Chapter 6: Synchronization

Prof. Li-Pin Chang

CS@NYCU

Module 6: Synchronization

- Background
- The Critical-Section Problem
- Synchronization Hardware
- Semaphores
- Classic Problems of Synchronization
- Monitors

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 Code

```
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 Code

```
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}

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

Race Condition Example #2

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

Thread 1:

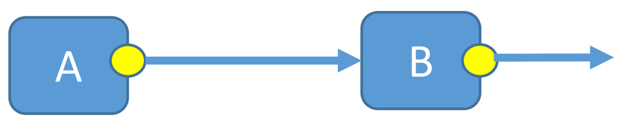
```
if( safe == TRUE)
{
 safe = FALSE
 … Do something…

}
```

Thread 2:

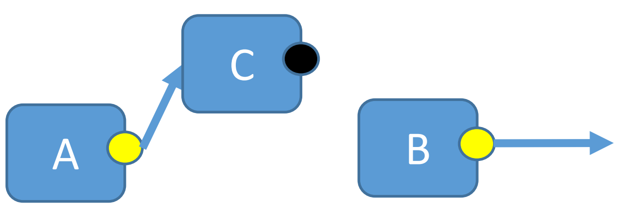
```
if( safe == TRUE)
{
 safe = FALSE
 … Do something…

}
```

Race Condition Example #3

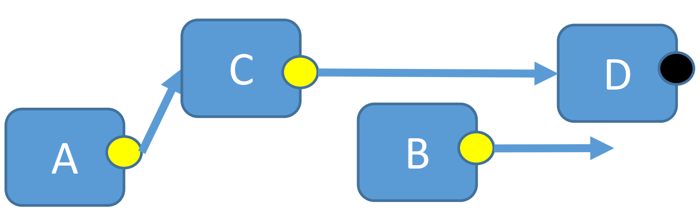
- Threads T1 and T2 share a link list



The original list



T1 inserts C but is preempted by T2 in the middle of insertion



T2 inserts D, corrupting the list

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

- Source of preemption: timer, IO completion
- Masking interrupts prevents the running process from being preempted
- Often used in kernel critical sections

- Privilege instruction, cannot be used in user mode!
- Does not work in multiprocessor systems; masking the interrupt of a CPU does not prevent racing processes from entering a critical section on another CPU

```
x86 example

CLI   // disable int.

… critical section…

STI   // enable int.
```

Atomic Instructions

- Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptable
  - No interrupts in the middle of an atomic instruction
  - In multi-processor environments, the CPU executing an atomic instruction has exclusive access to the target memory (e.g., XCHG in x86)
  - p.s. often used with bus locking semantic (for multi CPUs)

- Test memory word and set value
- Swap contents of two memory words

TestAndSet Instruction

- Definition (a description of its effect, **not** actual code):

```
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 (description):

```
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 implementation on Intel x86

```
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.
```

https://en.m.wikipedia.org/wiki/Spinlock#Example_implementation

TAS and SWAP

- Can be used in
  - both uniprocessor and multiprocessor systems
  - both user mode and kernel mode
- Variants exist, such as CAS (compare and swap)

- Issues
  - 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);
```

TAS(lock) =TRUE:
The critical section has been entered

Waiting[i]=TRUE:
Pi must for the entry of the critical section

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 the kernel space
  - Increasing the interrupt latency
- Spin lock (test and set, swap)
  - Works but wasting CPU cycles

Multiprocessor

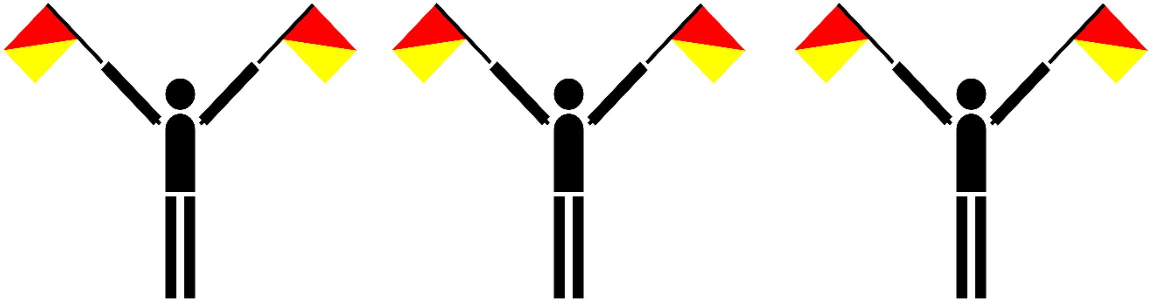
- Interrupt disabling
  - Does not work if two involved processes run on different processors
- Spin lock
  - Working with minor waste of CPU cycles

Remarks

- A good implementation of spinlocks involves many aspects, including (to name a few)
  - Cache coherence overhead: TTAS
  - Instruction reordering: barrier
  - Starvation: ticket spinlocks
  - Memory bus contention: random backoff

- Some good pointers to start with
  - LWN articles on spinlck
  - Other articles (mostly in Chinese) [1] [2] [3] [4] [5] [6] [7]

SEMAPHORES
-- a general approach



Semaphore

- Synchronization tool that does not require busy waiting
- Semaphore S – integer variable
  - Initial value of S must be >= 0
  - Can only be accessed via these two indivisible (atomic) operations 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 operations must be atomic
  - 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);
```

