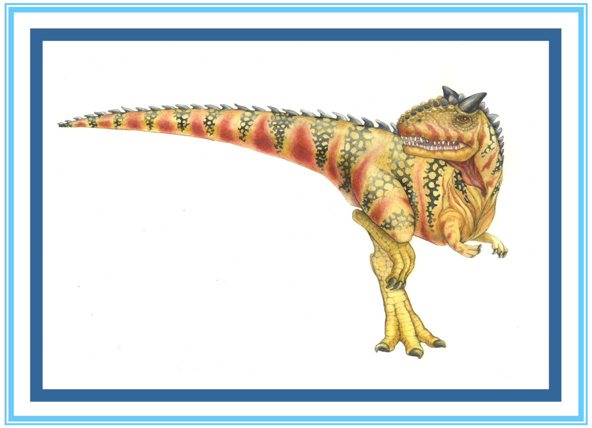
Chapter 6: Process Synchronization



Chapter 6: Process Synchronization

- Background
- The Critical-Section Problem
- Peterson's Solution
- Synchronization Hardware
- Mutex Locks
- Semaphores
- Classic Problems of Synchronization
- Monitors
- Synchronization Examples
- Alternative Approaches

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 examine several classical process-synchronization problems
- To explore several tools that are used to solve process synchronization problems

Background

Processes can execute concurrently

May be interrupted at any time, partially completing execution

Concurrent access to shared data may result in data inconsistency

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

Illustration of the problem:
Suppose that we wanted to provide a solution to the consumer-producer problem that fills ***all*** the buffers. We can do so by having an integer **`counter`** that keeps track of the number of full buffers. Initially, **`counter`** 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 in next produced */

     while (counter == BUFFER SIZE) ;
          /* do nothing */
     buffer[in] = next produced;
     in = (in + 1) % BUFFER SIZE;
     counter++;
}
```

*(________ is the only shared data by the two processes, which is initialized to 0)

Consumer

```
while (true) {
    while (counter == 0)
        ; /* do nothing */
    next consumed = buffer[out];
    out = (out + 1) % BUFFER SIZE;
    counter--;
    /* consume the item in next consumed */
}
```

Race Condition

`counter++` could be implemented as

```
register1 = counter
register1 = register1 + 1
counter = register1
```

`counter--` could be implemented as

```
register2 = counter
register2 = register2 - 1
counter = register2
```

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

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

* (_____ condition: the situation where several proc access and manipulate shared data concurrently. The
* final value of the shared data depends on which proc finishes last.)

(To prevent race condition, concurrent proc must be synchronized. If the 3 inst of the producer and consumer proc are executed as a group w/o interrupt (_______ execution), correct result is guaranteed.)

Critical Section Problem

- Consider system of n processes $\{p_0, p_1, \ldots p_{n-1}\}$ * (*n* processes all competing to use some shared data)
- Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc
  - When one process in critical section, no other may be in its critical section
- ***Critical section problem*** is to design protocol to solve this
- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**

Critical Section

General structure of process p_i is

```
do {
    entry section
        critical section
    exit section
        remainder section
} while (true);
```

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

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 * (related to ___________)

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 *(related to ___________)
   - Assume that each process executes at a nonzero speed
   - No assumption concerning **relative speed** of the ***n*** processes

   * (Must satisfy all the 3 conditions)

Two approaches depending on if kernel is preemptive or non-preemptive

- **Preemptive** – allows preemption of process when running in kernel mode
- **Non-preemptive** – runs until exits kernel mode, blocks, or voluntarily yields CPU
  - Essentially free of race conditions in kernel mode

Peterson's Solution

- Good algorithmic description of solving the problem
- 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);
```

* P_0	P_1
f(0)=1	f(1)=1
	turn=0 (occurs first)
turn=1	
	CS
	f(1)= 0
CS	
f(0)=0	

Provable that

1. Mutual exclusion is preserved
2. Progress requirement is satisfied * (‘ ____’ decides which will go ahead if both want to go)
3. Bounded-waiting requirement is met * (As soon as f(1) becomes __, P_0 can enter the CS. So, waiting time is bounded (actually 1))

