Chapter 6: Synchronization

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Module 6: Synchronization

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

BACKGROUND.

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 wanted 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 (1)
 {
     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}

Counter may be 4 or 6, depends on the sequence of S4 and S5
Counter can even be 5

Race Condition #2

- 2 threads, sharing a variable “safe” which is true initially

Thread 1:

```
if( safe == TRUE)
{
        safe = FALSE
        … Do something…

}
```

Thread 2:

```
if( safe == TRUE)
{
        safe = FALSE
        … Do something…

}
```

THE CRITICAL-SECTION PROBLEM

```
do {

    entry section

        critical section

    exit section

        remainder section

} while (TRUE);
```

Solution to Critical-Section Problem

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

Hardware-based approaches to process synchronization

Synchronization Hardware

- Many systems provide hardware support for critical section code
- Interrupt disabling
  - Uniprocessor: good
  - Multiprocessor: does not work
- Test and set or swap
  - Uniprocessor: works, but wastes CPU cycles
  - Multiprocessor: works

Interrupt Disabling

- Uniprocessor
  - Source of preemption: timer, IO completion
  - Masking interrupts prevents the running process from being preempted
- Multiprocessor
  - Masking the interrupt of a CPU does not prevent racing processes on the other CPUs from entering a critical section

- Privilege instruction, cannot be used in user mode!

Atomic Instructions

- Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptable
- Test memory word and set value
- Swap contents of two memory words
- Also called “spin locks”

TestAndndSet Instruction

- Definition (instruction behavior):

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

Solution using TestAndSet

- Shared boolean variable *lock*, initialized to false.

```
Solution:
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:
do {
     key = TRUE;
     while ( key == TRUE)
     Swap (&lock, &key );

     //    critical section

     lock = FALSE;

     //      remainder section

} while ( TRUE);
```

Spin lock in Linux

```
lock:                       # The lock variable. 1 = locked, 0 = unlocked.
    dd      0

spin_lock:
    mov     eax, 1          # Set the EAX register to 1.

loop:
    xchg    eax, [lock]     # Atomically swap the EAX register with
                            #  the lock variable.
                            # This will always store 1 to the lock, leaving
                            #  previous value in the EAX register.

    test    eax, eax        # Test EAX with itself. Among other things, this will
                            #  set the processor's Zero Flag if EAX is 0.
                            # If EAX is 0, then the lock was unlocked and
                            #  we just locked it.
                            # Otherwise, EAX is 1 and we didn't acquire the lock.

    jnz     loop            # Jump back to the XCHG instruction if the Zero Flag is
                            #  not set, the lock was locked, and we need to spin.

    ret                     # The lock has been acquired, return to the calling
                            #  function.

spin_unlock:
    mov     eax, 0          # Set the EAX register to 0.

    xchg    eax, [lock]     # Atomically swap the EAX register with
                            #  the lock variable.

    ret                     # The lock has been released.
```

TAS and SWAP

- Applicable to both uniprocessor and multiprocessor systems
- Can be used in user mode (and of course in kernel mode)

- Problems
  - Wasting CPU cycles in uniprocessor system
  - Because the contention is stateless, process starvation is possible

- The TAS/SWAP instruction as a solution of the critical section problem guarantees which one(s) of the following properties?
  - Mutual exclusive
  - Progressive
  - Bounded waiting

A bounded-waiting solution based on TAS/SWAP

```
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])
      j = (j + 1) % n;

   if (j == i)
      lock = FALSE;
   else
      waiting[j] = FALSE;

      // remainder section
}while (TRUE);
```

Waiting[i]=TRUE:
Pi wishes to enter the critical section

Key=TRUE:
there is at least 1 process waiting

To pick up the next process in waiting[] if there are any waiting processes

- The selection of the next process to go in is a part of the critical section
- Once a process wishes to go in, it will be selected by waiting at most n-1 processes, as waiting[] is visited circularly

Summary

- Uniprocessor
  - Interrupt disabling
    - Only available in kernel space
    - Increasing interrupt latency
  - Spin lock (test and set, swap)
    - Correct, but wasting CPU cycles
- Multiprocessor
  - Interrupt disabling
    - Does not work if two involved processes run on different processors
  - Spin lock
    - Correct, wasting CPU cycle in a minor degree

Pure-software approach to process synchronization (Peterson's solution)

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 Pi is ready to get in!

