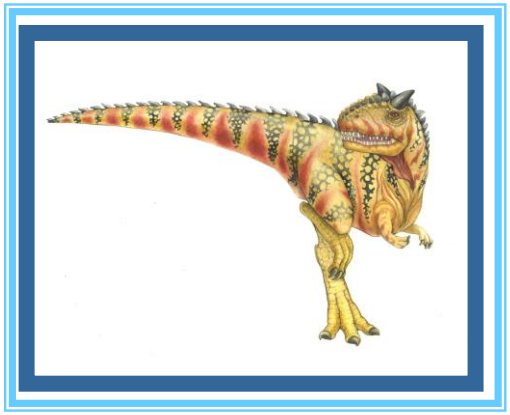
Chapter 6: Synchronization



Synchronization

- Background
- The Critical-Section Problem
- Peterson's Solution
- Synchronization Hardware
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
- Atomic Transactions

Objectives

To introduce the critical-section problem, whose solutions can be used to ensure the consistency of shared data

To present both software and hardware solutions of the critical-section problem

To introduce the concept of an atomic transaction and describe mechanisms to ensure atomicity

Background

Concurrent access to shared data may result in data inconsistency

Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes

Suppose that we want to provide a solution to the consumer-producer problem that fills all the buffers.

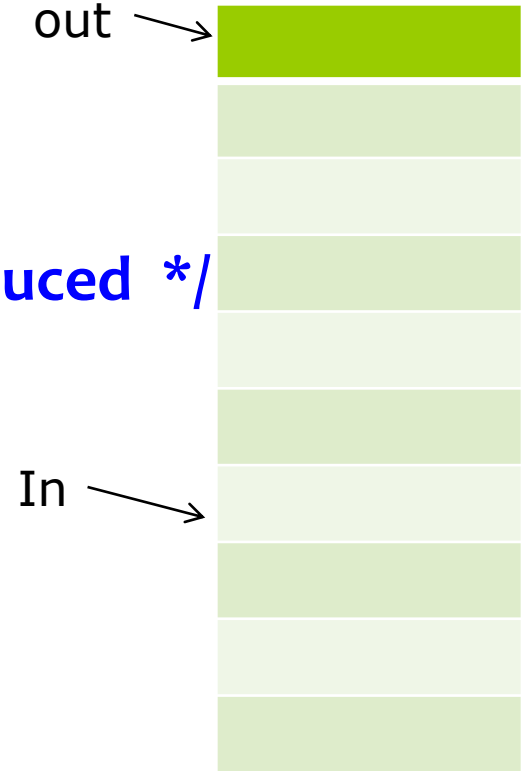
We can do so by having an integer count that keeps track of the number of full buffers.

Initially, count is set to 0. It is incremented by the producer after it produces a new buffer and is decremented by the consumer after it consumes a buffer.

Producer

```
while (true) {

        /*  produce an item and put in nextProduced  */
         while (count == BUFFER_SIZE)
                  ; // do nothing
              buffer [in] = nextProduced;
              in = (in + 1) % BUFFER_SIZE;
              count++;
}
```



Consumer

```
while (true)  {
        while (count == 0)
              ; // do nothing
              nextConsumed =  buffer[out];
               out = (out + 1) % BUFFER_SIZE;
               count--;

                  /*  consume the item in nextConsumed
}
```

Race Condition

count++ could be implemented as

```
register1 = count
register1 = register1 + 1
count = register1
```

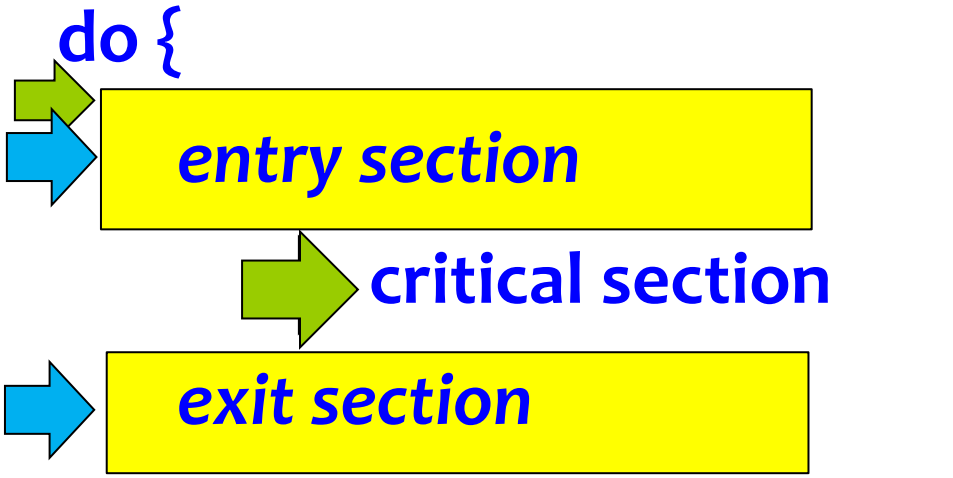
count-- could be implemented as

```
register2 = count
register2 = register2 - 1
count = register2
```

Consider this execution interleaving with "count = 5" initially:

S0: producer execute register1 = count {register1 = 5}
S1: producer execute register1 = register1 + 1 {register1 = 6}
S2: consumer execute register2 = count {register2 = 5}
S3: consumer execute register2 = register2 - 1 {register2 = 4}
S4: producer execute count = register1 {count = 6 }
S5: consumer execute count = register2 {count = 4}

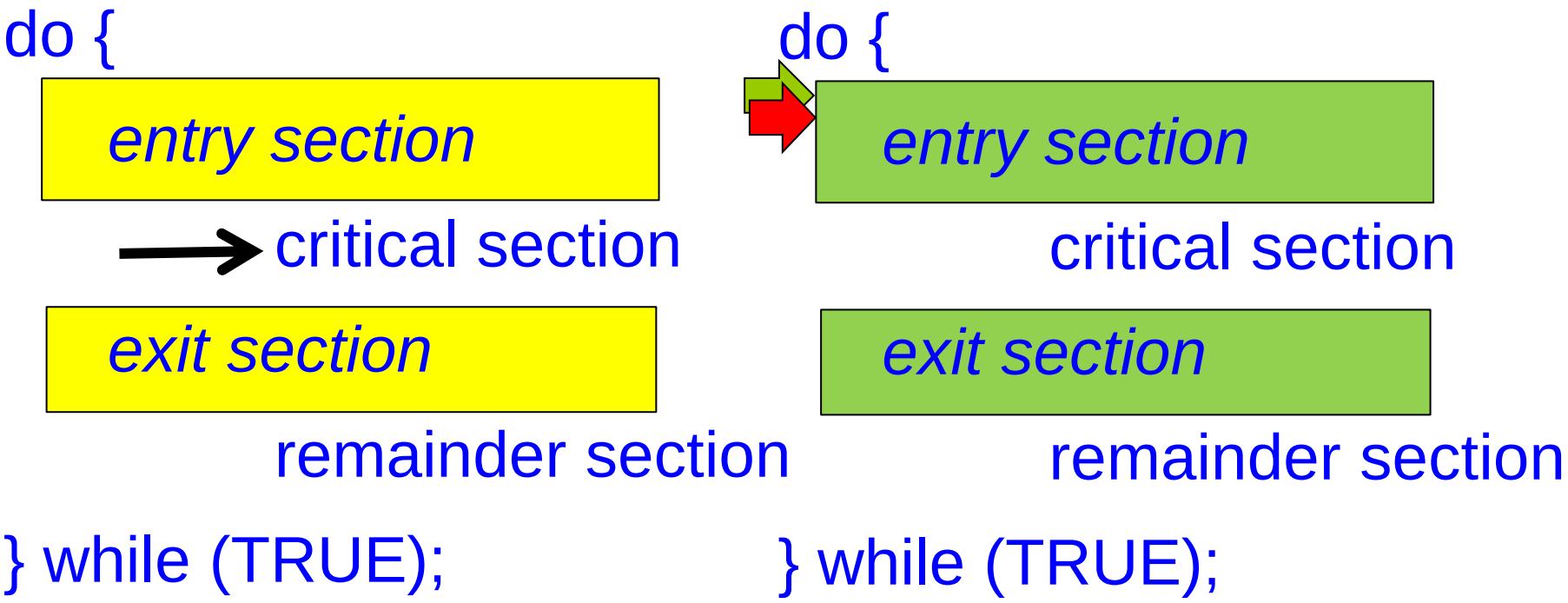
Critical-Section Problem



General structure of a typical Process P_i

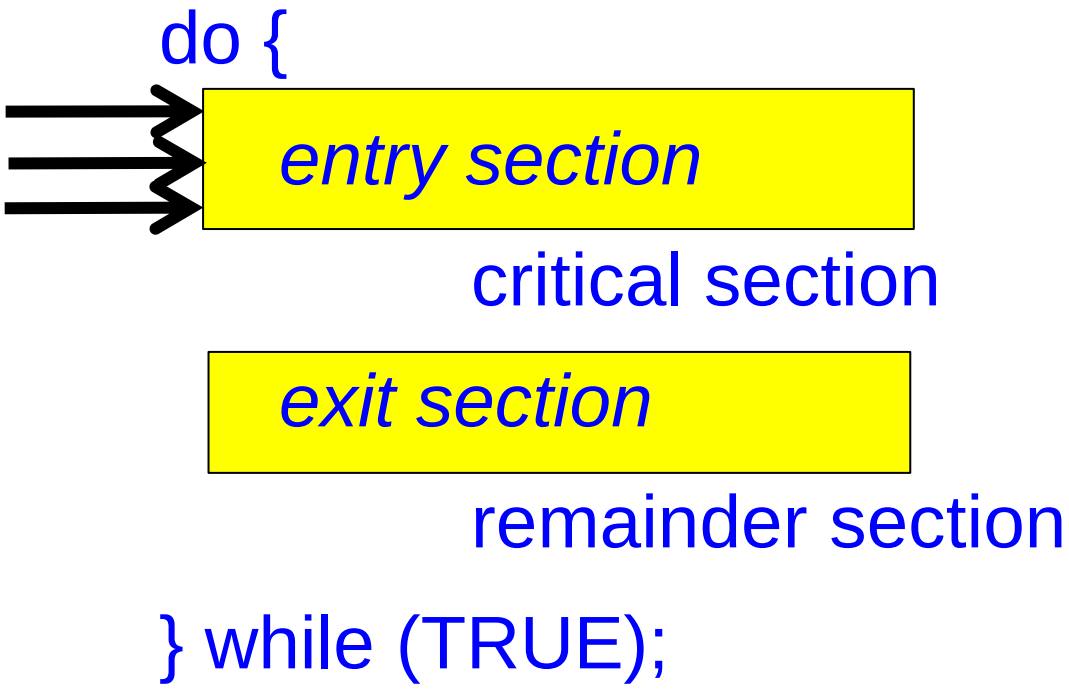
Solution to Critical-Section Problem

1. **Mutual Exclusion - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections**



Solution to Critical-Section Problem

2. **Progress - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely**



Solution to Critical-Section Problem

3. **Bounded Waiting** - A bound must exist on the number of times that other processes are allowed to enter their critical sections **after a process has made a request to enter its critical section and before that request is granted**
   - Assume that each process executes at a nonzero speed
   - No assumption concerning relative speed of the **N** processes

Peterson's Solution

Two-process solution

Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted.

The two processes share two variables:

int turn;

Boolean flag[2]

The variable turn indicates whose turn it is to enter the critical section.

The flag array is used to indicate if a process is ready to enter the critical section. flag[i] = true implies that process P_i is ready!

Algorithm for Process P_i

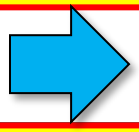
```
do {
    flag[i] = TRUE;
    turn = j;
    while (flag[j] && turn == j);

        critical section

    flag[i] = FALSE;

        remainder section

} while (TRUE);
```

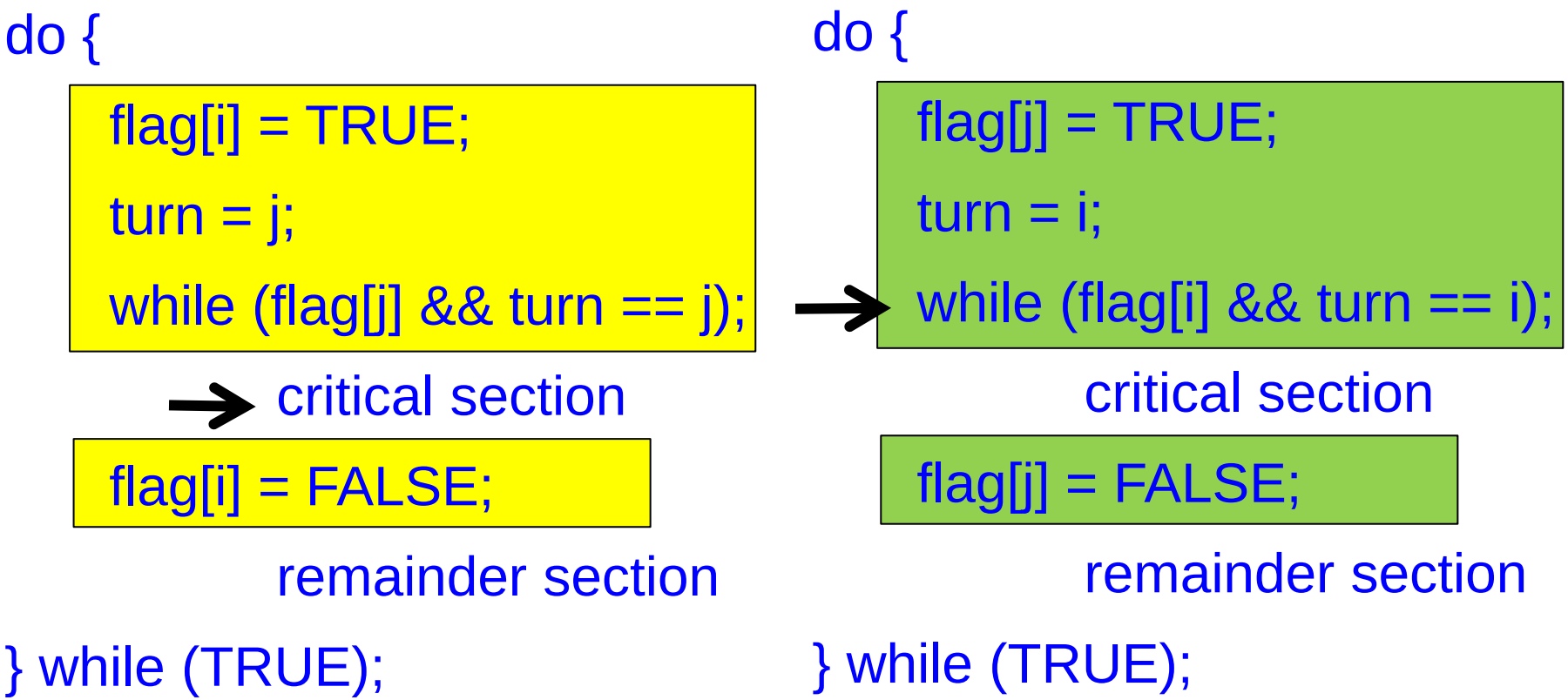


Prove this algorithm is correct

1. **Mutual exclusion** is preserved
2. The **progress** requirement is satisfied.
3. The **bounded waiting** requirement is met