Synchronization Hardware

Many systems provide hardware support for critical section code

* (Sync HW makes programming ________ and improves system efficiency)

All solutions below based on idea of **locking**

- Protecting critical regions via locks

Uniprocessors – could disable interrupts *(to allow correct sequence of execution while a shared variable is being modified)

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

  * (Since it needs to disable the int of other processors by sending msg to them which is time consuming)

Modern machines provide special atomic hardware instructions

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

Solution to Critical-section Problem Using Locks

```
do {
   acquire lock  *(Once 'lock' becomes ______, other processes cannot enter the CS)
         critical section
   release lock
         remainder section
} while (TRUE);
```

test_and_set Instruction

Definition:

```
boolean test_and_set (boolean *target)
 {
       boolean rv = *target;
       *target = TRUE;
       return rv:
 }
```

*(‘rv’ gets the current value of target)

* (Read-modify-write inst)

* (Test&Set (most CPU): read value, write back to mem)

Solution using test_and_set()

Shared boolean variable lock, initialized to FALSE

Solution:

```
do {
       while (test_and_set(&lock))
       ; /* do nothing */
    /* critical section */
    lock = false;
    /* remainder section */
} while (true);
```

★ (TS = 0 means no one is in the CS)

★ (lock= 1 means CS is (will be) used by someone)

* (Bounded waiting is not satisfied when more than two proc operate since TS inst is atomic. For a proc, it cannot be ever executed if the TS inst of other proc is always executed before itself.)

```
boolean test_and_set (boolean *target)
          {
               boolean rv = *target;
               *target = TRUE;
               return rv:
          }
```

★

P_0	P_1
★ TS=0 lock=1	
	TS=1 lock=1
CS lock=0	
	TS=0 lock=1 CS lock=0

compare_and_swap Instruction

★ (Compare and swap (68000): read value, if it matches reg, do exchange)

★ (Exchange (intel 80x86): swap values between reg & mem)

Definition:

```
int compare and swap(int *value, int expected, int new value) {
   int temp = *value;
   if (*value == expected)
      *value = new value;
   return temp;
}
```

* (Load-link/store-conditional (LL/SC) (R4000, Alpha)
  - Designed to fit better with load/store arch (speculative computation)
  - Read value. Do some operation. When store, check if modified. If not, Ok.
    Otherwise, abort, jump back to start)

Solution using compare_and_swap

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

Solution:

```
do {
      while (compare and swap(&lock, 0, 1) != 0)
      ; /* do nothing */
      /* critical section */
   lock = 0;
      /* remainder section */
} while (true);
```

★ P_0	P_1
CS()=0	
lock=1	
	CS()=1
	lock=1
CS	
lock=0	
	CS()=0
	lock=1
	CS
	lock=0

```
int compare and swap(int *value, int expected, int new value) {
   int temp = *value;
   if (*value == expected)
      *value = new value;
   return temp;
}
```

Bounded-waiting Mutual Exclusion with test_and_set

```
do {
   waiting[i] = true;
   key = true;
   while (waiting[i] && key)
      key = test_and_set(&lock);
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = false;
   else
      waiting[j] = false;
   /* remainder section */
} while (true);
```

```
boolean test_and_set (boolean *target)
        {
             boolean rv = *target;
             *target = TRUE;
             return rv:
        }
```

* (If ‘lock’ was _____ , key becomes false due to swap inst. Then comes out from while loop and enters CS. If other proc comes, key and lock are true, and thus keep swapping until lock becomes false)

Mutex Locks

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest is mutex lock
- Product critical regions with it by first **`acquire()`** a lock then **`release()`** it
  - Boolean variable indicating if lock is available or not
- Calls to **`acquire()`** and **`release()`** must be atomic
  - Usually implemented via hardware atomic instructions
- But this solution requires **busy waiting**
  - This lock therefore called a **spinlock**

acquire() and release()

```
acquire() {
   while (!available)
      ; /* busy wait */
   available = false;;
}
release() {
   available = true;
}

do {
   acquire lock
      critical section
   release lock
      remainder section
} while (true);
```