Algorithm for Process Pi & Pj

Pi

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

            CRITICAL SECTION

        flag[i] = FALSE;

              REMAINDER SECTION

    } while (TRUE);
```

Pj

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

            CRITICAL SECTION

        flag[j] = FALSE;

              REMAINDER SECTION

    } while (TRUE);
```

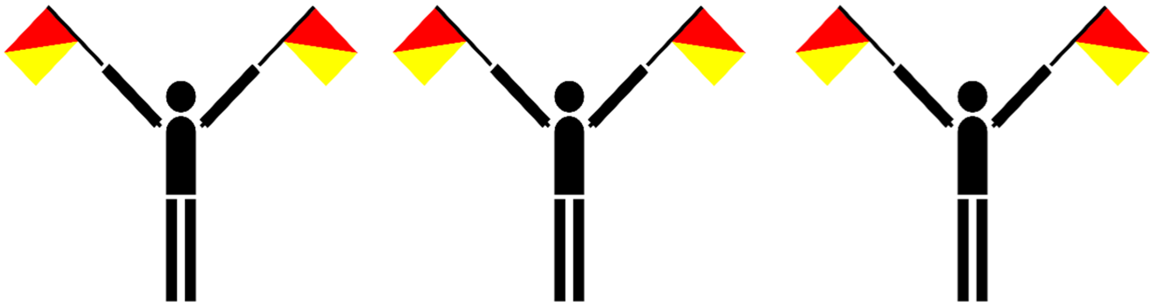
Algorithm for Process Pi

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

            CRITICAL SECTION

        flag[i] = FALSE;

            REMAINDER SECTION

   } while (TRUE);
```

Proof of

- Mutual exclusion
  - flag[i],flag[j] are both true
  - Turn is either i or j
  - Will “turn==i” become invalid after Pi enters CS?
    - Impossible because only Pi itself do the change (i.e., turn←j)
- Progressive
  - (!!) Pi will enter the critical section when Pj has no interest in entering the critical section (i.e., flag[j]=FALSE)
- Bounded-waiting
  - Consider an example
  - Pi←→Pj   Pi wins
  - Pi completes and Pi arrives again
  - →pi always gives the chance away first

SEMAPHORES
-- a general approach



Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore S – integer variable
  - Initial value of S cannot be negative
  - Can only be accessed via these two indivisible (atomic) operations
- Two standard operations modify S: wait() and signal()
  - Originally called P() and V()
  - Less complicated

Semaphore Implementation with no Busy waiting

- A semaphore is associated with a waiting queue
  - If a process is blocked on a semaphore, it is added to the waiting queue of the semaphore
- Two operations:
  - Block – place the process invoking the operation on the appropriate waiting queue: running→waiting
  - Wakeup – remove one of processes in the waiting queue and place it in the ready queue: waiting→ready

Semaphore Implementation

- Implementation of wait:

```
wait (S){
     S--;
     if (S < 0) {
            add this process to waiting queue
             block();  }
 }
```

- Implementation of signal:

```
Signal (S){
       S++;
        if (S <= 0) {
               remove a process P from the waiting queue
                wakeup(P);  }
}
```

Semaphore Implementation

- Semaphores themselves are critical sections
  - Techniques such as interrupt disabling or test-and-set, are used to implement signal() and wait()
  - plus a waiting queue

Semaphore as a General Synchronization Tool

- Counting semaphore – integer value can range over an unrestricted domain
  - Negative runtime values are legit
  - Negative initial values are not allowed in POSIX, however
- Binary semaphore – integer value can range only between 0
  and 1; can be simpler to implement
- Can implement a counting semaphore S using a binary semaphore; and vice versa

Typical Usages of a Counting Semaphore

- The purpose of a (counting) semaphore can typically be determined by the initial value of the semaphore

- *Mutex lock*: init value = 1
- *Sequencing or event*: init value = 0
- *Capacity control*: initial value=capacity

Mutual exclusion
Semaphore mutex=1

Pi