The most typical use of synchronization

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.
  - An FIFO as the waiting queue to avoid starvation

Easy Problems of Synchronization

Example #1

- 大頭跟長官一起吃飯，請使用semaphore 幫助大頭，讓他禮讓長官先用餐。

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

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

Example #2

- 阿呆和阿瓜相約去看電影，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
dumb()
{
        signal(J);
        wait(R);
        …
        // see the movie
}
dumber()
{
        signal(R);
        wait(J);
        …
        // see the movie
}
```

Example #3

- 資工系期中考快到了，總共有200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 xfer

```
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

        signal(S);
}
```

Classical Problems of Synchronization

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
  - Allowing many producers and many consumers
- Semaphore full initialized to the value 0
  - 0 items (for the consumer)
  - Blocked when no items
- Semaphore empty initialized to the value N.
  - N free slots (for the producer)
  - Blocked when no free slots

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

The First Readers-Writers Problem:
No readers will wait until the writer locked the shared object
Readers need not to synch with each other

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

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

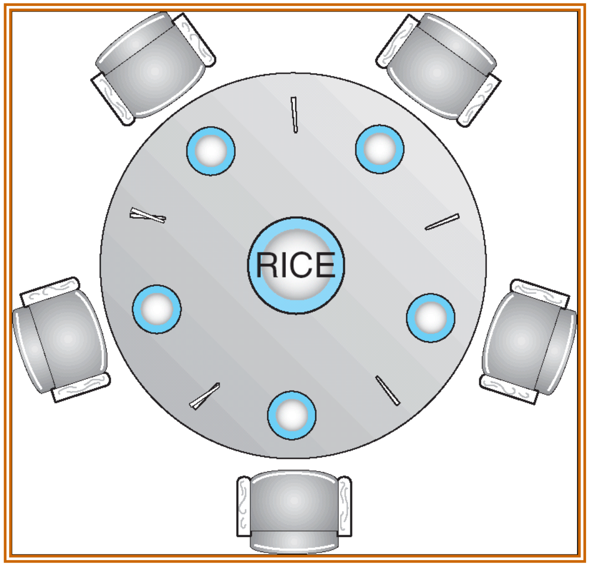
- Simply using one mutex for R/W violates the second condition
- If the first reader is blocked by wrt, then other readers are blocked by mutex
    - Otherwise, the writer is blocked

- The writer may starve?
    - Yes
    - The Second Readers-Writers Problem

Readers-Writers Problem (Cont.)

- Mutex
  - Protect the “readcount” among readers
- Wrt
  - Mutex, ensure mutual exclusion on the data set 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) ;
```

Dining-Philosophers Problem (Cont.)

- The proposed solution is subject to deadlocks
- Possible ways to prevent deadlocks
  - One person get the left stick first, the rest get the right stick first
  - Allow up to N (<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.
- Compare it with the Jack-Rose problem