Semaphore * (By Dijkstra late ’60s)

★ (Sync HW is not easy to generalize for complex problem)

- Synchronization tool that does not require busy waiting *(Main sync primitive in original UNIX)
- Semaphore ***S*** – integer variable * (initially 1)
- Two standard operations modify ***S***: **`wait()`** and **`signal()`** * (atomic operation)
  - Originally called **`P()`** and **`V()`**
- Less complicated
- Can only be accessed via two indivisible (atomic) operations

```
wait (S) {
     while (S <= 0)
         ; // busy wait
     S--;
}
signal (S) {
     S++;
}
```

* (For the first visitor, S=1 → S=0, enter CS. Other visitors no-op until S=1)

* (Still busy waiting (____ _____). It is solved by using block/wake up mechanism)

Semaphore Usage

Counting semaphore – integer value can range over an unrestricted domain

Binary semaphore – integer value can range only between 0 and 1

Then a **mutex lock**

Can implement a counting semaphore ***S*** as a binary semaphore

Can solve various synchronization problems

Consider P_1 and P_2 that require S_1 to happen before S_2

```
P1:
    S1;
    signal(synch);
P2:
    wait(synch);
    S2;
```

Semaphore Implementation

- Must guarantee that no two processes can execute **`wait ()`** and **`signal ()`** on the same semaphore at the same time
- Thus, implementation becomes the critical section problem where the wait and signal code are placed in the critical section
  - Could now have **busy waiting** in critical section implementation
    - But implementation code is short
    - Little busy waiting if critical section rarely occupied
- Note that applications may spend lots of time in critical sections and therefore this is not a good solution

* (Spin lock is useful when context switching takes time)
* (Spin lock is a problem with multiprogramming since CPU time is wasted)

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)
  - pointer to next record in the 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 (Cont.)

```
typedef struct{
   int value;  * (no. of processes waiting, initially 1)
   struct process *list;
} semaphore;
wait(semaphore *S) {
   S->value--;
   if (S->value < 0) {
      add this process to S->list;
      block();
   }
}
signal(semaphore *S) {
   S->value++;
   if (S->value <= 0) {
      remove a process P from S->list;
      wakeup(P);
   }
}
```

*

P_0	P_1
S=0 CS	
	S=-1 block(P_1)
S=0 wakeup(P_1)	
	CS S=1

* (Wait and Signal can't be executed simultaneously)

* (Solution)
Uniprocessor: Inhibit int during wait and signal
Multiprocessor: enclose wait and signal with critical section. This still causes busy waiting to enter the CS containing wait or signal. However, the time to spent to execute wait or signal is short, and thus not long busy waiting

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

P_0	P_1
`wait(S);` ★ (S=0)	`wait(Q);` ★ (Q=0)
`wait(Q);` (Q=−1; block)	`wait(S);` (S=−1; block)
.	.
`signal(S);`	`signal(Q);`
`signal(Q);`	`signal(S);`

Starvation – **indefinite blocking** * (occurs if LIFO is used)

A process may never be removed from the semaphore queue in which it is suspended

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

Solved via **priority-inheritance protocol**

Classical Problems of Synchronization

Classical problems used to test newly-proposed synchronization schemes

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded-Buffer Problem

- ***n*** buffers, each can hold one item
- Semaphore **`mutex`** initialized to the value 1
- Semaphore **`full`** initialized to the value 0
  - (number of filled entries)
- Semaphore **`empty`** initialized to the value n
  - (number of empty entries)

Bounded Buffer Problem (Cont.)

The structure of the producer process

```
do {
      ...
      /* produce an item in next_produced */
      ...
   wait(empty);
   wait(mutex);
      ...
      /* add next produced to the buffer */
      ...
   signal(mutex);
   signal(full);
} while (true);
```

*

P_0	P_1
e=n−1 m=0 add	e=n−2 m=−1, blocked
m=0, wake P_1 f= 1	add m=1 f=2

Bounded Buffer Problem (Cont.)