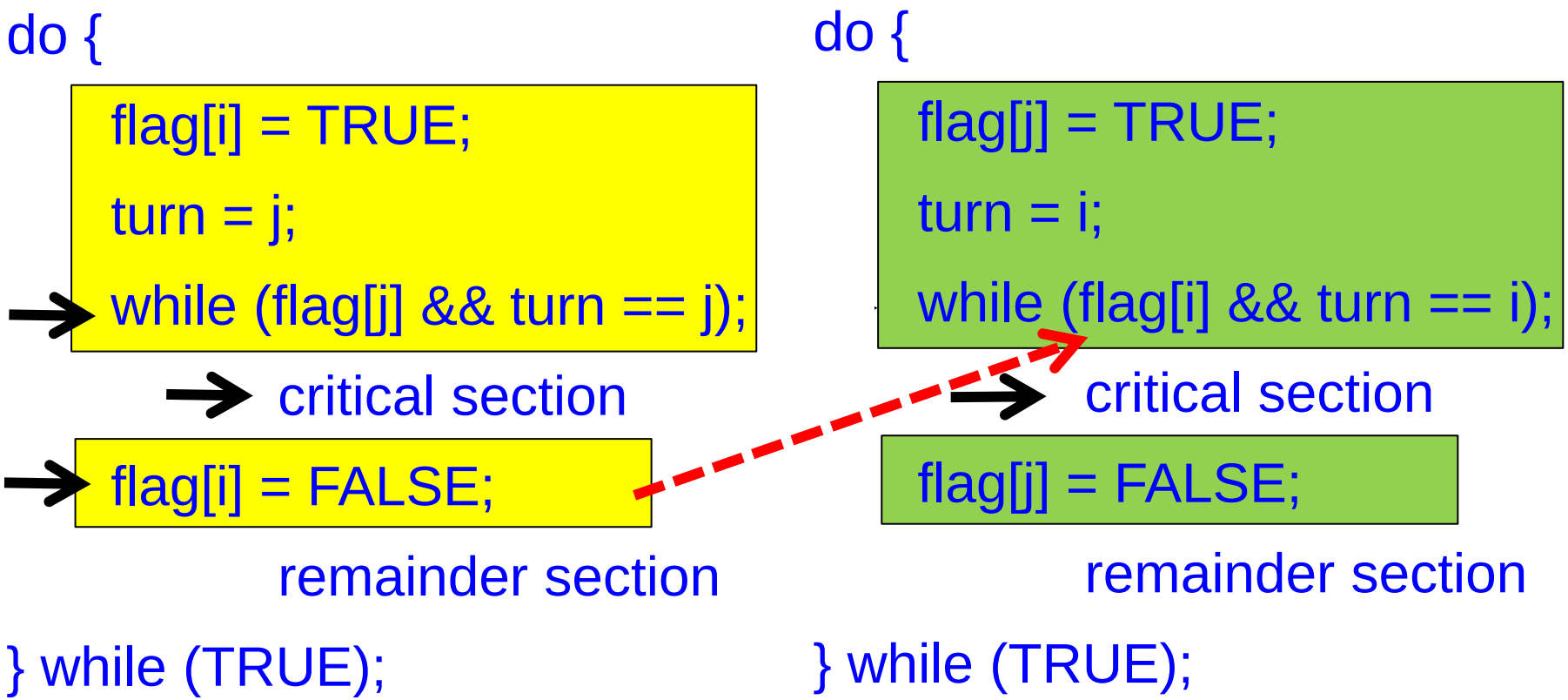
Prove this algorithm is correct

1. Mutual exclusion is preserved



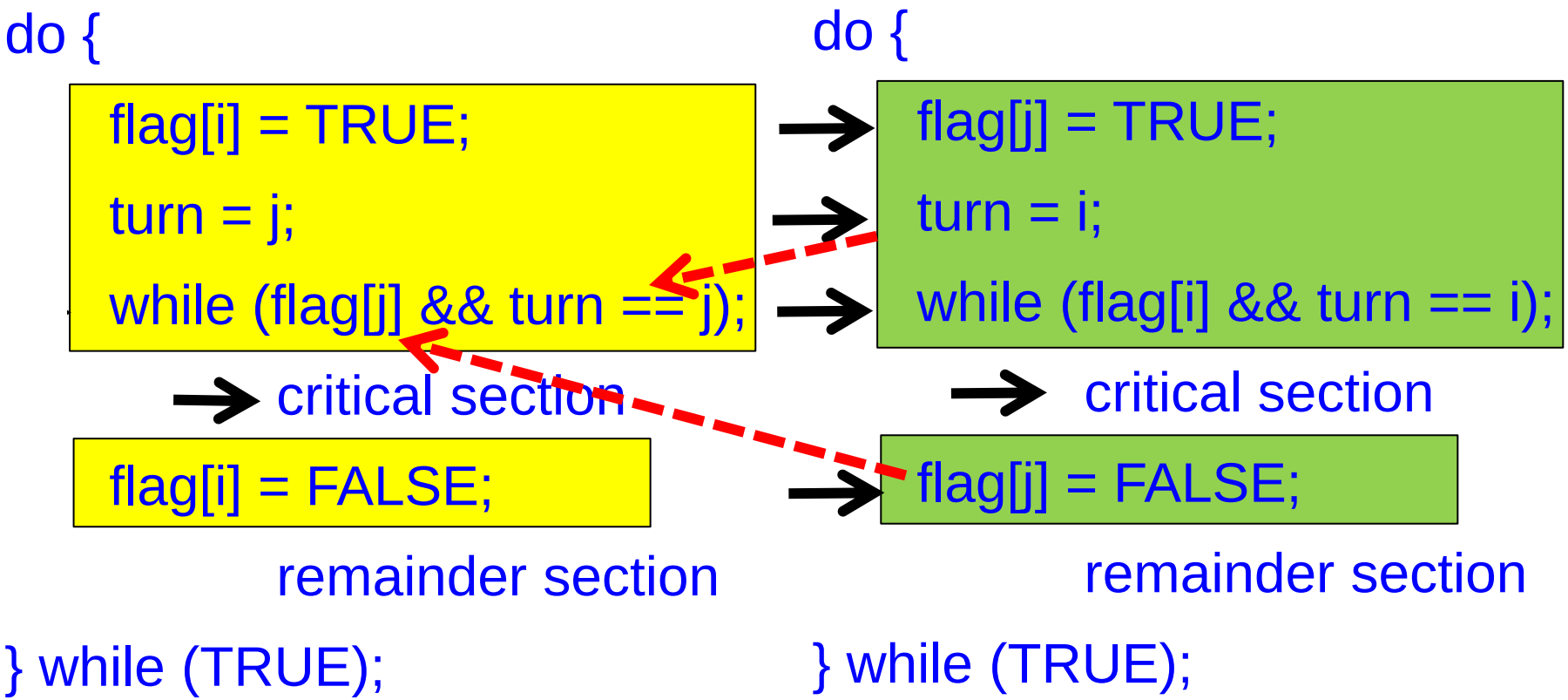
Prove this algorithm is correct

2. The progress requirement is satisfied.



Prove this algorithm is correct

3. The bounded waiting requirement is met



Synchronization Hardware

Any solution to the critical-section problem requires a simple tool – a lock.

Race conditions are prevented by requiring that critical regions be protected by locks

do {

→ acquire **lock**

→ critical section

release **lock**

remainder section

} while (TRUE);

Synchronization Hardware

Many systems provide hardware support for critical section code

Uniprocessors – could disable interrupts

- Currently running code would execute without preemption
- Generally too inefficient on multiprocessor systems
  - Operating systems using this not broadly scalable

Modern machines provide special atomic hardware instructions

- Atomic = non-interruptable
- Either test memory word and set value
- Or swap contents of two memory words

TestAndndSet Instruction

Definition:

```
boolean TestAndSet (boolean *target)
{
    boolean rv = *target;   /* Test */
    *target = TRUE;         /* Set */
    return rv:
}
```

Solution using TestAndSet

Shared boolean variable lock., initialized to false.

Solution (Mutual-Exclusion):

lock

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

        //    critical section

    lock = FALSE;

        //      remainder section

} while (TRUE);
```

Swap Instruction

Definition:

```
void Swap (boolean *a, boolean *b)
{
        boolean temp = *a;
→       *a = *b;
→       *b = temp:
}
```

Solution using Swap

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

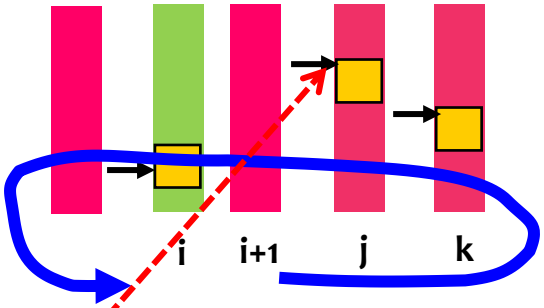
Solution(Mutual-Exclusion):

```
do {
    key = TRUE;
    while ( key == TRUE)
          Swap (&lock, &key );
        //  critical section
    lock = FALSE;
        //  remainder section
} while (TRUE);
```

lock

Bounded-waiting Mutual Exclusion with TestandSet()

```
do {
    waiting[i] = TRUE;
    key = TRUE;
    while (waiting[i] && key)
        key = TestAndSet(&lock);
    waiting[i] = FALSE;
        // critical section
    j = (i + 1) % n;
    while ((j != i) && !waiting[j])   (Find next waiting process)
        j = (j + 1) % n;
    if (j == i)
        lock = FALSE; (No one is waiting)
    else
        waiting[j] = FALSE; (process j enters next)
        // remainder section
} while (TRUE);
```



Prove this algorithm is correct

1. Mutual exclusion is preserved
2. The progress requirement is satisfied.
3. The bounded waiting requirement is met

Semaphores

The hardware-based solutions for the CS problem are complicated for application programmers to use.

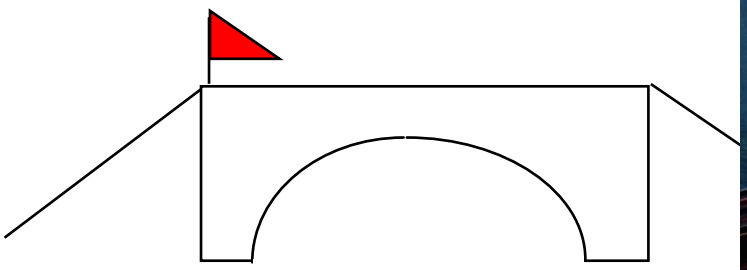
To overcome this difficulty, we use a synchronization tool called a semaphore.

Semaphore *S* – integer variable

Two standard operations modify S: wait() and signal()

Originally called P() and V()

Less complicated



Semaphores

Can only be accessed via two indivisible (atomic) operations

```
wait (S) {
        while S <= 0        /* Semaphore S is occupied */
            ; // no-op
          S--;              /* Semaphore S is available, get it */
    }
signal (S) {
      S++;                  /* Release the semaphore S */
    }
```

Semaphore Usage

Counting semaphore – integer range over an unrestricted domain

Binary semaphore – integer value can range only between 0 and 1; can be simpler to implement

> Also known as **mutex locks** as they are locks that provide **mut**ual **ex**clusion.

We can use binary semaphore to deal with the CS problem for multiple processes.

The n processes share a semaphore, **mutex**, initialized to 1

Mutual-Exclusion Implementation with semaphores

Provides mutual exclusion (for Process Pi)

```
Semaphore mutex;    //  initialized to 1
do {
    wait (mutex);
        // Critical Section
    signal (mutex);
    // remainder section
} while (TRUE);
```

Semaphore Usage

Counting semaphore can be used to control access to a given resource consisting of a finite number of instances.

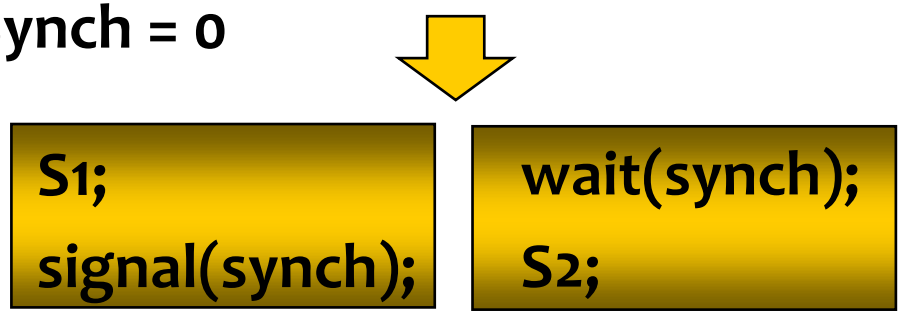
The semaphore is initialized to the number of resources available.

To use a resource, wait()

To release a resource, signal()

Semaphores can be used to solve various synchronization problem.

For example, we have two processes P1 and P2. Execute S1 and then S2: Synch = 0



Semaphore Implementation

The main disadvantage of previous mutual-exclusion solution is the *busy waiting* (CPU is wasting).

This type of semaphore is called a *spinlock.*

To overcome this, we can use the concept of *block* and *wakeup* operations.

```
Typedef struc  {
      int value;
      struct  process *list;
} semaphore
```

Semaphore Implementation with no Busy waiting

With each semaphore there is an associated waiting queue. Each entry in a waiting queue has two data items:

value (of type integer)

- Value > 0 indicates semaphore is still available
- Value = 0 indicates semaphore is just occupied and no waiting process
- Value < 0 indicates the number of waiting processes

pointer to next record in the list /* waiting list */

Two operations:

block – place the process invoking the operation on the appropriate waiting queue.

wakeup – remove one of processes in the waiting queue and place it in the ready queue.

Semaphore Implementation with no Busy waiting

Implementation of wait:

```
wait(semaphore *S) {
        S.value --;
        if (S.value < 0) {
                add this process to S.list;
                block();
        }
}
```

Semaphore Implementation with no Busy waiting

Implementation of signal:

```
signal(semaphore *S) {
        S.value ++;
        if (S.value <= 0) {
                remove a process P from S.list;
                wakeup(P);
        }
}
```

Semaphore Implementation with no Busy waiting

Note that the semaphore value may be negative.

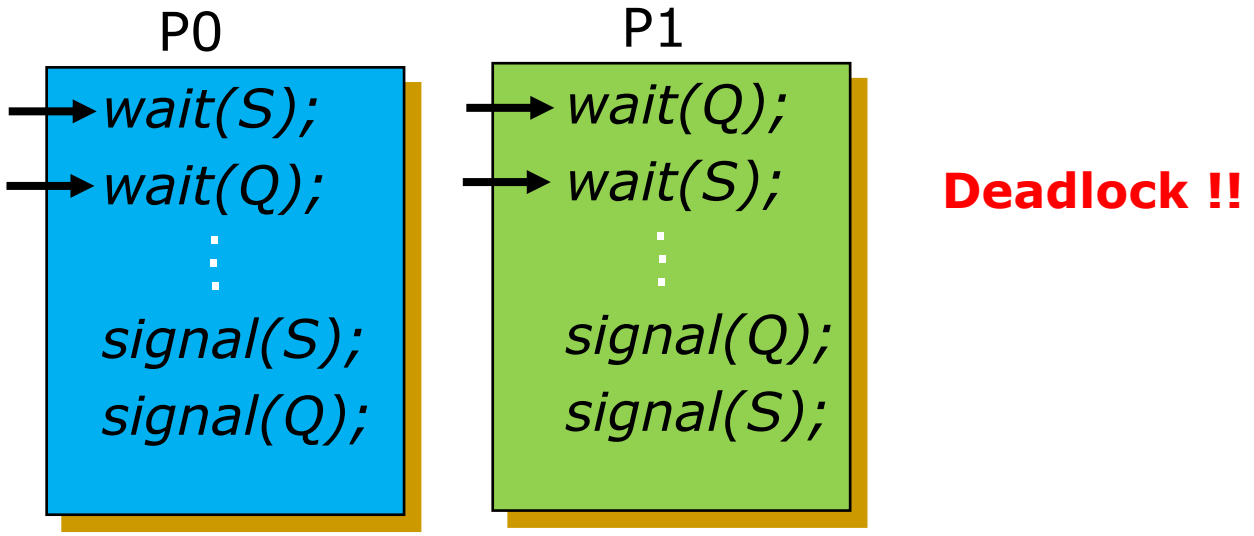
Its magnitude is the number of processes waiting on that semaphore.

The list of waiting processes can be easily implemented by a link field in each process control block (PCB).

Deadlock and Starvation

Deadlock – two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes

Let S and Q be two semaphores initialized to 1



Starvation – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended

Priority Inversion

Priority Inversion - Scheduling problem when lower-priority process holds a lock needed by higher-priority process.

Three processes L, M, H with priority L < M < H

Assume process H requires resource R, which is using by process L. **Process H waits.**

Assume process M becomes runnable, thereby preempting process L.

Indirectly, a process with lower priority – M – has affected how long H must wait for L to release R.

Priority-inheritance protocol – all processes that are accessing resources needed by a higher priority process **inherit the higher priority** until they are finished with the resources.

Classical Problems of Synchronization

Bounded-Buffer Problem

Readers and Writers Problem

Dining-Philosophers Problem

Bounded-Buffer Problem

Used to illustrate the power of synchronization primitives.

N buffers, each can hold one item

Semaphore mutex initialized to the value 1

Semaphore full initialized to the value 0

Semaphore empty initialized to the value N.

Bounded Buffer Problem (Cont.)

The structure of the producer process