Sleeping Barber Problem

- Semaphore Customers = 0;
  - Event: customer(s) are waiting
  - 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)
```

Mutex Locks 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

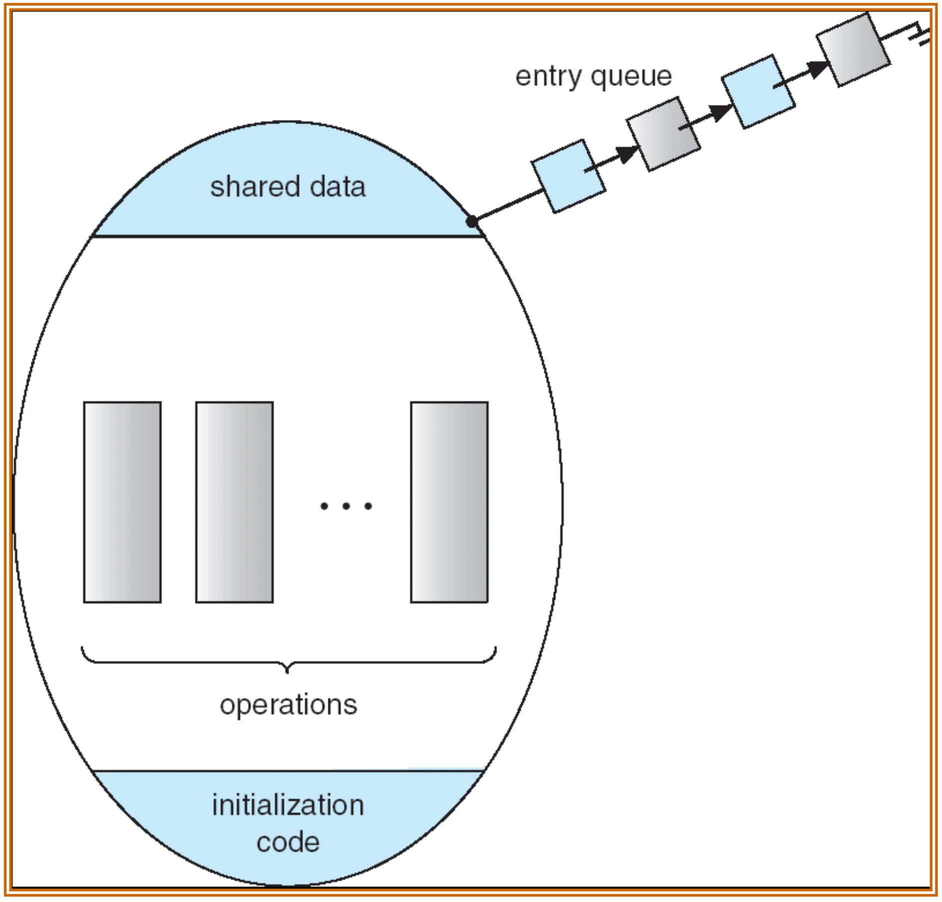
- pthread_mutex_xxxx()
  - pthread.h
  - Functionally equivalent to semaphore with init value=1
  - Applicable to (implement on) threads only
  - A mutex can only be unlocked by the thread that has locked the mutex
- sem_xxx()
  - semaphore.h
  - Applicable to threads and processes
  - A semaphore can be signaled by any process/thread
  - sem_wait(), sem_post(), …

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 ( ….) { … }

}
```