```
do {
   waiting(mutex);

      // critical section

   signal(mutex);

      // remainder section
}while (TRUE);
```

Pj

```
do {
   waiting(mutex);

      // critical section

   signal(mutex);

      // remainder section
}while (TRUE);
```

Sequencing or event
Semaphore synch=0

Pi

S_1;
```
signal(synch);
```

Pj

```
wait(synch);
```
S_2;

Capacity control
Semaphore sem=capacity

```
Pi, Pj, Pk, …
{
        …

        wait(sem);

        …

        signal(sem);
        …
}
```

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);	wait (Q);
wait (Q);	wait (S);
.	.
.	.
.	.
signal (Q);	signal (S);
signal (S);	signal (Q);

- Starvation – indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.
  - Waking up blocked processes in a first-come first-served manner is a solution

Classical Problems of Synchronization

Example #1

- ［有酒食，先生饌］小明和老師中午一起吃飯，請使用semaphore 幫助小明，讓他禮讓老師先用餐。

```
S=0;
ming()
{
        wait(S);
        // eat
}

professor()
{
        // eat
        signal(S);
}
```

Example #2

- [蜘蛛人] 傑克和羅絲相約去看電影，兩人約在電影院門口見面， 如果有人先到的話，要等另一人到了，才可以進入電影院。

```
R=0;J=0
jack()
{
        signal(J);
        wait(R);
        …
        // see the movie
}
ross()
{
        signal(R);
        wait(J);
        …
        // see the movie
}
```

Example #3

- [睡成一片] 資工系期中考快到了，總共有1000 位同學想進入自習室。因為座位有限，所以只能 50 個人同時進入。

```
S=50

student()
{
        wait(S);

        // go studying

        signal(S);
}
```

Example #4

- A DMA controller supports four channels of data transfer

```
S=4;T=1;c[4]={F,F,F,F};
proc()
{
        wait(S);
        wait(T);

        // pick one unused channel among c[0],c[1],c[2],c[3]
        // setup DMA transfer

        signal(T);

        // start DMA
        // wait for DMA completion

        signel(S);
}
```

Classical Problems of Synchronization

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

Bounded-Buffer Problem

- N buffers, each can hold one item
- Semaphore mutex initialized to the value 1
  - To protect the buffer
  - There can be many producers and consumers!!
- Semaphore full initialized to the value 0
  - 0 items (for the consumer)
  - Block on no items
- Semaphore empty initialized to the value N.
  - N free slots (for the producer)
  - Block on no free slot

Bounded Buffer Problem (Cont.)

- The structure of the producer process

```
do {

    //   produce an item

  wait (empty);
  wait (mutex);

    //  add the item to the  buffer

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

Producers produce items
Consumers “produce” free slots

What are the initial values of empty and full?

What happens of mutex is placed in the outer scope?

Bounded Buffer Problem (Cont.)

- The structure of the consumer process

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

      //  remove an item from  buffer

   signal (mutex);
   signal (empty);

      //  consume the removed item

} while (true);
```

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.
- Shared Data
  - Data set
  - Semaphore mutex initialized to 1. (to protect "readcount")
  - Semaphore wrt initialized to 1.
  - Integer readcount initialized to 0.

The first R-W problem

- No readers will wait until the writer locked the shared object
- Readers need not to synch with each other

Readers-Writers Problem (Cont.)

- The structure of a writer process

```
do {
      wait (wrt) ;

       //    writing is performed

      signal (wrt) ;
  } while (true)
```

Initially, wrt=1 mutex=1

Readers-Writers Problem (Cont.)

- The structure of a reader process

```
do {
     wait (mutex) ;
     readcount ++ ;
     if (readercount == 1)  wait (wrt) ;
     signal (mutex)