```
do {
        // produce an item in nextp

        wait (empty);
        wait (mutex);

        // add the item to the buffer

        signal (mutex);
        signal (full);
} while (TRUE);
```

The structure of the consumer process

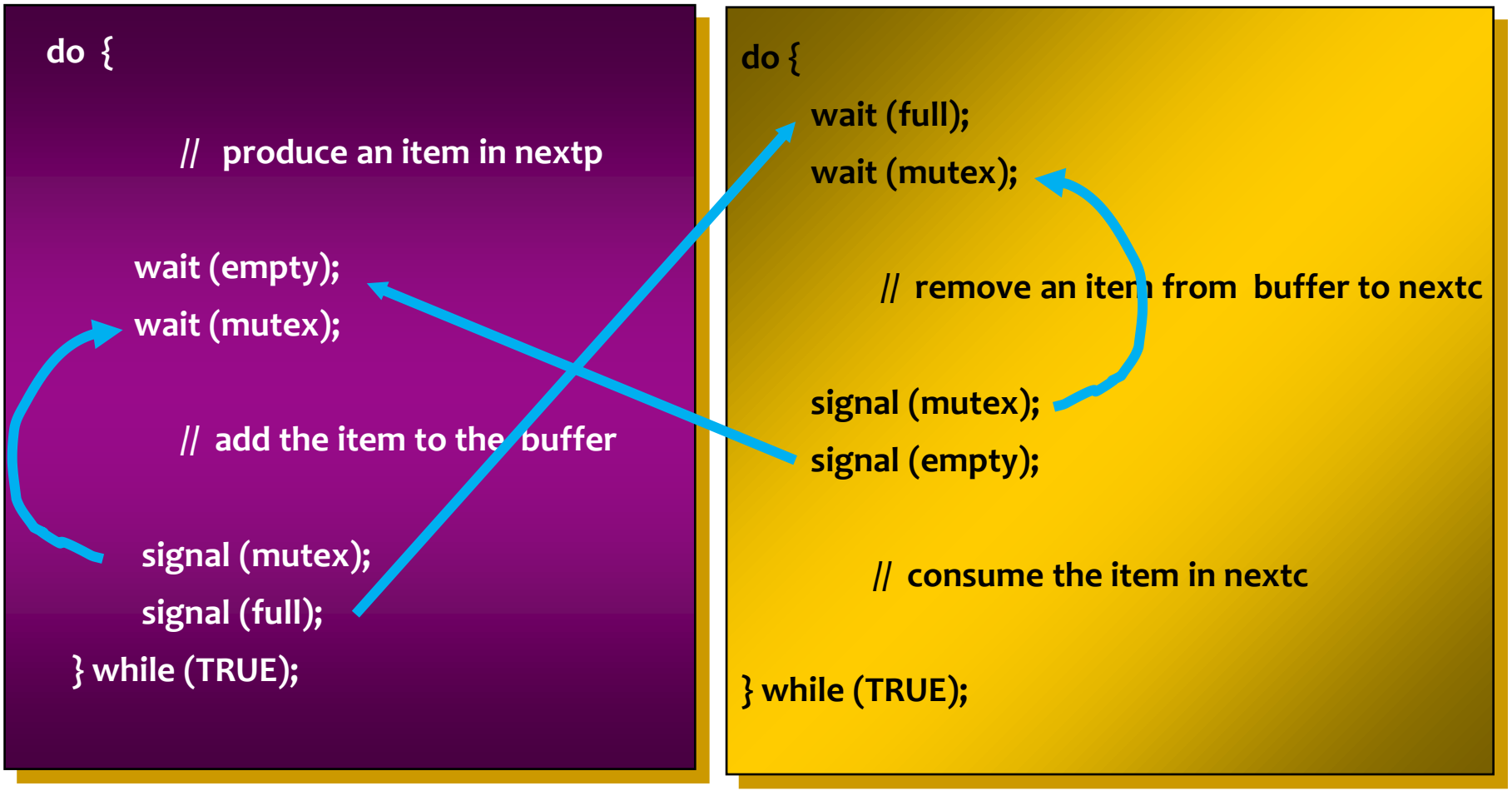
```
do {
        wait (full);
        wait (mutex);

        // remove an item from buffer to nextc

        signal (mutex);
        signal (empty);

        // consume the item in nextc

} while (TRUE);
```



Initial, Empty = N, Full = 0

The Reader and Writers Problem

A data object, such as a file or record, is to be shared among several concurrent processes.

The writers are required to have exclusive access to the shared object.

The readers-writers problem has several variations, all involving priorities.

The First problem -- require no reader will be kept waiting unless a writer has already obtained permission to use the shared object. Thus, no reader should wait for other readers to finish even a writer is waiting.

The Reader and Writers Problem

The Second problem -- require once a writer is ready, that writer performs its write as soon as possible, after old readers (or writer) are completed. Thus, if a writer is waiting to access the object, no new readers may start reading.

A solution to either problem may result in *starvation*.

The first problem : Writers

- **Writers wait, but readers come in one after one**

The second problem : Readers

- **Readers wait, but writers come in one after one**

A solution for the first problem

Shared Data

- **Semaphore mutex initialized to 1**
- **Semaphore wrt initialized to 1**
- **Integer readcount initialized to 0**

The *mutex* semaphore is used to ensure mutual exclusion when the variable readcount is updated.

***Readcount* keeps track of how many processes are currently reading the object.**

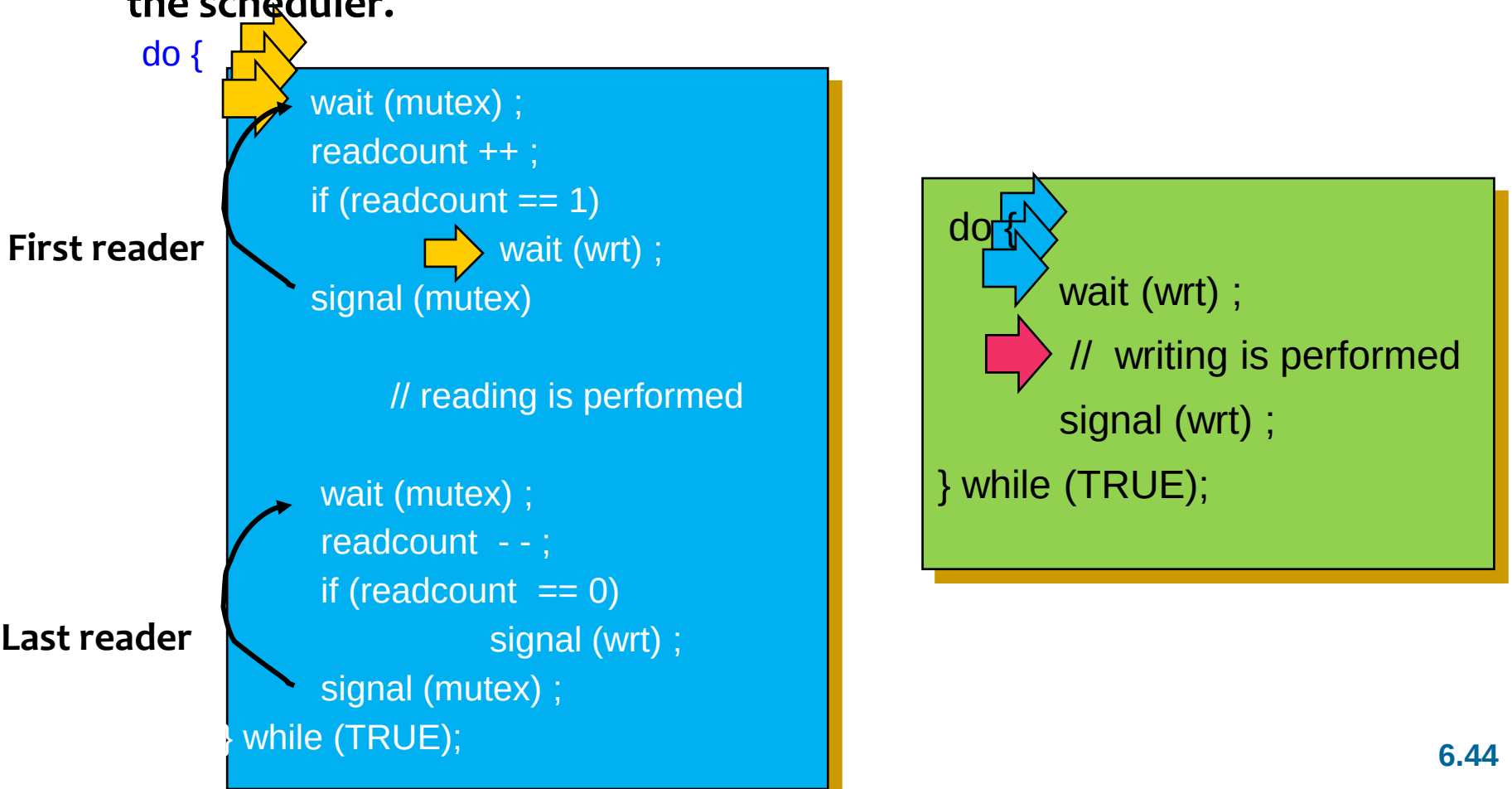
The *wrt* semaphore functions as a mutual exclusion semaphore for the writers.

- **It also is used by the *first* or *last* reader that enters or exits the critical section.**
- **It is not used by the readers who enter or exit while other processes are in their critical sections.**

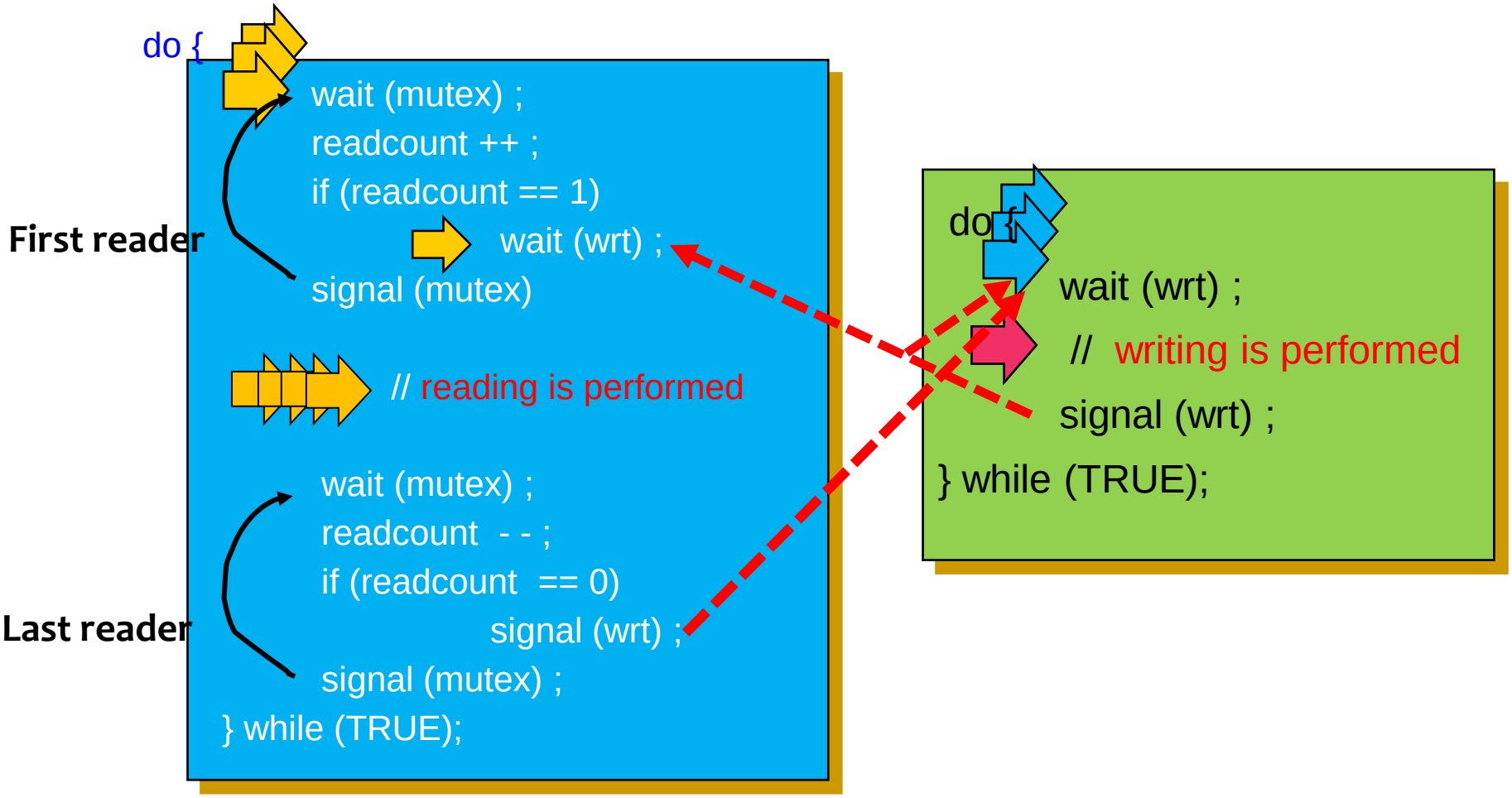
A solution for the first problem

If a writer is in the CS and *n* readers are waiting, then one reader is queued on *wrt* and n-1 readers are queued on *mutex*.

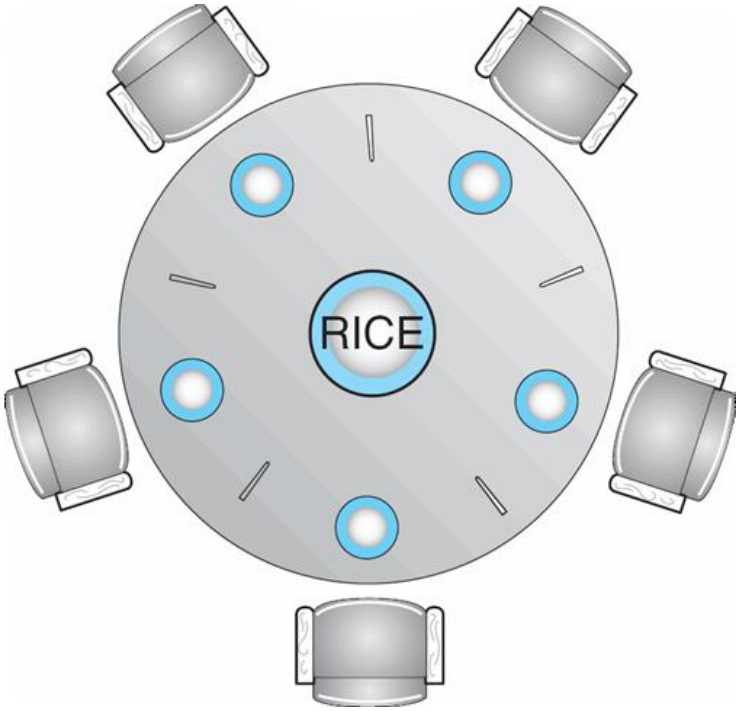
When a writer executes signal(wrt), we may assume the execution of either the waiting writers or a single reader. The selection is made by the scheduler.



A solution for the first problem



6.6.3 Dining-Philosophers Problem



Shared data

- **Bowl of rice (data set)**
- **Semaphore chopstick [5] initialized to 1**

Dining-Philosophers Problem (Cont.)

Represent each chopstick by a semaphore.

Wait and Signal on the semaphores.

Var *chopstick:* array [0..4] of *semaphores;*

The structure of Philosopher *i*:

