or above current position; then it reverses direction
  - When elevator is moving down, it services all requests at or below current position; then it reverses direction
- We will present a monitor that governs the motion according to these scheduling rules

Elevator Algorithm

- Two monitor calls
  - request(i): called when a stop at floor i is requested, either by pushing call button at floor i or by pushing button i inside the elevator.
  - release(): called when elevator door closes
- Usage:
  - Process representing users call request(i)
  - Elevator process (or hardware) calls release()
- Two condition variables (upsweep, downsweep)
- Boolean busy indicates that either
  - the door is open or
  - the elevator is moving to a new floor.

Elevator algorithm

- When call arrives for floor dest and elevator is currently at floor position
  - If elevator is busy
    - If position < dest wait in upsweep queue
    - If position > dest wait in downsweep queue
    - If position == dest wait in upsweep or downsweep queue, depending on current direction
  - Otherwise, no wait is necessary
- On return from wait (i.e., when corresponding signal is received), or if no wait was necessary, service the request
  - set busy = 1
  - move to the requested floor (dest)

Elevator algorithm

```
Monitor elevator {
  int direction =1, up = 1, down = 0,
    position =1, busy = 0;
  condition upsweep, downsweep;

  request(int dest) {
    if (busy) {
      if (position < dest) ||
             ( (position == dest) &&
               (direction == up) ) )
        upsweep.wait(dest);
      else
        downsweep.wait(-dest);
    }
    busy = 1;
    position = dest;
  }
```

```
  //Called when door closes
release() {
  busy = 0;
  if (direction==up)
    if (!empty(upsweep))
      upsweep.signal;
    else {
      direction = down;
      downsweep.signal;
    }
  else  /*direction==down*/
    if (!empty(downsweep))
      downsweep.signal;
    else {
      direction = up;
      upsweep.signal;
    }
  }
}
```

Logical Clocks

- Many applications need to *time-stamp* events for debugging, recovery, distributed mutual exclusion, ordering of broadcast messages, transactions, etc.
- In a *centralized* system, can attach a clock value:
  - C(e1) < C(e2) means e1 happened before e2
- Physical clocks in *distributed* systems are skewed. This can cause anomalies…

Skewed Physical Clocks

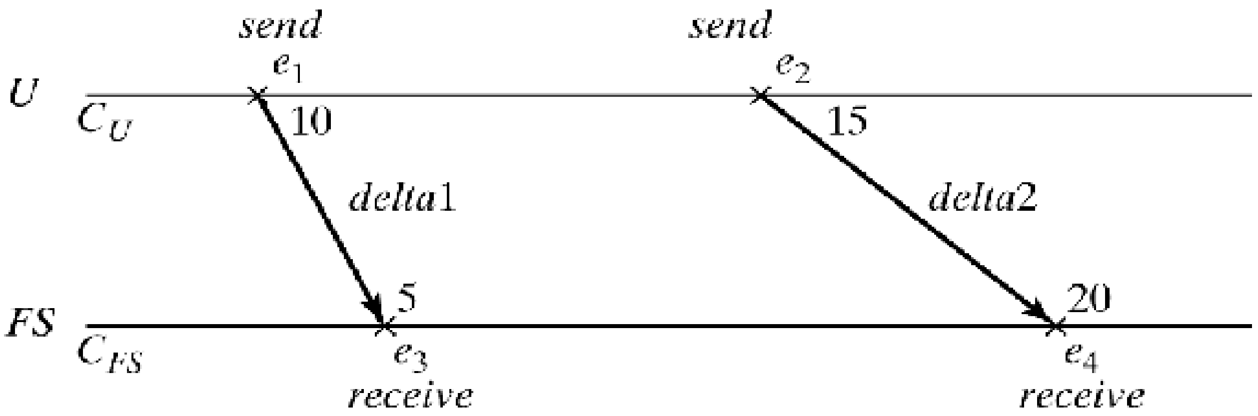


Figure 3-7

Based on times, the log shows an impossible sequence:

e3, e1, e2, e4

Message arrived before it was sent!!