The structure of the consumer process

```
do {
   wait(full);
   wait(mutex);
      ...
      /* remove an item from buffer to next_consumed */
      ...
   signal(mutex);
   signal(empty);
      ...
      /* consume the item in next consumed */
      ...
   } while (true);
```

* (Assume f = 1)

P_0	P_1
f=0	
m=0	f=−1, blocked
consume	
m=1, wake P_1	
e= n	

Readers-Writers Problem

A data set is shared among a number of concurrent processes

- Readers – only read the data set; they do ***not*** perform any updates
- Writers – can both read and write

Problem – allow multiple readers to read at the same time

- Only one single writer can access the shared data at the same time

Several variations of how readers and writers are treated – all involve priorities

Shared Data

- Data set
- Semaphore **`rw_mutex`** initialized to 1
- Semaphore **`mutex`** initialized to 1
- Integer **`read_count`** initialized to 0

Readers-Writers Problem (Cont.)

The structure of a writer process

```
do {
     wait(rw mutex);
     ...
     /* writing is performed */
     ...
   signal(rw mutex);*
} while (true);
```

(After signal(rw), the scheduler decides either waiting readers or single waiting writer among possibly many waiting writers)

Readers-Writers Problem (Cont.)

The structure of a reader process

```
do {
    wait(mutex);
      read count++;
      if (read count == 1)
            wait(rw mutex);
    signal(mutex);
    /* reading is performed */
    wait(mutex);
      read count--;
      if (read count == 0)
            signal(rw mutex);
    signal(mutex);
} while (true);
```

★ (for protecting ____________) — annotation on wait(mutex) … signal(mutex)

*(last exiting reader opens ________) — annotation on signal(rw mutex)

R_0	R_1	R_2
m=0 r=1	m=−1, block	
rw=0;		
m=0, wake(R_1) read		
	r=2 m=1 read	
m=0 r =1 m=1		
	m=0 r=0 rw=1 m=1	

*(If a writer is in CS and *n* readers are waiting, the first reader hangs on wait(___) while the subsequent readers are on wait(_____))

Readers-Writers Problem Variations

* (Assume that Reader-A is reading while Writer-B is waiting, and then Reader-C and D arrive)

First variation – no reader kept waiting unless writer has permission to use shared object

* (No reader waits for other reader to finish even though a writer is waiting
  → causes __________ starvation)

Second variation – once writer is ready, it performs write asap

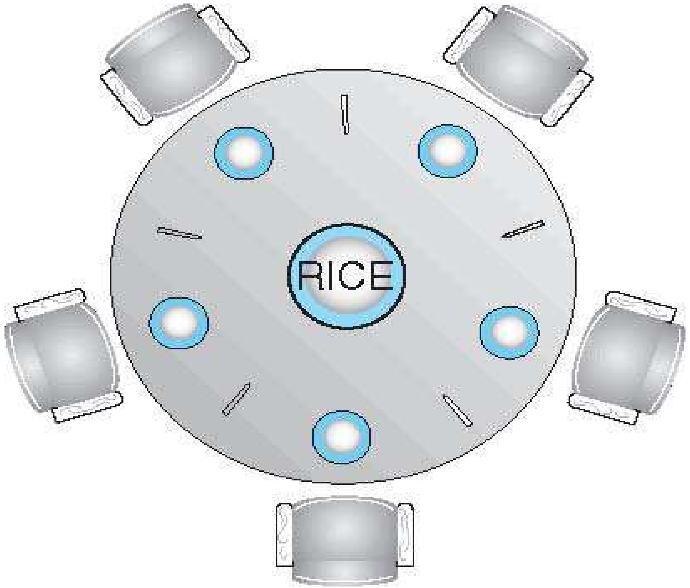
* (If a writer is waiting, no reader may start reading → causes _________ starvation)

Both may have starvation leading to even more variations

Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

★(Typical concurrency control problem and resource allocation problem)