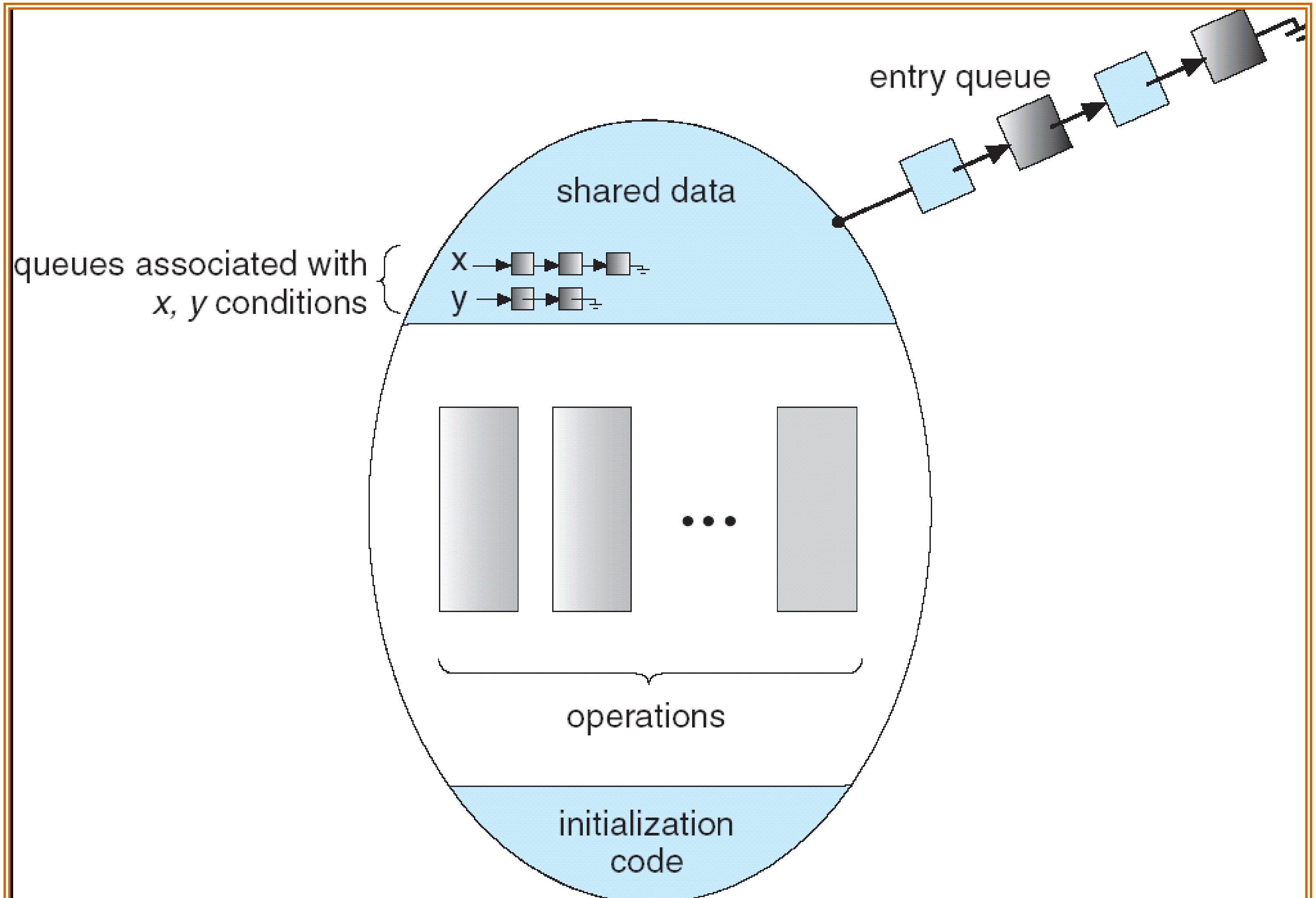
Schematic view of a Monitor



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



```
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);
      }

   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;
   }
}
```

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.

Java Monitors

- Java objects can be treated as a monitor
- Use the prefix “synchronized” to declare a function to be mutually exclusive access
- Use wait(), notify(), and notifyall()
  - Simpler than conditional variable
  - Condition variables are available for explicit control if necessary

```java
class Buffer {
	private char [] buffer;
	private int count = 0, in = 0, out = 0;

	Buffer(int size)
	{
		buffer = new char[size];
	}

	public synchronized void Put(char c) {
		while(count == buffer.length)
		{
			try { wait(); }
			catch (InterruptedException e) { }
			finally { }
		}
		System.out.println("Producing " + c + " ...");
		buffer[in] = c;
		in = (in + 1) % buffer.length;
		count++;
		notify();
	}

	public synchronized char Get() {
		while (count == 0)
		{
			try { wait(); }
			catch (InterruptedException e) { }
			finally { }
		}
		char c = buffer[out];
		out = (out + 1) % buffer.length;
		count--;
		System.out.println("Consuming " + c + " ...");
		notify();
		return c;
	}
}
```

Java solution to the bounded-buffer problem

- Use wait()/notify() instead of condition variables
- Use the synchronized prefix for mutual exclusion