```
do {
        wait ( chopstick[i] );
        wait ( chopstick[ (i + 1) % 5] );
            // eat
        signal ( chopstick[i] );
        signal (chopstick[ (i + 1) % 5] );
            // think
} while (TRUE);
```

Deadlock !!

Several possible solutions to the deadlock problem

Allow at most four philosophers to be sitting simultaneously at the table.

Allow a philosopher to pick up her chopsticks only if both chopsticks are available (note that she must pick them up in a critical section).

Use an asymmetric solution. Thus,

an odd philosopher picks up first her left chopstick and then her right chopstick, whereas

an even philosopher picks up her right chopstick and then her left chopstick.

Problems with Semaphores

Correct use of semaphore operations: Otherwise, some problems may happen

signal (mutex) …. wait (mutex)

wait (mutex) … wait (mutex)

Omitting of wait (mutex) or signal (mutex) (or both)

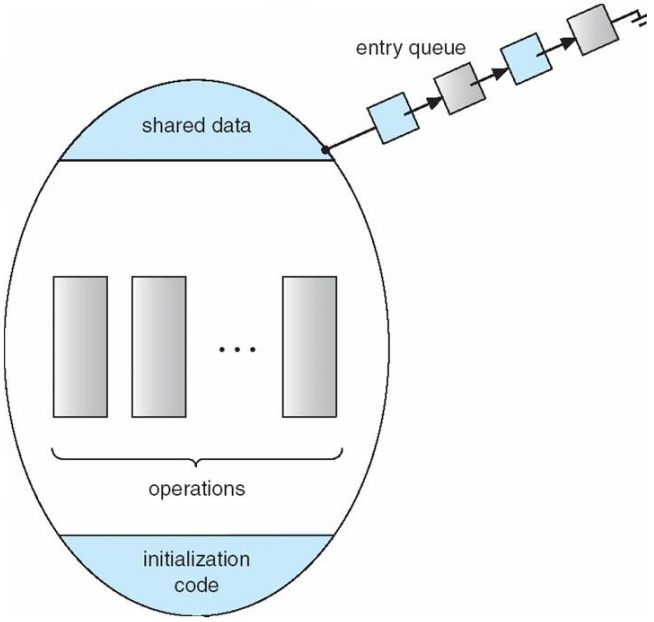
6.7 Monitors

A high-level abstraction that provides a convenient and effective mechanism for process synchronization

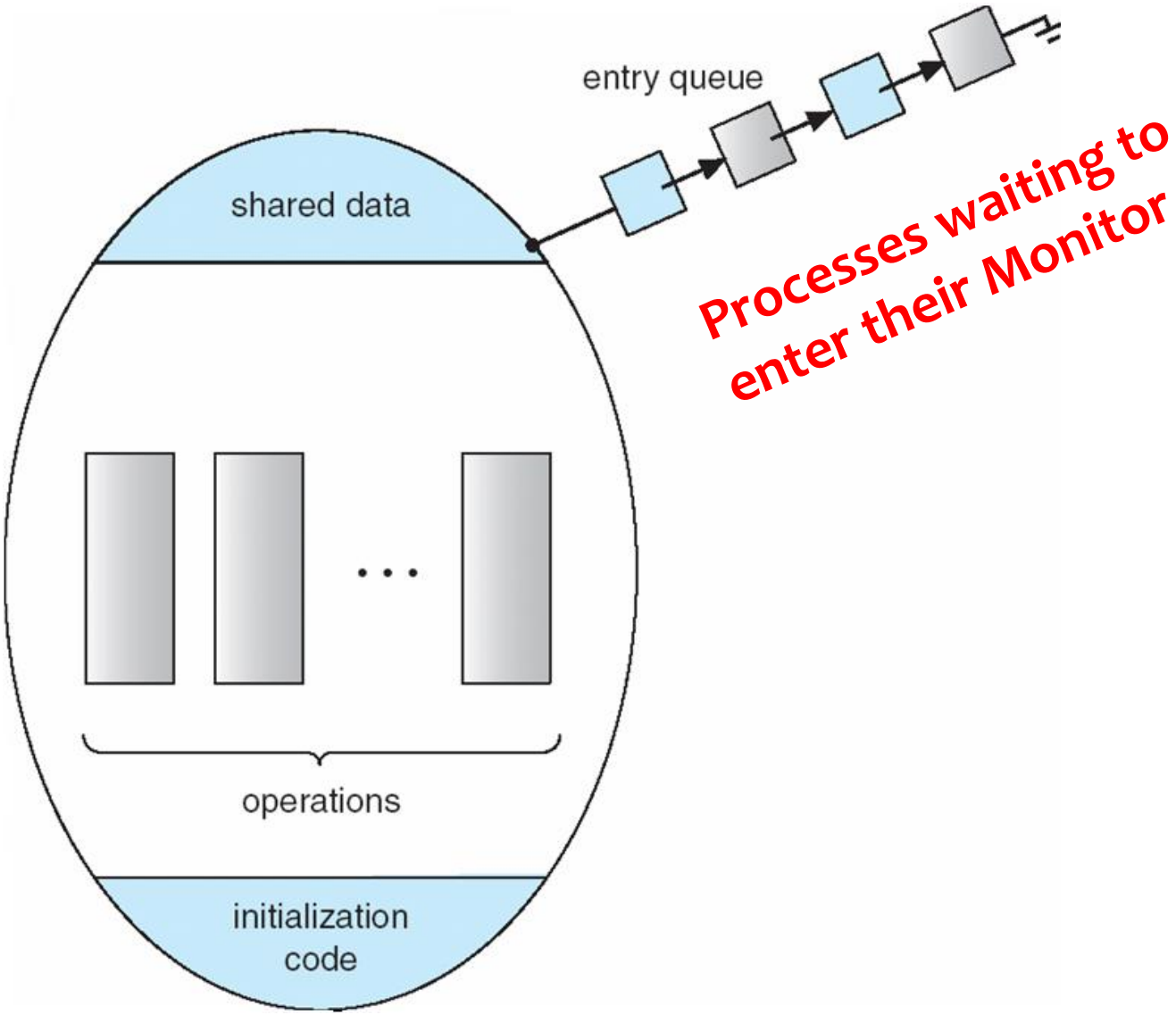
Only one process may be active within the monitor at a time

```
monitor monitor-name
{ // shared variable declarations
    procedure P1 (… ) { …. }
        …
    procedure Pn (… ) {……}

  Initialization code ( ….) { … }
        …
}
```



Schematic view of a Monitor



Monitors

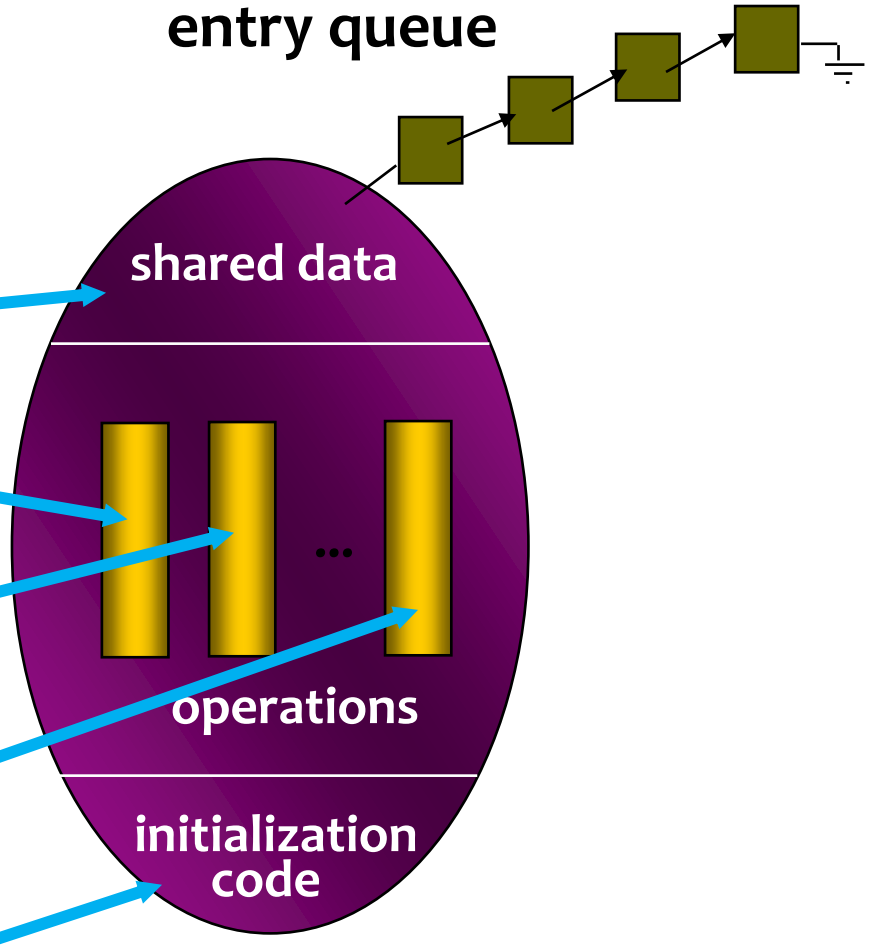
- Syntax of a monitor

```
type monitor-name = monitor
    variable declarations

    procedure entry P1(...);
        begin ... end;

    procedure entry P2(...);
        begin ... end;

    procedure entry Pn(...);
        begin ... end;
    begin
        initialization code
    end.
```



- Schematic view of a monitor

Condition Construct

A programmer who needs to write her own tailor-made synchronization scheme can define one or more variables of type *condition.*

Var *x,y : condition;*

The only operations that can be invoked on a condition variable are *wait* and *signal*. For example, *x.wait, x.signal*.

The x.signal resumes exactly one suspended process. If no process is suspended, then the signal operation has no effect.

Suppose P invokes x.signal and Q is suspended with x. Two possibilities exist:

P either waits Q leaves or another condition

Q either waits P leaves or another condition

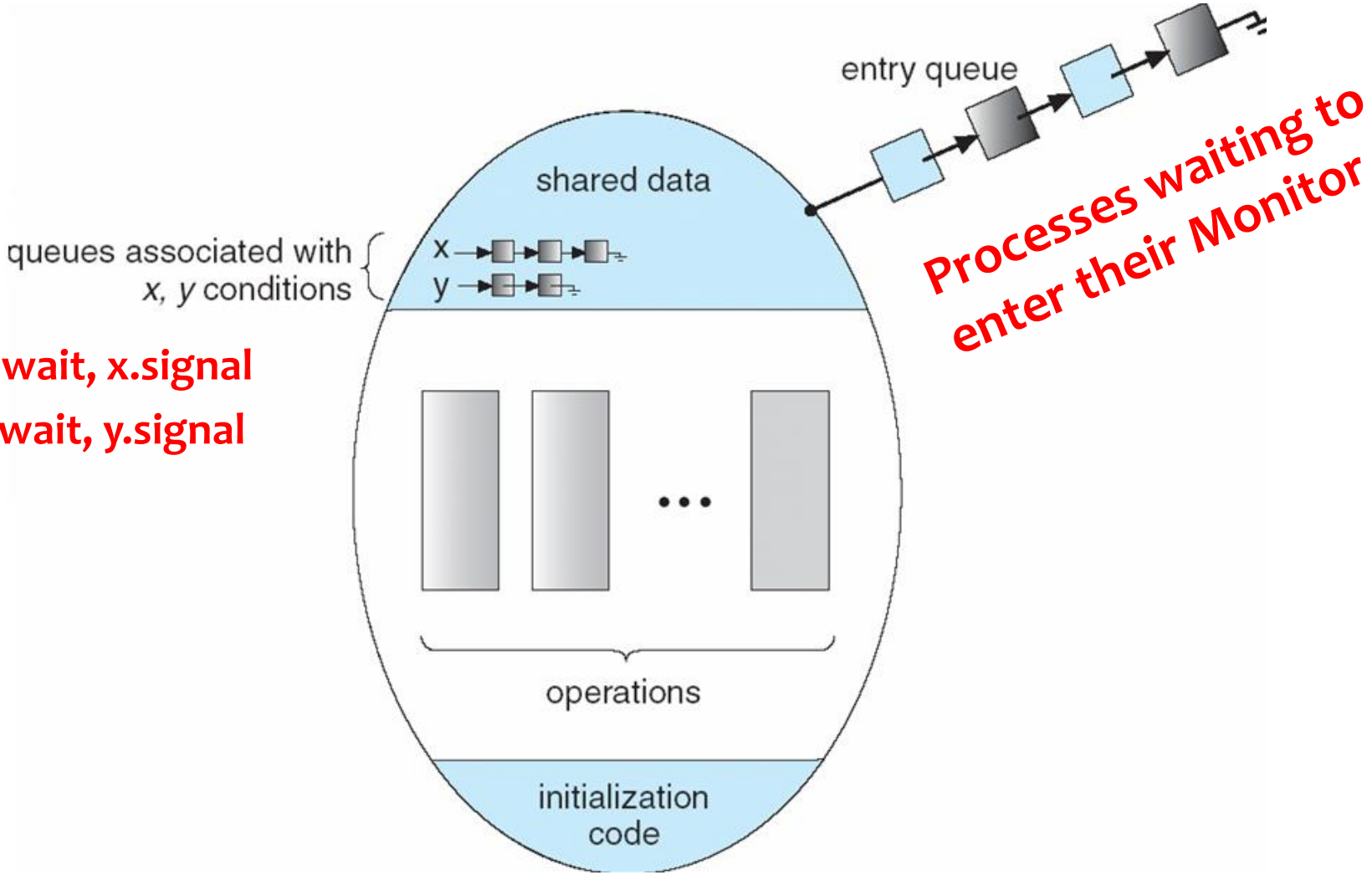
Condition Variables

condition x, y;

Two operations on a condition variable:

- x.wait () – a process that invokes the operation is suspended.
- x.signal () – resumes one of processes (if any) that invoked x.wait ()

Monitor with Condition Variables



A Deadlock-free Monitor Solution for the Dining-Philosophers Problem

A philosopher is allowed to pick up her chopsticks only if both of them are available.

Data structure:

Var *state*: array [0..4] of (*thinking*, *hungry*, *eating*);

Var *self*: array [0..4] of *condition*;

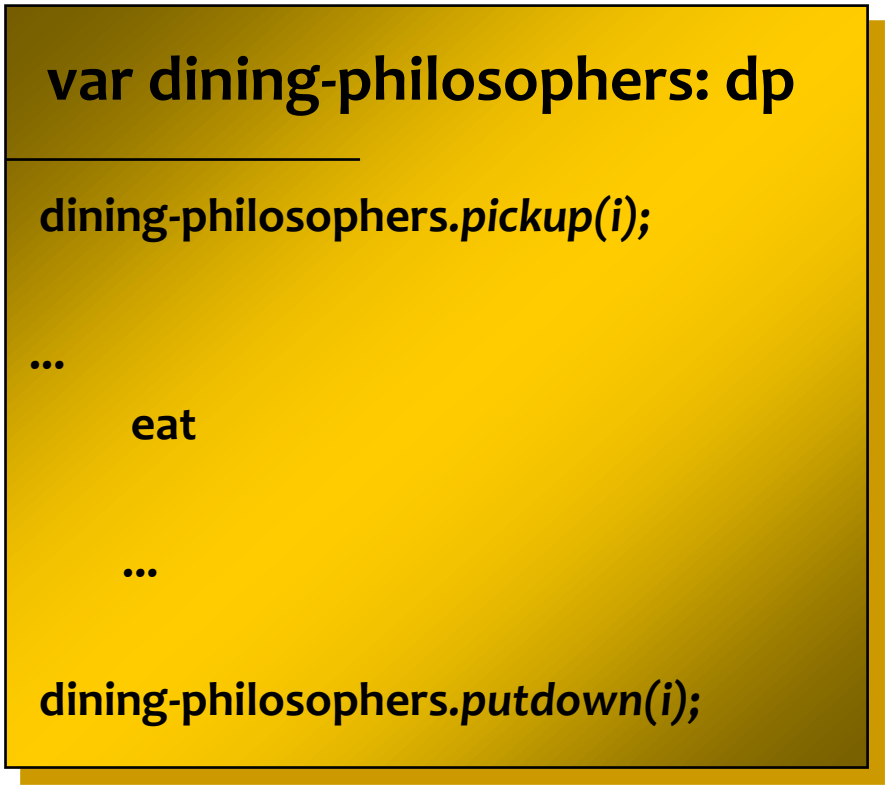
Philosopher *i* can delay herself when she is hungry, but is unable to obtain the chopsticks she needs.

Operations:

pickup and *putdown* on the instance *dp* of the *dining-philosophers* monitor

Solution to Dining Philosophers (cont)

Each philosopher *i* must invoke the operations pickup() and putdown() in the following sequence:



Process *i*

A Deadlock-free Monitor Solution for the Dining-Philosophers Problem