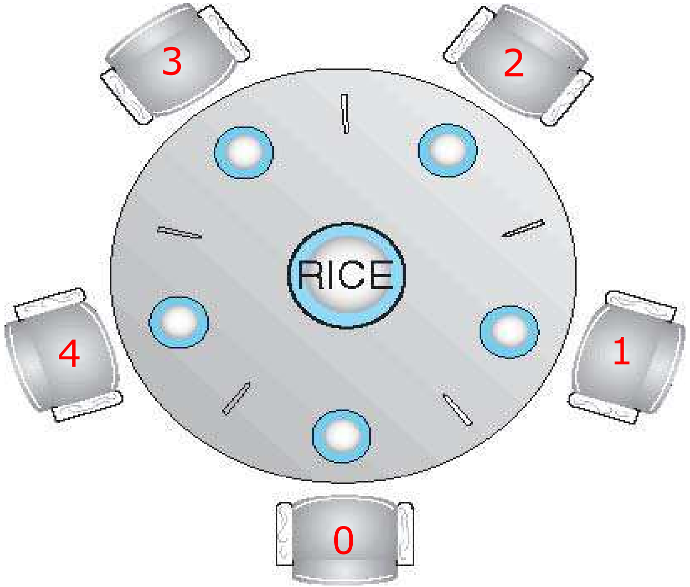
- Philosophers spend their lives thinking and eating
- Don't interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers
  - Shared data
    - Bowl of rice (data set)
    - Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem Algorithm