Possible sequences:

e1, e3, e2, e4 or e1, e2, e3, e4

Logical Clocks

- Solution: time-stamp events using *counters* as *logical clocks*:
  1. Within a process p, increment counter for each new event:

     $L_p(e_{i+1}) = L_p(e_i) + 1$

  2. Label each **send** event with new clock value:

     $L_p(e_s) = L_p(e_i) + 1$

  3. Label each **receive** event with new clock value based on maximum of local clock value and label of corresponding **send** event:

     $L_q(e_r) = \max(\ L_p(e_s), L_q(e_i)\ ) + 1$

Logical Clocks

- Logical Clocks yield a distributed *happened-before* relation:
  - $e_i \rightarrow e_k$ holds if
    - e_i and e_k belong to the same process and e_i happened before e_k , or
    - e_i is a **send** and e_k is the corresponding **receive**

Logical Clocks

$L_{p1}(u)=4$

$L_{p2}(v)=max(4,1)+1=5$

$L_{p3}(x)=max(6,12)+1=13$

$L_{p2}(y)=max(7,14)+1=15$

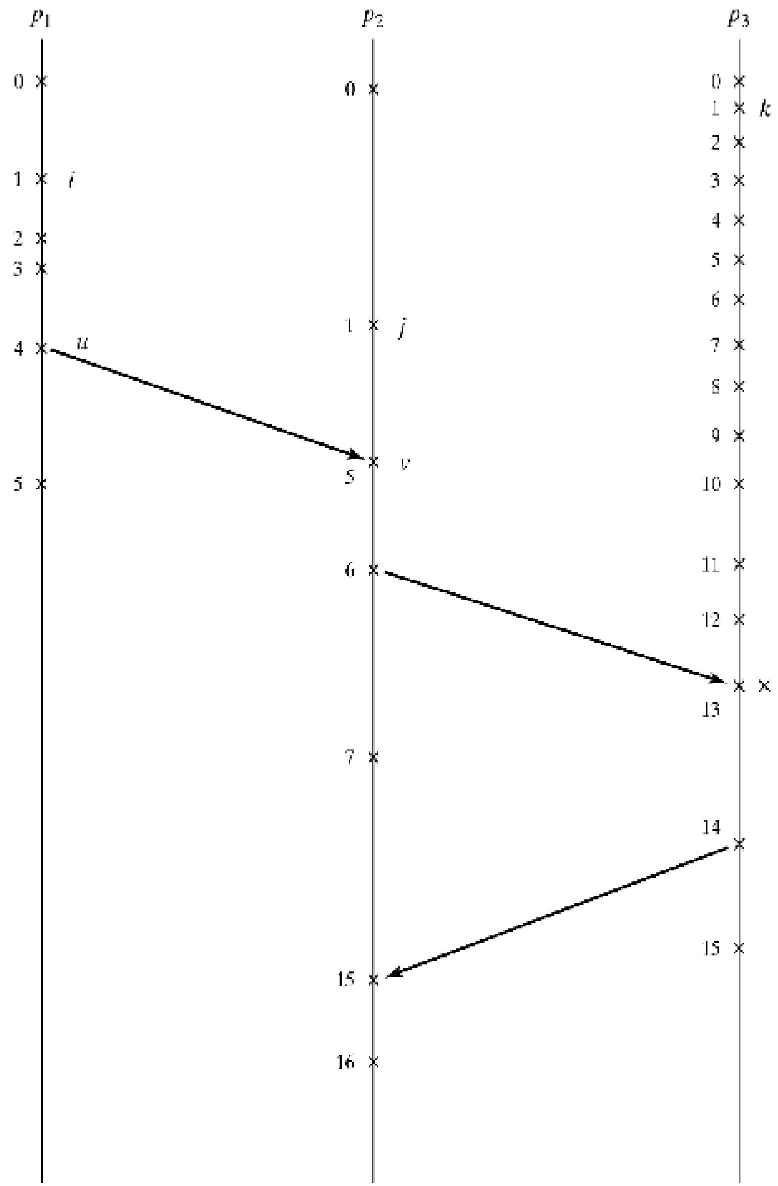


Figure 3-8

History

- Originally developed by Steve Franklin
- Modified by Michael Dillencourt, Summer, 2007
- Modified by Michael Dillencourt, Spring, 2009
- Modified by Michael Dillencourt, Winter, 2010
- Modified by Michael Dillencourt, Summer, 2012