```
monitor dp
 {
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5];

    void pickup (int i) {
        state[i] = HUNGRY;
        test(i);
        if (state[i] != EATING) self [i].wait;
    }

    void putdown (int i) {
        state[i] = THINKING;
           // test left and right neighbors
        test((i + 4) % 5);
        test((i + 1) % 5);
    }
```

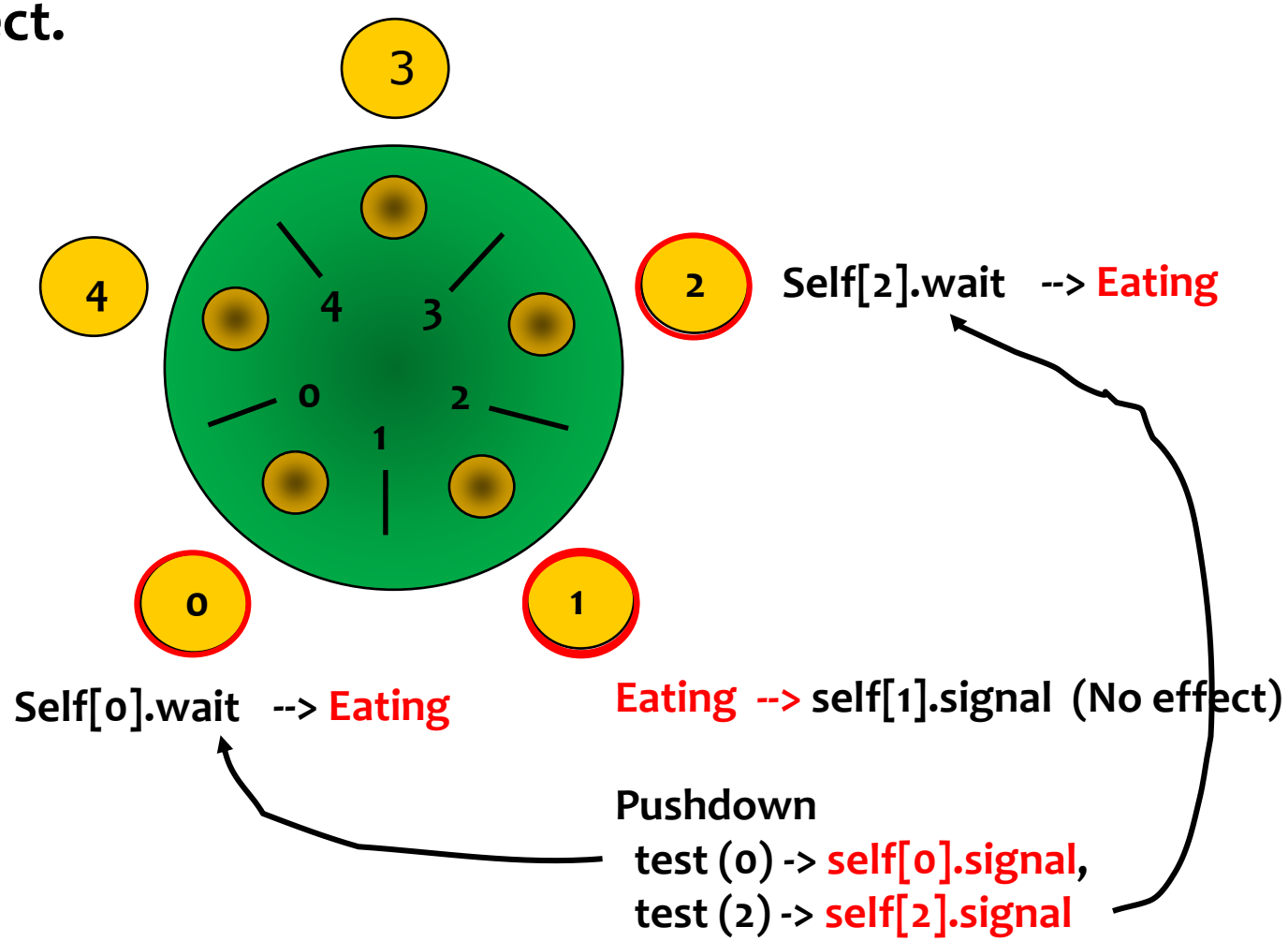
Test if both chopsticks are available

```
    void test (int i) {
        if ( (state[(i + 4) % 5] != EATING) &&
        (state[i] == HUNGRY) &&
        (state[(i + 1) % 5] != EATING) ) {
            state[i] = EATING ;
            self[i].signal () ;
        }
    }

    initialization_code() {
        for (int i = 0; i < 5; i++)
        state[i] = THINKING;
    }
}
```

Illustration of the algorithm

The x.signal resumes exactly one suspended process.
If no process is suspended, then the signal operation has no effect.



Monitor Implementation Using Semaphores

A possible implementation of the monitor mechanism using semaphores.

For each monitor, a semaphore mutex (init to 1) is provided.

A process must execute wait (mutex) before entering the monitor and must execute signal (mutex) after leaving the monitor

Since a signaling process must wait until the resumed process either leaves or waits, an additional semaphore, next, is introduced (init to 0).

The signaling processes can use *next* to suspend themselves.

An integer variable next_count is also provided to count the number of processes suspended on next.

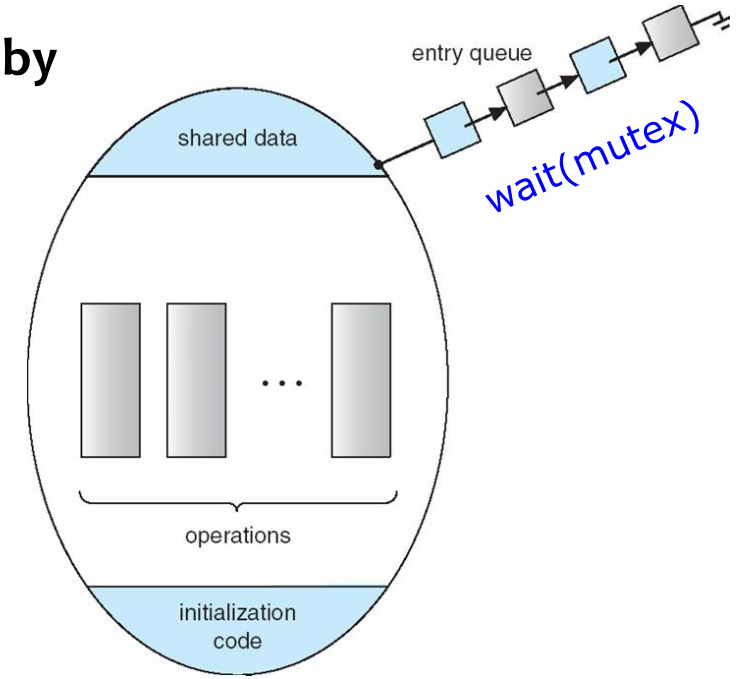
Monitor Implementation Using Semaphores

Variables

```
semaphore mutex;  // (initially = 1)
semaphore next;   // (initially = 0)
int next-count = 0;
```

Each external procedure *F* will be replaced by

```
wait(mutex);
   ...
   body of F
   ...
if (next_count > 0)
     signal(next)
else
     signal(mutex);
```



Mutual exclusion within a monitor is ensured.

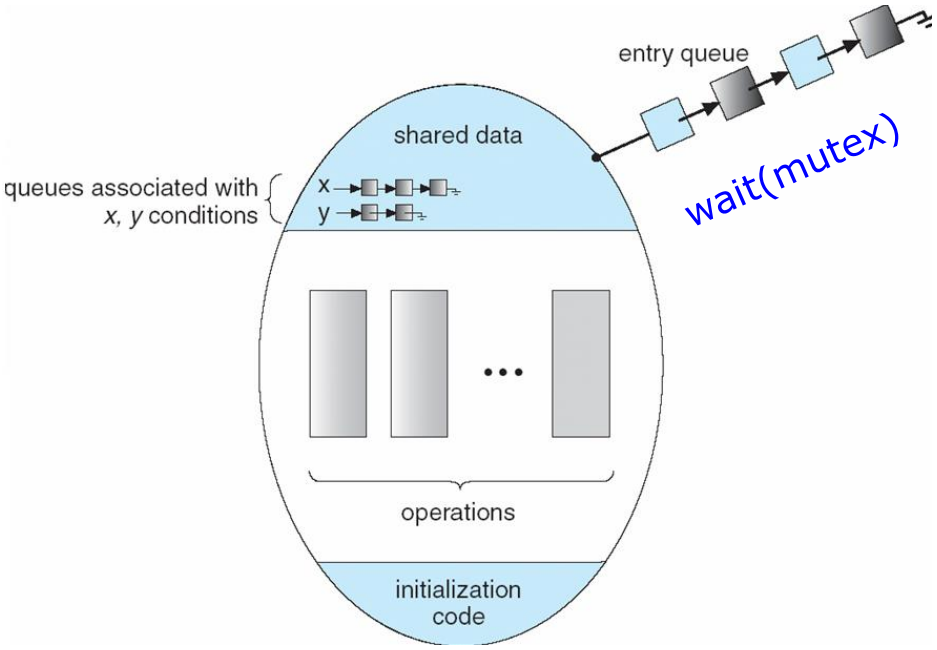
Monitor (Condition Variable) Implementation Using Semaphores

For each condition variable x, we have:

```
semaphore x_sem; // (initially = 0)
int x-count = 0;
```

The operation x.wait can be implemented as:

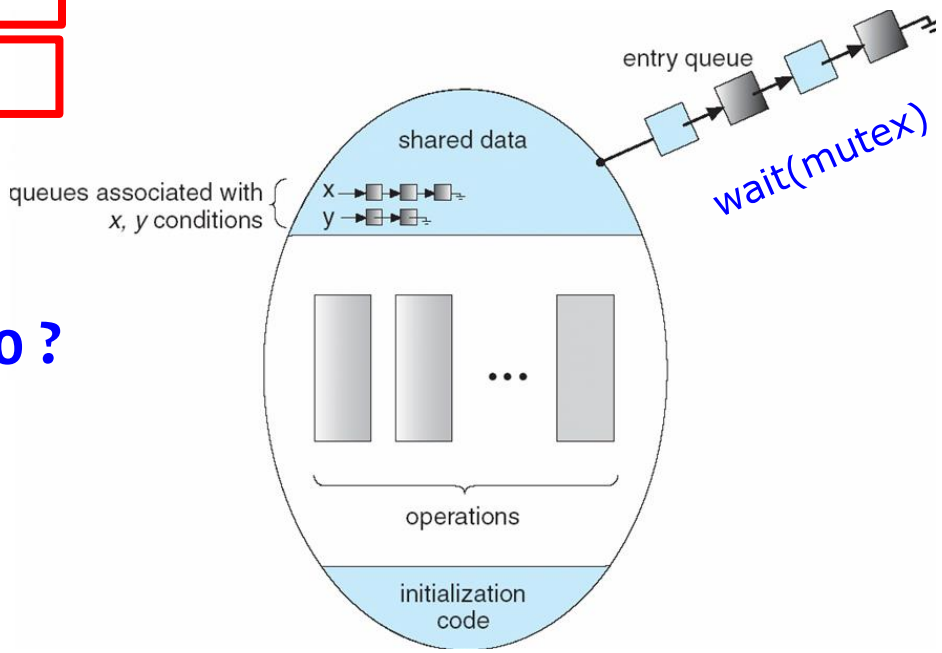
```
x-count++;
if (next_count > 0)
        signal(next);
 else
        signal(mutex);
wait(x_sem);
x-count--;
```



Monitor Implementation Using Semaphores

The operation x.signal can be implemented as:

```
if (x-count > 0) {
    next_count++;
    signal(x_sem);
    wait(next);
    next_count--;
}
```



What happen if x-count <= 0 ?

Nothing will happen !!

Resuming Processes within a Monitor

If several processes are suspended on condition x, and an x.signal() operation is executed by some process, how do we determine which of the suspended processes should be resumed next ?

FCFS ordering is simple, but may not adequate

Conditional-wait construct

x.wait (c)

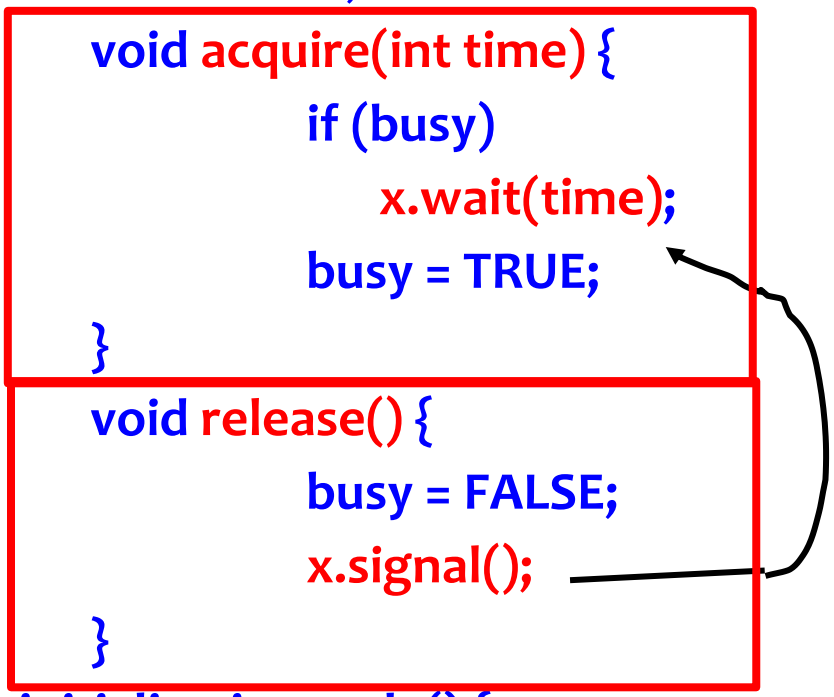
c is an integer expression that is evaluated when the wait() operation is executed.

c is called a priority number.

When x.signal () is executed, the process with smallest priority number is resumed next.

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
    boolean busy;
    condition x;
    void acquire(int time) {
            if (busy)
                x.wait(time);
            busy = TRUE;
    }
    void release() {
            busy = FALSE;
            x.signal();
    }
initialization code() {
     busy = FALSE;
    }
}
```



The process with smallest priority number is resumed next

Resuming Processes within a Monitor

The monitor allocates the resource that has the shortest time-allocation request.

A process that needs to access the resource in question must observe the following sequence:

```
R.acquire (t);   ← Get the resource, or wait for it !!
……
   access the resource
……
R. release();
```

Where R is an instance of type ResourceAllocator.