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);
```

*



What is the problem with this algorithm? *(Deadlock when everyone picks up the left one at the same time)

* ((Sol)
- put at most __ people
-Allow to pick up chopsticks only when ____ are available (does that in CS)
- Odd position person picks left first while even position person does _____ first))

* (Deadlock-free does not guarantee no starvation)

Problems with Semaphores

Incorrect use of semaphore operations:

signal (mutex) …. wait (mutex) * (Several entrances (so no mutex))

wait (mutex) … wait (mutex) * (Deadlock)

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

*(__________) * (__________)

Deadlock and starvation

Monitors

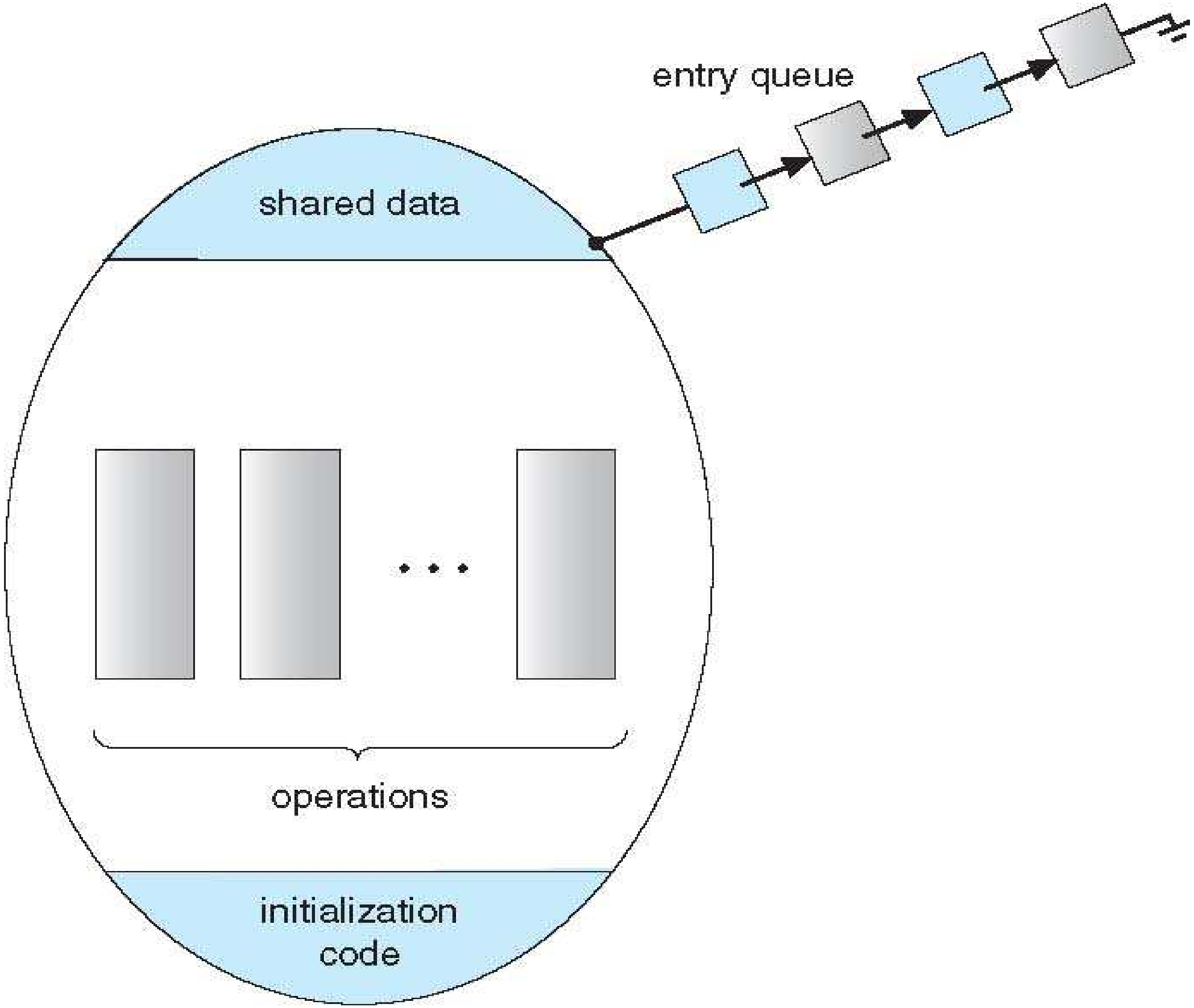
★ (Semaphore is for both ______ and ___________. So, hard to read & write)

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- *Abstract data type*, internal variables only accessible by code within the procedure
- Only one process may be active within the monitor at a time
- But not powerful enough to model some synchronization schemes

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

   procedure Pn (…) {……}

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