          // reading is performed

     wait (mutex) ;
     readcount  - - ;
     if redacount  == 0)  signal (wrt) ;
     signal (mutex) ;
 } while (true)
```

1. No readers will wait until the writer locked the shared object
2. Readers need not to synch with each other

•Simply using one mutex for R/W violates the second condition
•If the first reader is blocked by wrt, then other readers are blocked by mutex
    •Otherwise, the writer is blocked

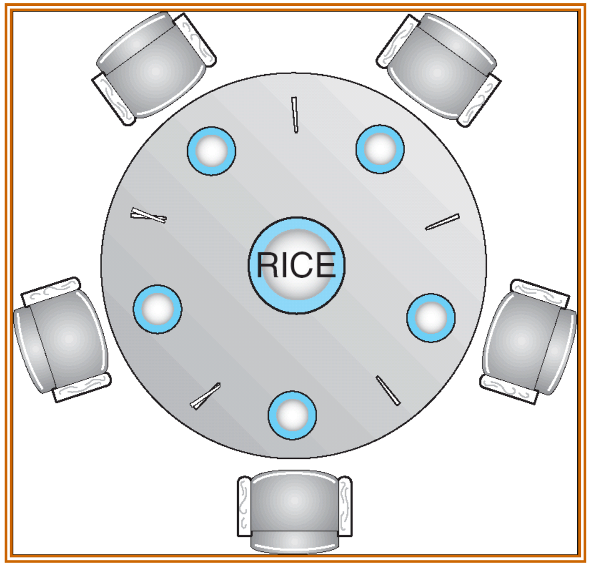
•The writer may starve?

Readers-Writers Problem (Cont.)

- Mutex
  - Protect the data set and the "readcount"

- Wrt
  - Mutex, ensure mutual exclusion among
    - A writer
    - A writer
    - …
    - A group of readers

Dining-Philosophers Problem



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

Dining-Philosophers Problem (Cont.)

- 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) ;
```

Potential deadlocks!

Dining-Philosophers Problem (Cont.)

- Possible ways to prevent deadlocks
  - One person get the left stick first, the rest get the right stick first
  - Allow up to 2 (or less than 5) people having stick(s)
  - Picking up two sticks simultaneously

Sleeping Barber Problem

Sleeping Barber Problem

- A barbershop consists of awaiting room with *n* chairs and a barber room with one barber chair. If there are no customers to be served, the barber goes to sleep.

- If a customer enters the barbershop and all chairs are occupied, then the customer leaves the shop.
- If chairs are available but the barber is busy, then the customer sits in one of the free chairs.
    - If the barber is asleep, the customer wakes up the barber.

Sleeping Barber Problem

- Semaphore Customers = 0;
  - Event: there are waiting customers
  - The barber waits on it if there is no customer
- Semaphore Barber = 0;
  - Event: barber is ready
  - The customer waits on it if the barber is busy

- Semaphore accessSeats = 1;
  - int NumberOfFreeSeats = N; //total number of seats

Costumer’s process

```
while(1) {
	wait(accessSeats) //mutex protect the number of available seats

	if ( NumberOfFreeSeats > 0 )
	{                                       //if any free seats
		NumberOfFreeSeats--;    //sitting down on a chair
		signal(Customers) ;     //notify the Barber
		signal (accessSeats);   //release the lock
		wait(Barber);           //wait if the B is busy
		....                    //here the C is having his hair cut
	}
	else
	{                                       //there are no free seats
		signal (accessSeats);   //release the lock on the seats
		...                     //C leaves without a haircut
	}
}//while(1)
```

Barber process

```
while(1) {
        wait(Customers) ;     //wait for C and sleep
        wait (accessSeats);   //mutex protect the number of
                              // available seats

        NumberOfFreeSeats++;      //one chair gets free

        signal(Barber);           //Bring in a C for haircut
        signal (accessSeats);     //release the mutex on the chairs

        …….                   //here the B is cutting hair

}//while(1)
```

Mutexes and Monitors

Mutex locks

- “MUTually EXclusive” access
- Conceptually equivalent to semaphores with initial value = 1
- Only the locker of a mutex can unlock the mutex
- APIs
  - pthread_mutex_lock()
  - pthread_mutex_unlock()
  - …