6.8 Synchronization Examples

Solaris

Windows XP

Linux

Pthreads

Solaris Synchronization

Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing

Uses adaptive mutexes for efficiency when protecting data from short code segments

Uses condition variables and readers-writers locks when longer sections of code need access to data

Uses turnstiles to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock

Windows XP Synchronization

Uses interrupt masks to protect access to global resources on uniprocessor systems

Uses spinlocks on multiprocessor systems

Also provides dispatcher objects which may act as either mutexes and semaphores

Dispatcher objects may also provide events

- An event acts much like a condition variable

Linux Synchronization

Linux:

- Prior to kernel Version 2.6, disables interrupts to implement short critical sections
- Version 2.6 and later, fully preemptive

Linux provides:

- semaphores
- spin locks

Pthreads Synchronization

Pthreads API is OS-independent

It provides:

- mutex locks
- condition variables

Non-portable extensions include:

- read-write locks
- spin locks

6.9 Atomic Transactions

Make sure that a critical section forms a single logical unit of work that either is performed in its entirety or is nor performed at all.

Consistency of data, along with storage and retrieval of data, is a concern often associated with database systems.

System Model

Log-based Recovery

Checkpoints

Concurrent Atomic Transactions

6.9.1 System Model

Assures that operations (a collection of instructions) happen as a single logical unit of work, in its entirety, or not at all

Related to field of database systems

Challenge is assuring atomicity despite computer system failures

Transaction - collection of instructions or operations that performs single logical function

- Here we are concerned with changes to stable storage – disk
- Transaction is series of read and write operations
- Terminated by commit (transaction successful) or abort (transaction failed) operation
- Aborted transaction must be rolled back to undo any changes it performed

Types of Storage Media

Volatile storage – information stored here does not survive system crashes

Example: main memory, cache

Nonvolatile storage – Information usually survives crashes

Example: disk and tape

Stable storage – Information never lost

Not actually possible, so approximated via **replication** or **RAID** to devices with independent failure modes

Goal is to assure transaction atomicity where failures cause loss of information on volatile storage

6.9.2 Log-Based Recovery

Record to stable storage information about all modifications by a transaction

Most common is write-ahead logging

Log on stable storage, each log record describes single transaction write operation, including

- Transaction name
- Data item name
- Old value
- New value

<T_i starts> written to log when transaction T_i starts

<T_i commits> written when T_i commits

Log entry must reach stable storage before operation on data occurs

Log-Based Recovery Algorithm

- Using the log, system can handle any volatile memory errors
  - Undo(T_i) restores value of all data updated by T_i
  - Redo(T_i) sets values of all data in transaction T_i to new values
- Undo(T_i) and redo(T_i) must be idempotent
  - Multiple executions must have the same result as one execution
- If system fails, restore state of all updated data via log
  - If log contains <T_i starts> without <T_i commits>, undo(T_i)
  - If log contains <T_i starts> and <T_i commits>, redo(T_i)

6.9.3 Checkpoints

Log could become long, and recovery could take long

Checkpoints shorten log and recovery time.

Checkpoint scheme:

1. Output all log records currently in volatile storage to stable storage
2. Output all modified data from volatile to stable storage
3. Output a log record <checkpoint> to the log on stable storage

Now recovery only includes Ti, such that Ti started executing before the most recent checkpoint, and all transactions after Ti

All other transactions already on stable storage

6.9.4 Concurrent Atomic Transactions

Must be equivalent to serial execution – serializability

Could perform all transactions in critical section

- Inefficient, too restrictive

Concurrency-control algorithms provide serializability

Serializability

Consider two data items A and B

Consider Transactions T_0 and T_1

Execute T_0, T_1 atomically

Execution sequence called schedule

Atomically executed transaction order called serial schedule

For *N* transactions, there are *N!* valid serial schedules

Schedule 1: T_0 then T_1

T_0	T_1
read(A)	
write(A)	
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Nonserial Schedule

Nonserial schedule allows overlapped execute

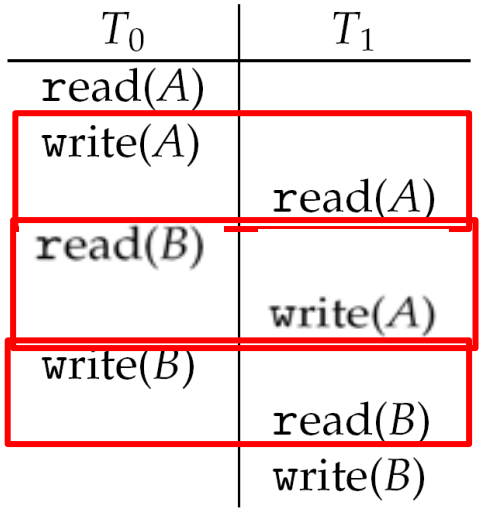
- Resulting execution not necessarily incorrect

Consider schedule S, operations O_i , O_j of Transactions T_i and T_j,

- **Conflict** if access same data item, with at least one write

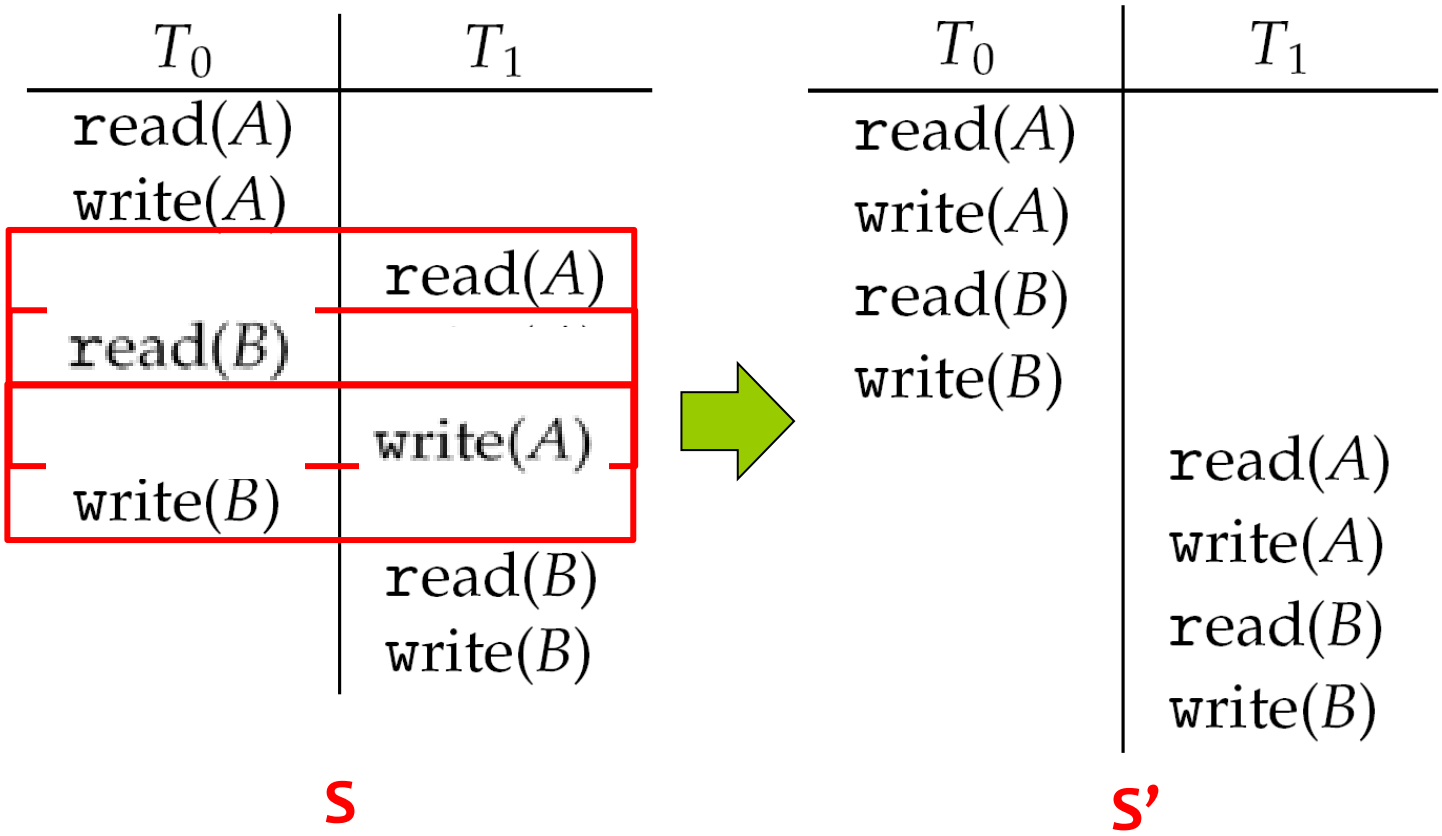
If O_i, O_j are consecutive and operations of different transactions & O_i and O_j don't conflict

- Then S' with swapped order O_j O_i equivalent to S



Nonserial Schedule

We say that S is conflict serializable, if it can be transformed into a serial schedule S' by a series of swaps of nonconflicting operations.



Locking Protocol

One way to ensure serializability is to associate a lock with each data item and each transaction follows locking protocol for access control.

Locks

- Shared – T_i has shared-mode lock (S) on item Q, T_i can read Q but not write Q
- Exclusive – Ti has exclusive-mode lock (X) on Q, T_i can read and write Q

Require every transaction on item Q acquire appropriate lock

If lock already held, new request may have to wait

- Similar to readers-writers algorithm

Two-phase Locking Protocol

The two-phase locking protocol ensures conflict serializability

Each transaction issues lock and unlock requests in two phases

- Growing – A transaction may obtain locks but may not release any locks
- Shrinking – A transaction may release locks but may not obtain any new locks.

Initially, a transaction is a the growing phase. The transaction acquires locks as needed. Once the transaction releases a lock, it enters the shrinking phase, and no more lock requests can be issued

Does not prevent deadlock

Timestamp-based Protocols

Select order among transactions in advance – timestamp-ordering

Transaction T_i associated with timestamp $TS(T_i)$ before T_i starts

- $TS(T_i) < TS(T_j)$ if T_i entered system before T_j
- TS can be generated from system clock or as logical counter incremented at each entry of transaction

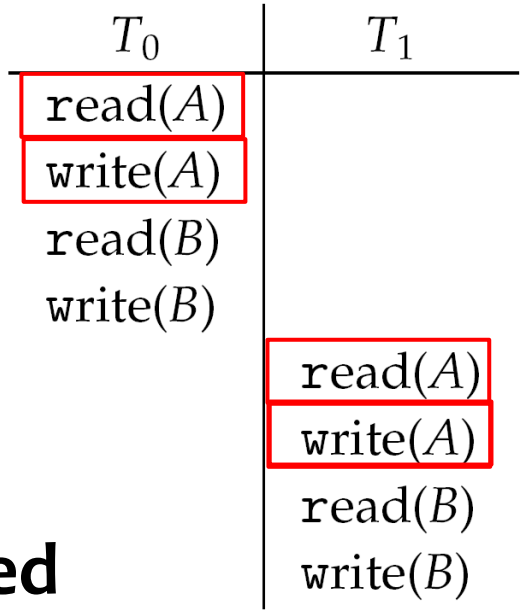
Timestamps determine serializability order

- If $TS(T_i) < TS(T_j)$, system must ensure produced schedule equivalent to serial schedule where T_i appears before T_j

Timestamp-based Protocol Implementation

Data item Q gets two timestamps

- W-timestamp(Q) – largest timestamp of any transaction that executed write(Q) successfully
- R-timestamp(Q) – largest timestamp of successful read(Q)
- Updated whenever read(Q) or write(Q) executed



Timestamp-ordering protocol assures any **conflicting read and write** executed in timestamp order

Timestamp-based Protocol Implementation

Suppose T_i executes read(Q)

If $TS(T_i) < W\text{-timestamp}(Q)$, Ti needs to read value of Q that was already overwritten

- **read** operation rejected and T_i rolled back

If $TS(T_i) \geq W\text{-timestamp}(Q)$

- **read** executed, R-timestamp(Q) set to max(R-timestamp(Q), $TS(T_i)$)

Timestamp-ordering Protocol

Suppose Ti executes write(Q)

If $TS(T_i) < R\text{-}timestamp(Q)$, value Q produced by T_i was needed previously and T_i assumed it would never be produced

- **Write operation rejected, T_i rolled back**

If $TS(T_i) < W\text{-}timestamp(Q)$, T_i attempting to write obsolete value of Q

- **Write operation rejected and T_i rolled back**

Otherwise, write executed

A transaction T_i is rolled back as a result of either a read or write operation is assigned a new timestamp and is restarted

Timestamp-ordering Protocol Example

Assume a transaction is assigned a timestamp immediately before its first instruction.

Thus, $TS(T_2) < TS(T_3)$

The following schedule is possible under Timestamp Protocol

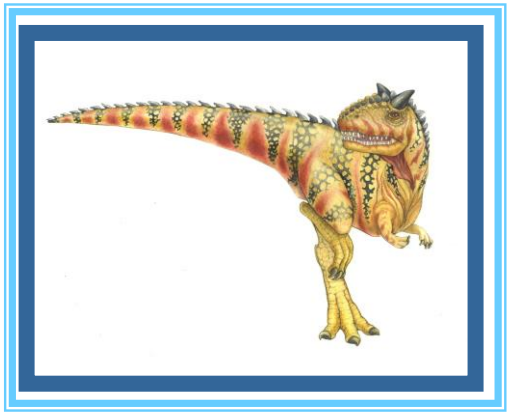
T_2	T_3
read(B)	
	read(B)
	write(B)
read(A)	
	read(A)
	write(A)

Timestamp-ordering Protocol

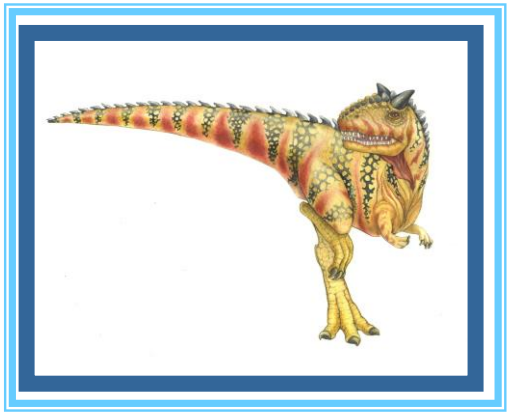
This algorithm ensures

- conflict serializability – conflicting operations are processed in timestamp order, and
- freedom from deadlock – no transactions ever waits

End of Chapter 6



Chapter 7: Deadlocks



Chapter 7: Deadlocks

The Deadlock Problem

System Model

Deadlock Characterization

Methods for Handling Deadlocks

Deadlock Prevention

Deadlock Avoidance

Deadlock Detection

Recovery from Deadlock

Chapter Objectives

To develop a description of deadlocks, which prevent sets of concurrent processes from completing their tasks

To present a number of different methods for preventing or avoiding deadlocks in a computer system

The Deadlock Problem

A set of blocked processes each holding a resource and waiting to acquire a resource held by another process in the set

Example

System has 2 disk drives

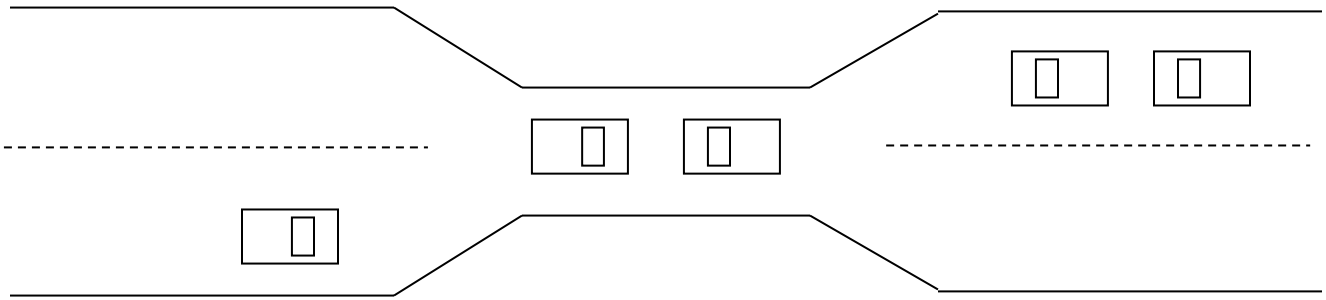
P_1 and P_2 each holds one disk drive and each needs another one

Example

semaphores *A* and *B*, initialized to 1

P_0	P_1
wait (A);	wait(B)
wait (B);	wait(A)

Bridge Crossing Example



Traffic only in one direction

Each section of a bridge can be viewed as a resource

If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback)

Several cars may have to be backed up if a deadlock occurs

Starvation is possible

Note – Most OSes do not prevent or deal with deadlocks

System Model

Resource types $R_1, R_2, \ldots, R_m$

CPU cycles, memory space, I/O devices

Each resource type R_i has W_i instances.