*(The procedures can use only the _____ variables within the monitor)

Schematic view of a Monitor



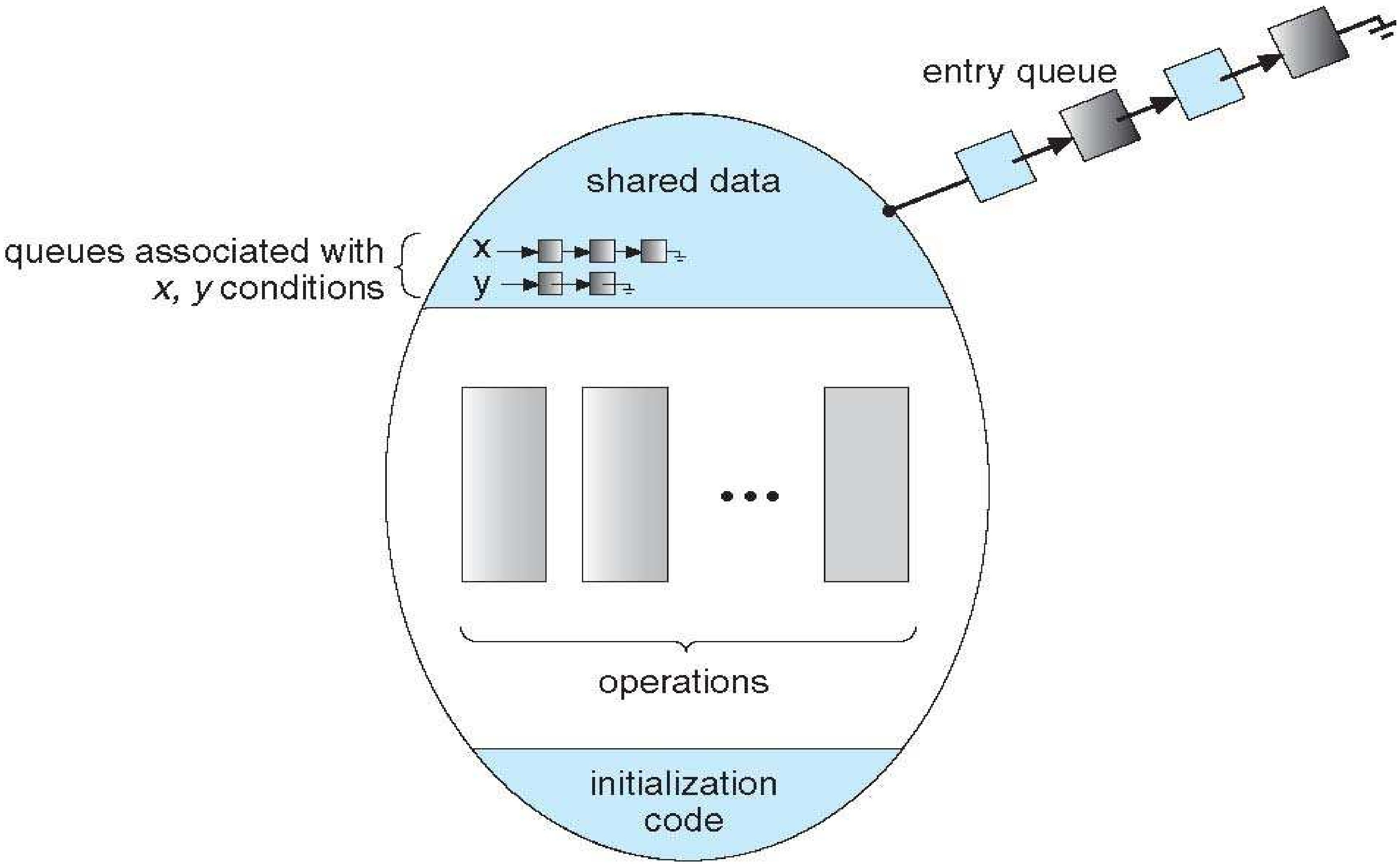
Condition Variables

condition x, y; *(use LOCKs for mutex and CONDITION VARIABLES for scheduling)

Two operations on a condition variable:

- x.wait () – a process that invokes the operation is suspended until x.signal ()
- x.signal () – resumes one of processes (if any) that invoked x.wait ()
  - If no x.wait () on the variable, then it has no effect on the variable
  - * (x.broadcast() is also supported for waking up all waiters)

Monitor with Condition Variables



Condition Variables Choices

- If process P invokes x.signal (), with Q in x.wait () state, what should happen next?
  - If Q is resumed, then P must wait
- Options include
  - **Signal and wait** – P waits until Q leaves monitor or waits for another condition
  - **Signal and continue** – Q waits until P leaves the monitor or waits for another condition
  - Both have pros and cons – language implementer can decide
  - Monitors implemented in Concurrent Pascal compromise
    - P executing signal immediately leaves the monitor, Q is resumed
  - Implemented in other languages including Mesa, C#, Java

Solution to Dining Philosophers