Semaphores vs. mutexes

- pthread_mutex_xxxx()
  - pthread.h
  - Functionally equivalent to semaphore with init value=1
  - Applicable to threads only
- sem_xxx()
  - semaphore.h
  - Applicable to threads and processes
  - A semaphore can be signaled by any process/thread
  - sem_wait(), sem_post(), ...\

Problems with Semaphores

- Incorrect use of semaphore operations:
  - signal (s) …. signal(s)
  - wait (s) … wait (s)
  - Omitting of wait (s) or signal (s)

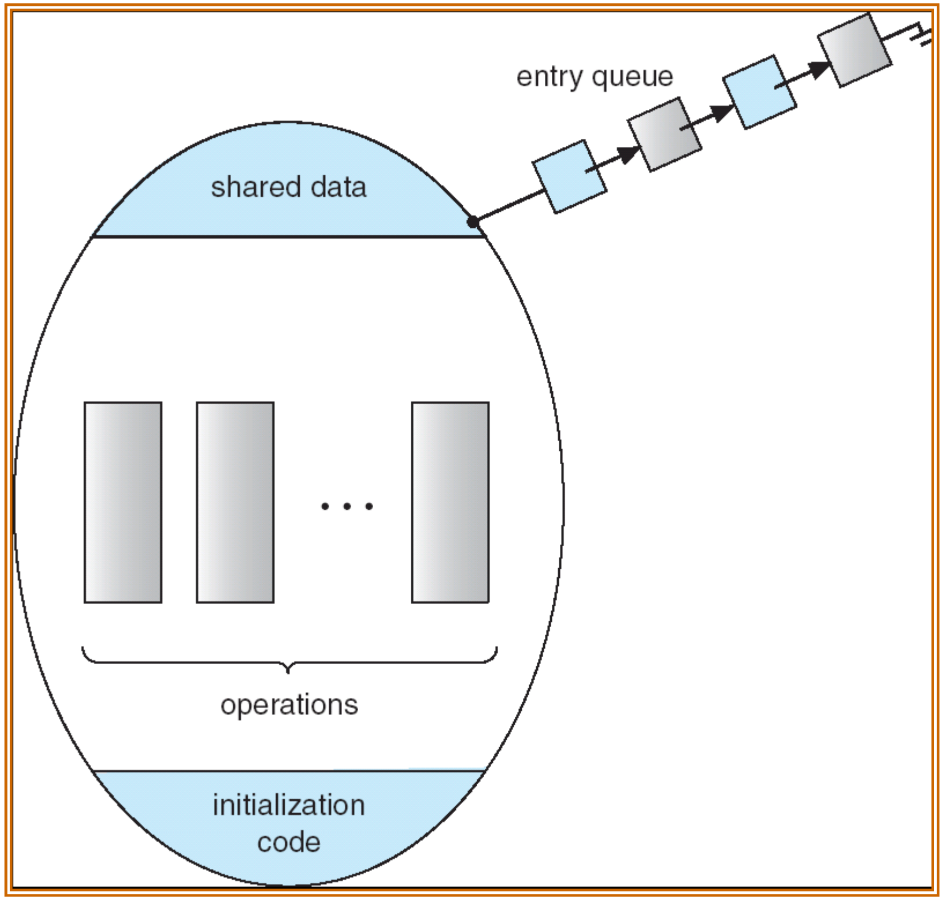
- Monitor provides a higher level abstraction of critical section to avoid these programming errors