Each process utilizes a resource as follows:

request

use

release

Deadlock Characterization

Deadlock can arise if four conditions hold **simultaneously**.

Mutual exclusion: only one process at a time can use a resource

Hold and wait: a process holding at least one resource is waiting to acquire additional resources held by other processes

No preemption: a resource can be released only voluntarily by the process holding it, after that process has completed its task

Circular wait: there exists a set $\{P_0, P_1, \ldots, P_n\}$ of waiting processes such that P_0 is waiting for a resource that is held by P_1, P_1 is waiting for a resource that is held by $P_2, \ldots, P_{n-1}$ is waiting for a resource that is held by P_n, and P_n is waiting for a resource that is held by P_0.

Resource-Allocation Graph

A set of vertices V and a set of edges E.

V is partitioned into two types:

$P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system

$R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system

request edge – directed edge $P_1 \rightarrow R_j$

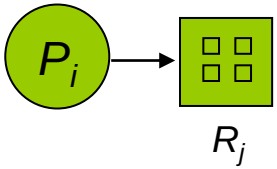
assignment edge – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

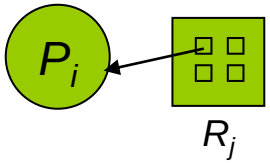
Process

Resource Type with 4 instances

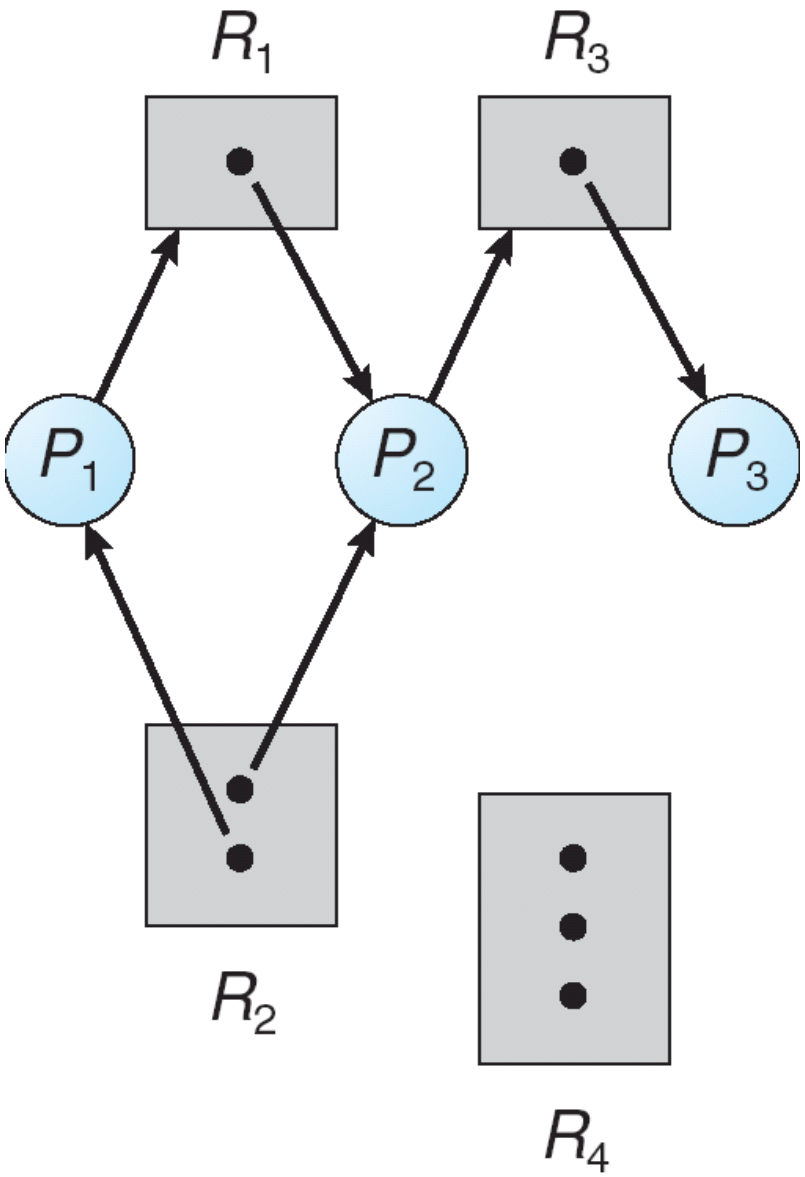
P_i requests instance of R_j



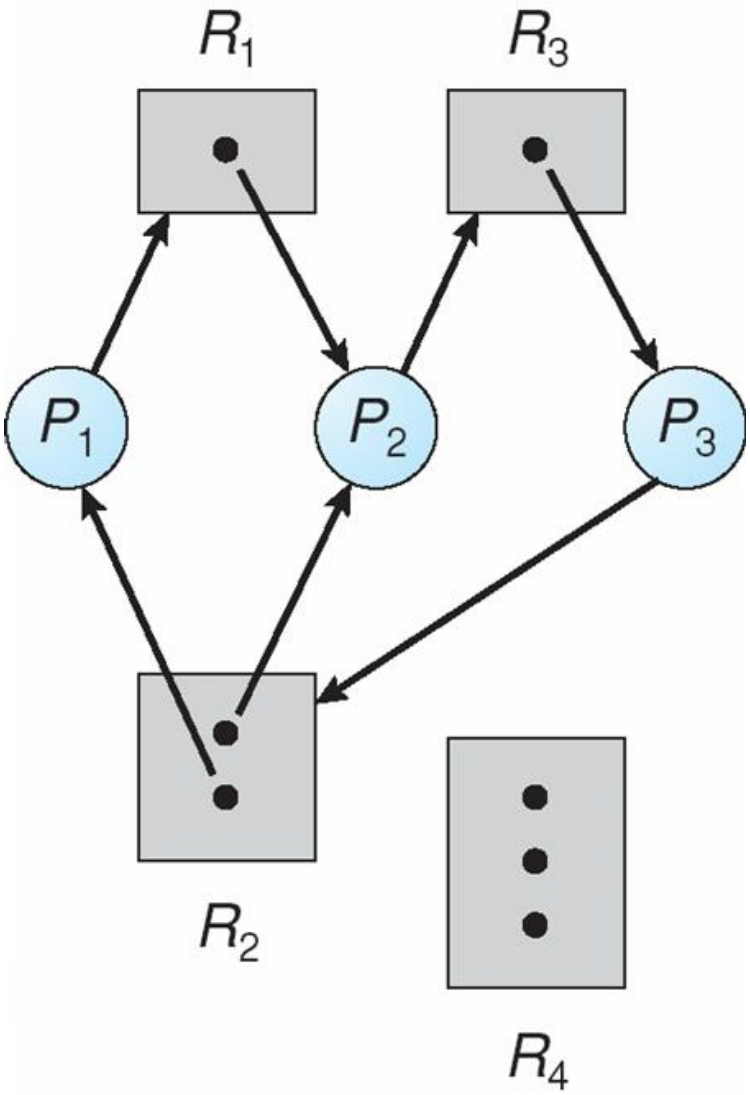
P_i is holding an instance of R_j



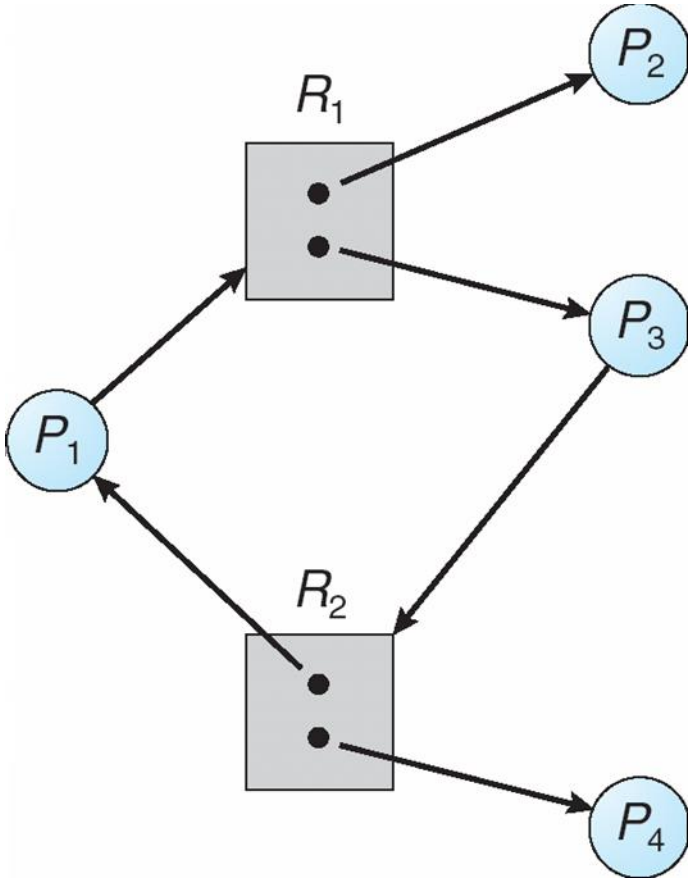
Example of a Resource Allocation Graph



Resource Allocation Graph With A Deadlock



Graph With A Cycle But No Deadlock



Basic Facts

If graph contains no cycles ⇒ no deadlock

If graph contains a cycle ⇒

- if only one instance per resource type, then deadlock
- if several instances per resource type, possibility of deadlock

Methods for Handling Deadlocks

Ensure that the system will *never* enter a deadlock state

Allow the system to enter a deadlock state and then recover

Ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, including UNIX

Deadlock Prevention

Restrain the ways request can be made

Mutual Exclusion – not required for sharable resources; must hold for nonsharable resources

Hold and Wait – must guarantee that whenever a process requests a resource, it does not hold any other resources

- Require process to request and be allocated all its resources before it begins execution, or allow process to request resources only when the process has none
- Low resource utilization; starvation possible

Deadlock Prevention (Cont.)

No Preemption –

- If a process that is holding some resources requests another resource that cannot be immediately allocated to it, then all resources currently being held are released
- Preempted resources are added to the list of resources for which the process is waiting
- Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting

Circular Wait – impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration

Deadlock Avoidance

Requires that the system has some additional *a priori* information available

- Simplest and most useful model requires that each process declares the *maximum number* of resources of each type that it may need
- The deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that there can never be a circular-wait condition
- Resource-allocation *state* is defined by the number of available and allocated resources, and the maximum demands of the processes

Safe State

When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state

System is in safe state if there exists a sequence $<P_1, P_2, \ldots, P_n>$ of ALL the processes in the systems such that

for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all the P_j, with $j < i$

Safe State

That is:

If P_i resource needs are not immediately available, then P_i can wait until all P_j have finished

When P_j is finished, P_i can obtain needed resources, execute, return allocated resources, and terminate

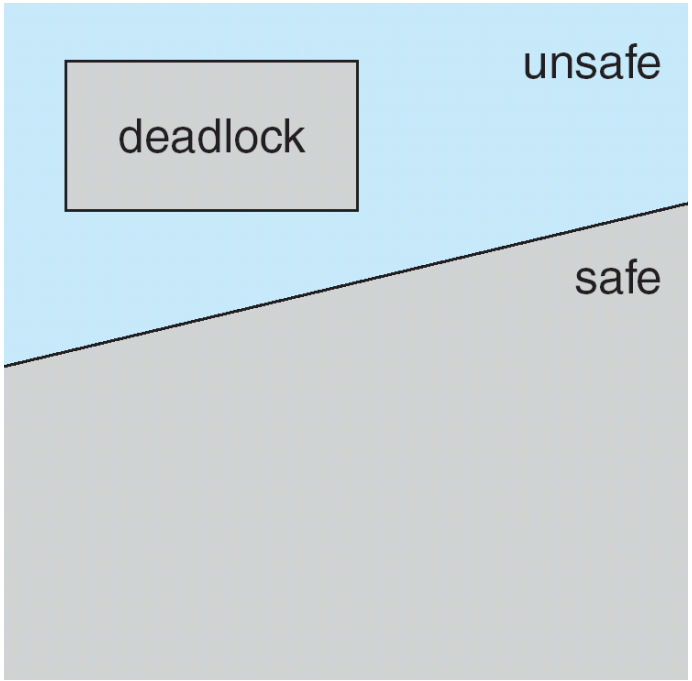
When P_i terminates, P_{i+1} can obtain its needed resources, and so on

Basic Facts

If a system is in safe state ⇒ no deadlocks

If a system is in unsafe state ⇒ possibility of deadlock

Avoidance ⇒ ensure that a system will never enter an unsafe state.



Avoidance algorithms

Single instance of a resource type

Use a resource-allocation graph

Multiple instances of a resource type

Use the banker's algorithm

Resource-Allocation Graph Scheme

Claim edge $P_i \rightarrow R_j$ indicated that process P_i may request resource R_j ; represented by a dashed line

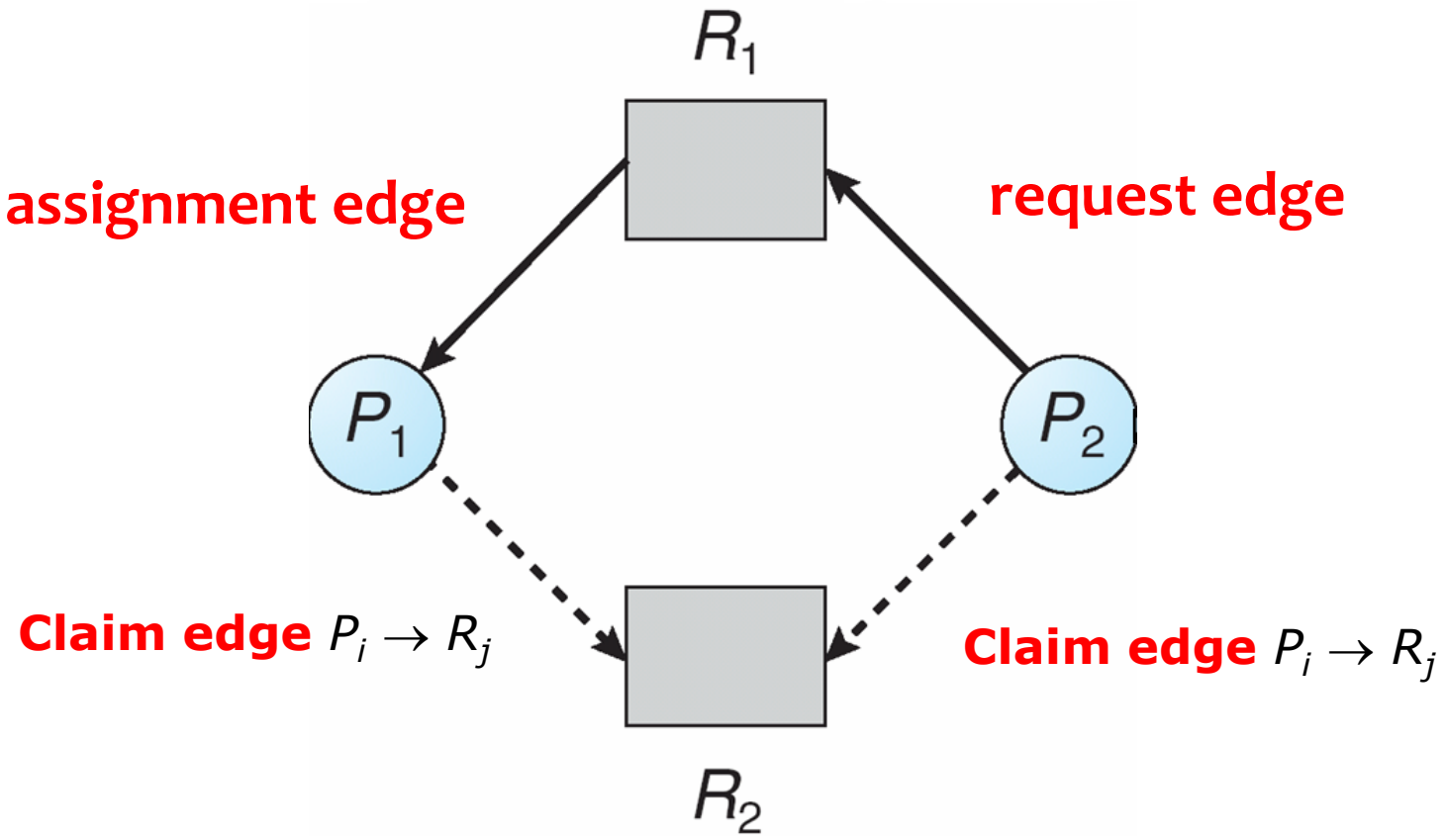
Claim edge converts to request edge when a process requests a resource