http://www.csc.villanova.edu/~mdamian/threads/javamonitors.html

End of Chapter 6

Review Questions

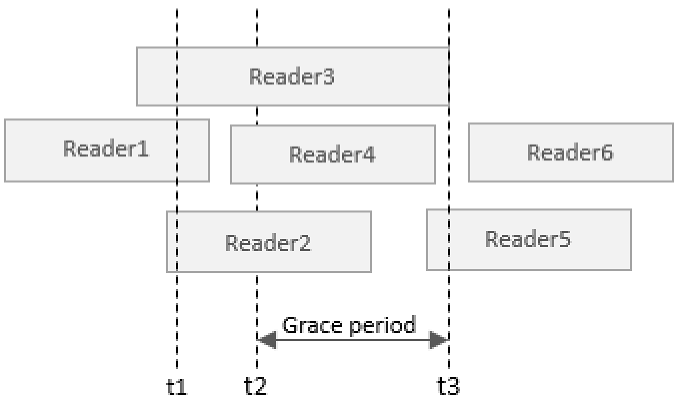
1. What is the limitations of interrupt disabling?
2. What is the drawbacks of spin locks?
3. Give two solutions to the dining philosopher's problem
4. Study RCU in the following slides. Compare RCU with read-write lock for their pros and cons
5. Survey the design of TTAS (test and test-and-set)
6. Survey the design of futex (fast user-space mutex)
7. Compare pthread_mutex_trylock() and pthread_mutex_lock()

RCU (Read-Copy-Update)

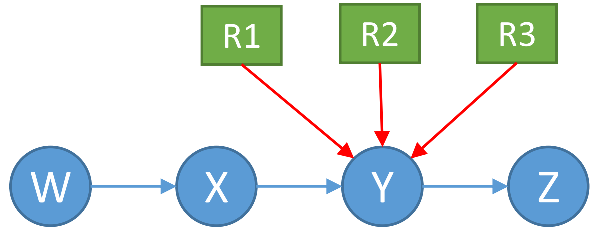
- rw lock: a writer gains globally exclusive access
- RCU: N readers and 1 writer can run in parallel
  - Good for many concurrent readers with infrequent update
  - Writer: copy on write → commit changes later
  - Commonly used in Linux kernel

- Readers
  - Define the "read critical section"; in this period, a reader sees a read-only view of data
  - Multiple readers run and share with the same view of data
- Writer
  - Use "copy-on-write" for update
  - When readers finish, commit changes

Grace Period (when to commit?)

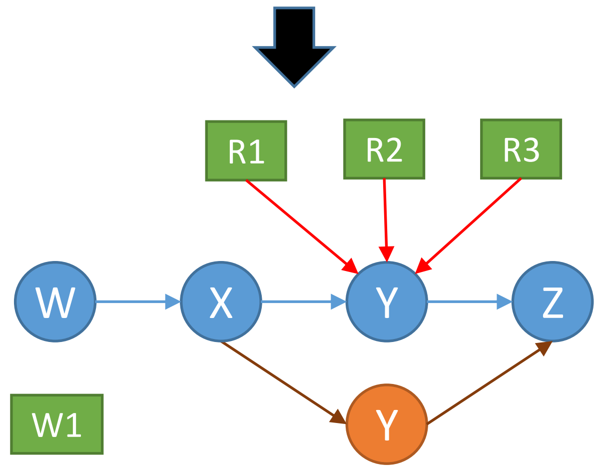


- Changes are committed at t1
- Readers 1, 2, 3 gain read access before t1, they share the same view of data (odd)
- t2: synchronize point
- Grace period begins at t2
- t2 ~ t3: grace period
- Grace period ends at t3, as Readers 1, 2, 3 all finished their read critical sections
- Readers 4, 5, 6 gains read access after t1, they share the same view of data (new)



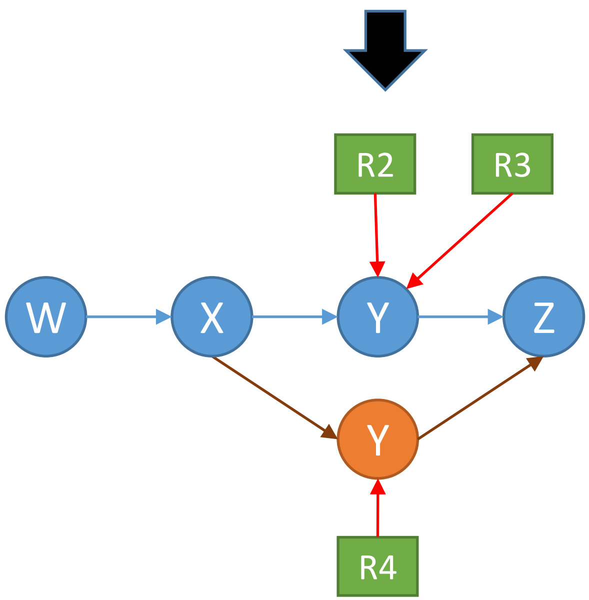
R1 R2 R3 run concurrently

t1



W1 runs with copy on write

t2



Grace period

t3 reclaim old data