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 ( ….) { … }

}
```

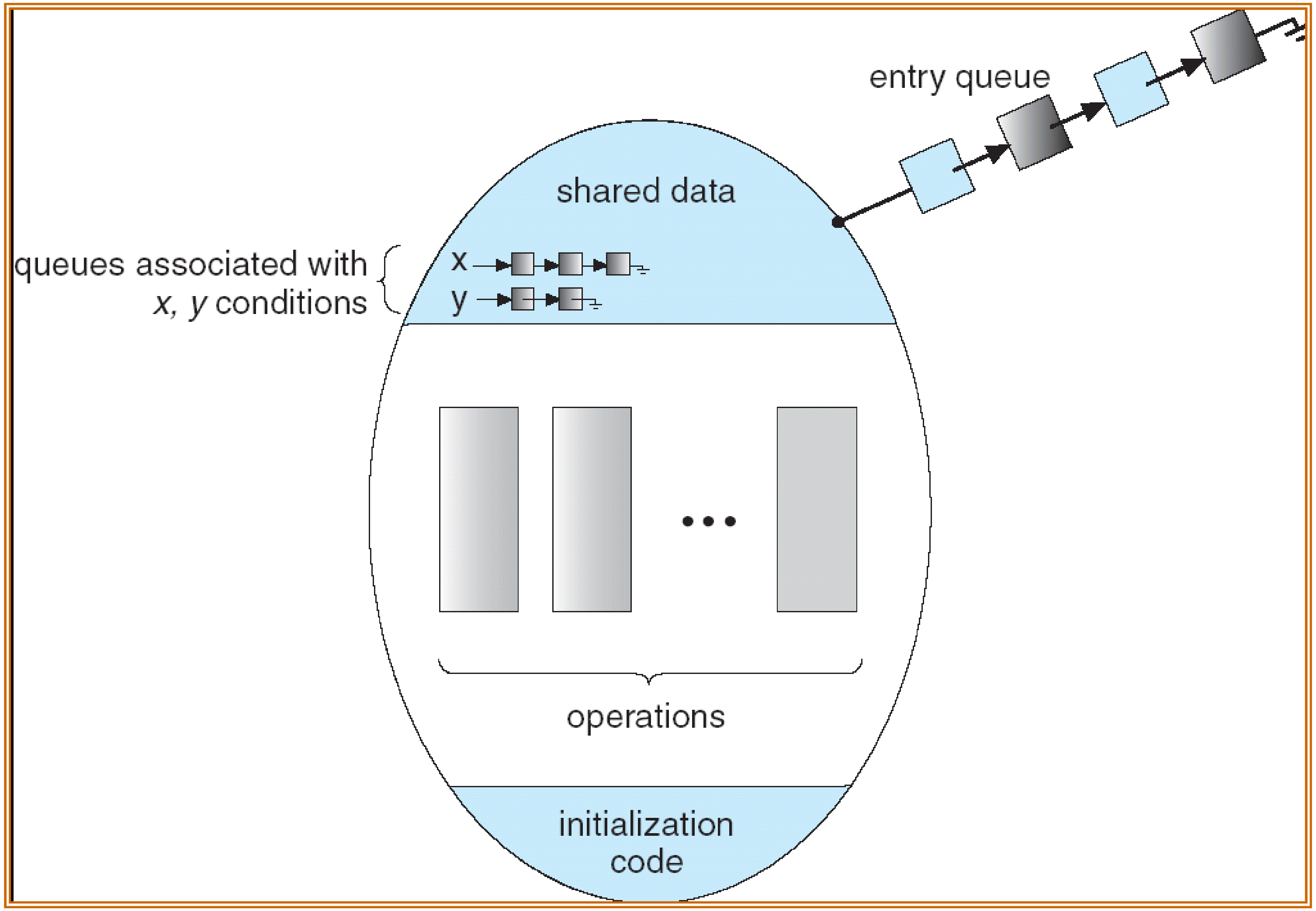
Schematic view of a Monitor



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 itself provides nothing but mutex
  - To implement other synch policy, conditional variables are needed
- signal→if there is no process waiting, nothing happens and the next process calls wait is blocked
  - Different from semaphore. For capacity control, a monitor must contain a counter

Monitor with Condition Variables



Solution to Dining Philosophers

```
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);
      }
```

Highlights to this solution:

- A philosopher picks up 2 chopsticks at a time
  - If he can not pick up 2 chopsticks, he waits
- After a philosopher done eating, he will check if his 2 neighbors can eat.

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 () ;
         }
 }

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

- How to implement semaphore using a monitor?
  - Signals to condition variables do not affect processes that are not in a monitor
  - Use a counter to keep track of “signals to semaphores”
- How to implement monitor using semaphores?
  - See the text book

End of Chapter 6