```
monitor DiningPhilosophers
  {                         *(State eating: only when two neighboring people are not _______ )
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5]; *(Self[ ] is condition variable used for scheduling)

    void pickup (int i) {
          state[i] = HUNGRY;
          test(i);
          if (state[i] != EATING) self [i].wait;
    }     *          (true if at least one neighbor is ______ )

     void putdown (int i) {
          state[i] = THINKING;
               // test left and right neighbors
          test((i + 4) % 5); *(for making ____ person eat first if the person wants)
          test((i + 1) % 5);
     }
```

Solution to Dining Philosophers (Cont.)

```
void test (int i) {
        if ( (state[(i + 4) % 5] != EATING) &&
        (state[i] == HUNGRY) &&
        (state[(i + 1) % 5] != EATING) ) {
             state[i] = EATING ;
         self[i].signal () ;
         }
 } * (test[]: if left and right person do not eat and itself is _______ , makes its state eating and executes self[i].signal)

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

Solution to Dining Philosophers (Cont.)

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

```
DiningPhilosophers.pickup (i);

    EAT

DiningPhilosophers.putdown (i);
```

No deadlock, but starvation is possible

Monitor Implementation Using Semaphores

Variables

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

Each 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

* (A proc must execute wait(mutex) before entering the monitor, siganl(mutex) after leaving the monitor)

Monitor Implementation – Condition Variables

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 (Cont.)

The operation x.signal can be implemented as:

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

Resuming Processes within a Monitor

If several processes queued on condition x, and x.signal() executed, which should be resumed?

FCFS frequently not adequate

conditional-wait construct of the form x.wait(c)

- Where c is **priority number**
- Process with lowest number (highest priority) is scheduled 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;
      }
}
```

Synchronization Examples

- Solaris
- Windows XP
- Linux
- Pthreads

Solaris Synchronization

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

* (SunOS uses CS with highest int level (so not interruptible))

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

- Starts as a standard semaphore spin-lock *(≤ ___'s insts)
- If lock held, and by a thread running on another CPU, spins * (since it will be available soon)
- If lock held by non-run-state thread, block and sleep waiting for signal of lock being released

Uses **condition variables**

Uses **readers-writers** locks when longer sections of code need access to data

* (better than semaphore since it allows multiple thr to access data simultaneously)

Uses **turnstiles** to order the list of threads waiting to acquire either an adaptive mutex or reader-writer lock ★(queue containing thr blocked on a lock)

- Turnstiles are per-lock-holding-thread, not per-object

Priority-inheritance per-turnstile gives the running thread the highest of the priorities of the threads in its turnstile

Windows XP Synchronization

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

Uses **spinlocks** on multiprocessor systems

- Spinlocking-thread will never be preempted

Also provides **dispatcher objects** user-land which may act mutexes, semaphores, events, and timers

- **Events**
  - An event acts much like a condition variable *(Notify a waiting thr when a desired condition occurs)
- Timers notify one or more thread when time expired
- Dispatcher objects either **signaled-state** (object available) or **non-signaled state** (thread will block)

Linux Synchronization

Linux:

Prior to kernel Version 2.6, disables interrupts to implement short critical sections* (so nonpreemptive kernel)

Version 2.6 and later, fully preemptive

Linux provides:

semaphores

spinlocks

reader-writer versions of both

On single-cpu system, spinlocks replaced by enabling and disabling kernel preemption

*(holding spinlock ≡ ________ kernel preemption;
releasing spinlock ≡ enables kernel preemption)

Pthreads Synchronization

Pthreads API is OS-independent

It provides:

- mutex locks
- condition variables

Non-portable extensions include:

- read-write locks
- spinlocks

Atomic Transactions

- System Model
- Log-based Recovery
- Checkpoints
- Concurrent Atomic Transactions

System Model

- Assures that operations 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

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)

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

Concurrent 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
  - Conflict if access same data item, with at least one write
- If O_i, O_j 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
- If S can become S' via swapping nonconflicting operations
  - S is conflict serializable

Schedule 2: Concurrent Serializable Schedule

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

Locking Protocol

- Ensure serializability by associating lock with each data item
  - Follow 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

- Generally ensures conflict serializability
- Each transaction issues lock and unlock requests in two phases
  - Growing – obtaining locks
  - Shrinking – releasing locks
- 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 Ti 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
- Suppose Ti executes read(Q)
  - If $TS(T_i)$ < W-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-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-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-timestamp(Q), T_i attempting to write obsolete value of Q
  - Write operation rejected and T_i rolled back
- Otherwise, write executed

Any rolled back transaction T_i is assigned new timestamp and restarted

Algorithm ensures conflict serializability and freedom from deadlock

Schedule Possible Under Timestamp Protocol

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