Request edge converted to an assignment edge when the resource is allocated to the process

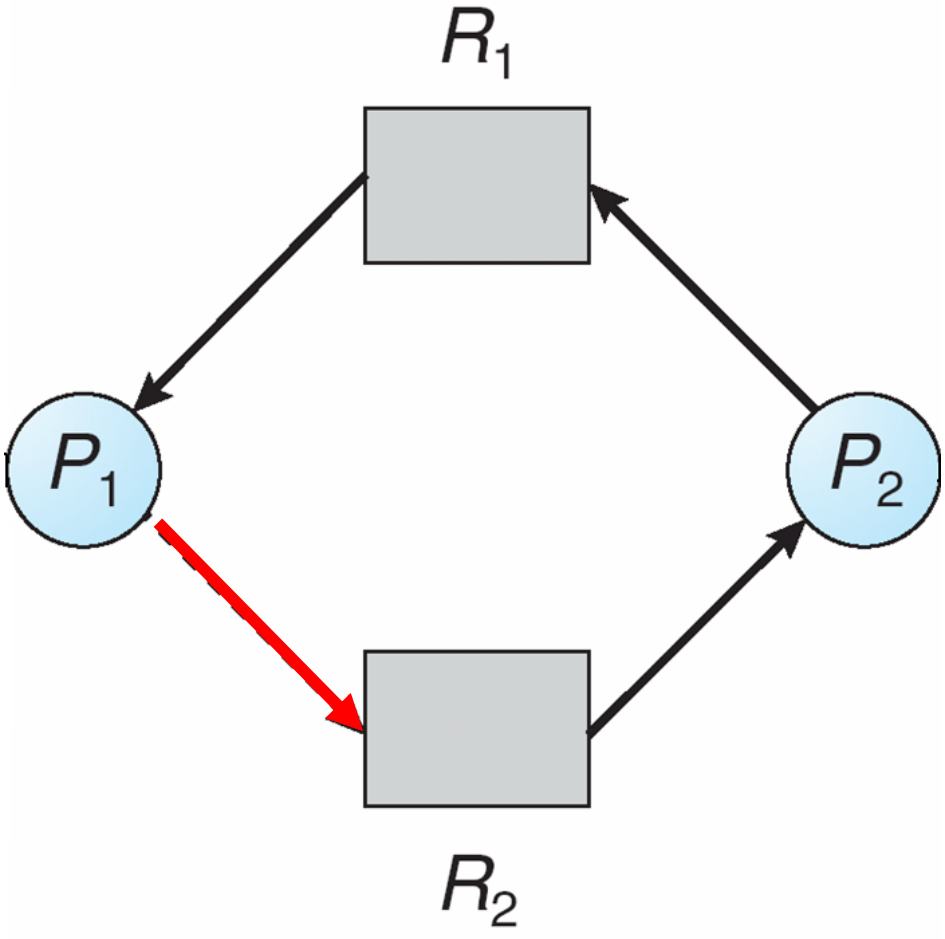
When a resource is released by a process, assignment edge reconverts to a claim edge

Resources must be claimed *a priori* in the system

Resource-Allocation Graph



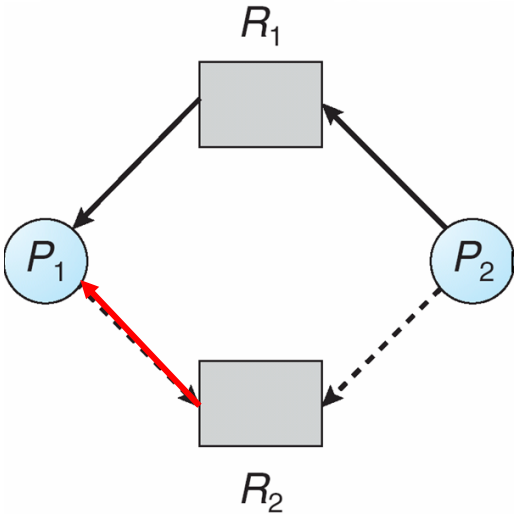
Unsafe State In Resource-Allocation Graph



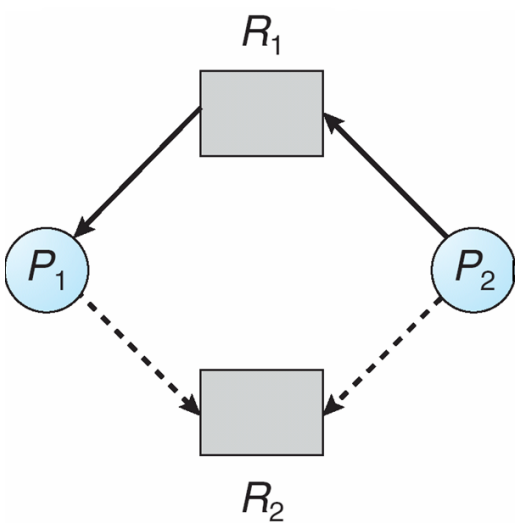
Resource-Allocation Graph Algorithm

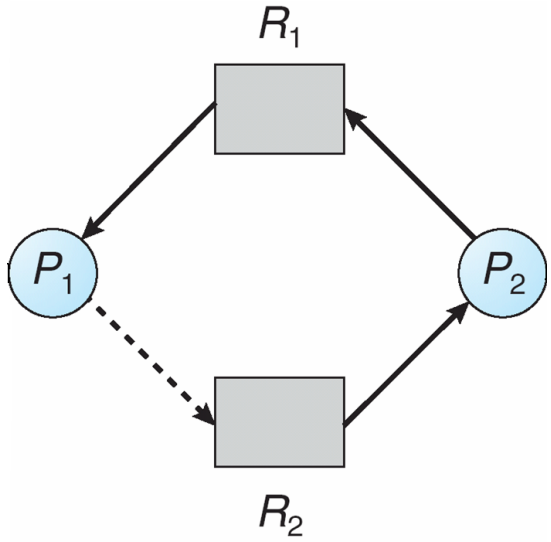
Suppose that process P_i requests a resource R_j

The request can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph



$P_1 \rightarrow R_2$ *accept*





$P_2 \rightarrow R_2$ *reject, otherwise, a cycle is formed*

Banker's Algorithm

Multiple instances

Each process must a priori claim maximum use

When a process requests a resource it may have to wait

When a process gets all its resources it must return them in a finite amount of time

Data Structures for the Banker's Algorithm

Let n = number of processes, and

m = number of resources types.

Available: Vector of length m. If available $[j] = k$, there are k instances of resource type R_j available

Max: n x m matrix. If $Max\ [i,j] = k$, then process P_i may request at most k instances of resource type R_j

Allocation: n x m matrix. If $Allocation[i,j] = k$ then P_i is currently allocated k instances of R_j

Need: n x m matrix. If $Need[i,j] = k$, then P_i may need k more instances of R_j to complete its task

$$Need\ [i,j] = Max[i,j] - Allocation\ [i,j]$$

Safety Algorithm

1. Let *Work* and *Finish* be vectors of length *m* and *n*, respectively. Initialize:

   Work = *Available*

   Finish [*i*] = *false* for *i* = 0, 1, …, *n*- 1

2. Find any *i* such that both:

   (a) *Finish* [*i*] = *false*

   (b) $Need_i \leq Work$

   If no such *i* exists, go to step 4

3. $Work = Work + Allocation_i$
   Finish[*i*] = *true*
   go to step 2

4. If *Finish* [*i*] == true for all *i*, then the system is in a safe state

Resource-Request Algorithm for Process P_i

$Request_i$ = request vector for process P_i. If $Request_i[j] = k$ then process P_i wants k instances of resource type R_j

1. If $Request_i \leq Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $Request_i \leq Available$, go to step 3. Otherwise P_i must wait, since resources are not available
3. Pretend to allocate requested resources to P_i by modifying the state as follows:

$$Available = Available - Request;$$

$$Allocation_i = Allocation_i + Request_i;$$

$$Need_i = Need_i - Request_i;$$

If safe $\Rightarrow$ the resources are allocated to P_i

If unsafe $\Rightarrow$ P_i must wait, and the old resource-allocation state is restored

Example of Banker's Algorithm

5 processes P_0 through P_4;

3 resource types:

A (10 instances), *B* (5instances), and C (7 instances)

Snapshot at time T_0:

	Allocation	*Max*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

Example (Cont.)

The content of the matrix *Need* is defined to be

Max – Allocation

	Need	*Available*
	A B C	*A B C*
P_0	7 4 3	3 3 2
P_1	1 2 2	
P_2	6 0 0	
P_3	0 1 1	
P_4	4 3 1	

The system is in a safe state since the sequence

$< P_1, P_3, P_4, P_2, P_0 >$ satisfies safety criteria

Example: P_1 Request (1,0,2)

Check that Request ≤ Available (that is, (1,0,2) ≤ (3,3,2) ⇒ true)

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 4 3	2 3 0
P_1	3 0 2	0 2 0	
P_2	3 0 1	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

Executing safety algorithm shows that sequence $< P_1, P_3, P_4, P_0, P_2 >$ satisfies safety requirement

Can request for (3,3,0) by P_4 be granted?

Can request for (0,2,0) by P_0 be granted?

Deadlock Detection

Allow system to enter deadlock state

Detection algorithm

Recovery scheme

Single Instance of Each Resource Type

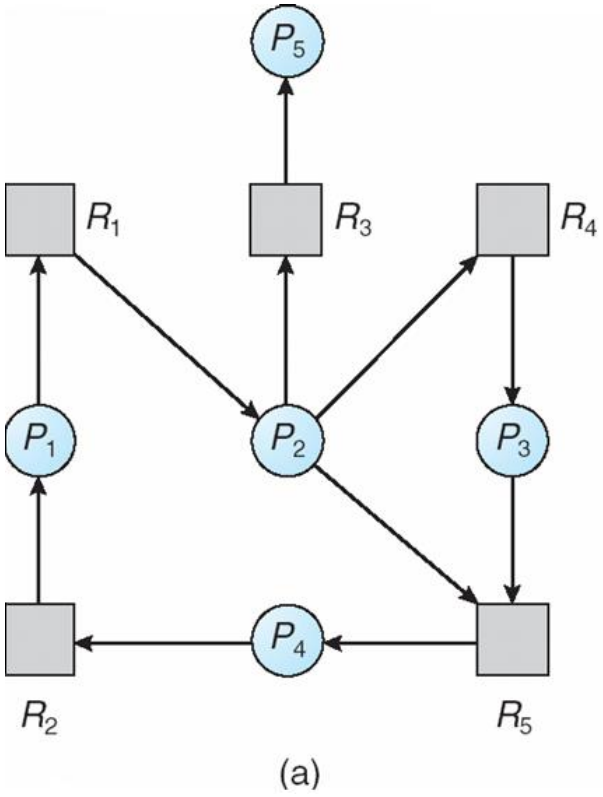
Maintain *wait-for* graph

- Nodes are processes
- $P_i \rightarrow P_j$ if P_i is waiting for P_j

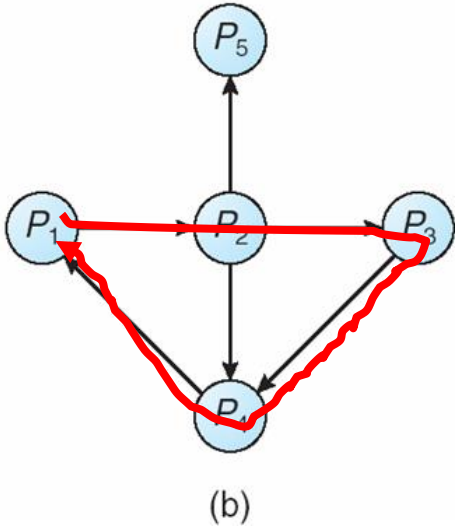
Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock

An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph

Resource-Allocation Graph and Wait-for Graph



Resource-Allocation Graph



Corresponding wait-for graph

Several Instances of a Resource Type

Available: A vector of length *m* indicates the number of available resources of each type.

Allocation: An *n* x *m* matrix defines the number of resources of each type currently allocated to each process.

Request: An *n* x *m* matrix indicates the current request of each process. If *Request* [*i*, *j*] = *k*, then process P_i is requesting *k* more instances of resource type R_j.

Detection Algorithm

1. Let *Work* and *Finish* be vectors of length *m* and *n*, respectively Initialize:

   (a) *Work* = *Available*

   (b) For $i = 1,2, \ldots, n$, if $Allocation_i \neq 0$, then
   Finish[i] = false; otherwise, *Finish*[i] = *true*

2. Find an index *i* such that both:

   (a) *Finish*[*i*] == *false*

   (b) $Request_i \leq Work$

   If no such *i* exists, go to step 4

Detection Algorithm (Cont.)

3. $Work = Work + Allocation_i$
   $Finish[i] = true$
   go to step 2
4. If $Finish[i] ==$ false, for some i, $1 \leq i \leq n$, then the system is in deadlock state. Moreover, if $Finish[i] == false$, then P_i is deadlocked

Algorithm requires an order of $O(m \times n^2)$ operations to detect whether the system is in deadlocked state

Example of Detection Algorithm

Five processes P_0 through P_4; three resource types
A (7 instances), B (2 instances), and C (6 instances)

Snapshot at time T_0:

	Allocation	*Request*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	0 0 0	0 0 0
P_1	2 0 0	2 0 2	
P_2	3 0 3	0 0 0	
P_3	2 1 1	1 0 0	
P_4	0 0 2	0 0 2	

Sequence $\langle P_0, P_2, P_3, P_1, P_4 \rangle$ will result in *Finish*[*i*] = true for all *i*

Example (Cont.)

P_2 requests an additional instance of type C

	Request
	A B C
P_0	0 0 0
P_1	2 0 2
P_2	0 0 1
P_3	1 0 0
P_4	0 0 2

State of system?

Can reclaim resources held by process P_0, but insufficient resources to fulfill other processes' requests

Deadlock exists, consisting of processes P_1, P_2, P_3, and P_4

Detection-Algorithm Usage

When, and how often, to invoke depends on:

- How often a deadlock is likely to occur?
- How many processes will need to be rolled back?
  - one for each disjoint cycle

If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph and so we would not be able to tell which of the many deadlocked processes "caused" the deadlock

Recovery from Deadlock: Process Termination

- Abort all deadlocked processes
- Abort one process at a time until the deadlock cycle is eliminated
- In which order should we choose to abort?
  - Priority of the process
  - How long process has computed, and how much longer to complete
  - Resources the process has used
  - Resources process needs to complete
  - How many processes will need to be terminated
  - Is process interactive or batch?

Recovery from Deadlock: Resource Preemption

Selecting a victim – minimize cost

Rollback

return to some safe state, restart process for that state

Starvation

same process may always be picked as victim,

include number of rollbacks in cost factor

End of Chapter 7