# ICS 143 - Principles of Operating Systems

**Lecture Set 4 - Process Synchronization**

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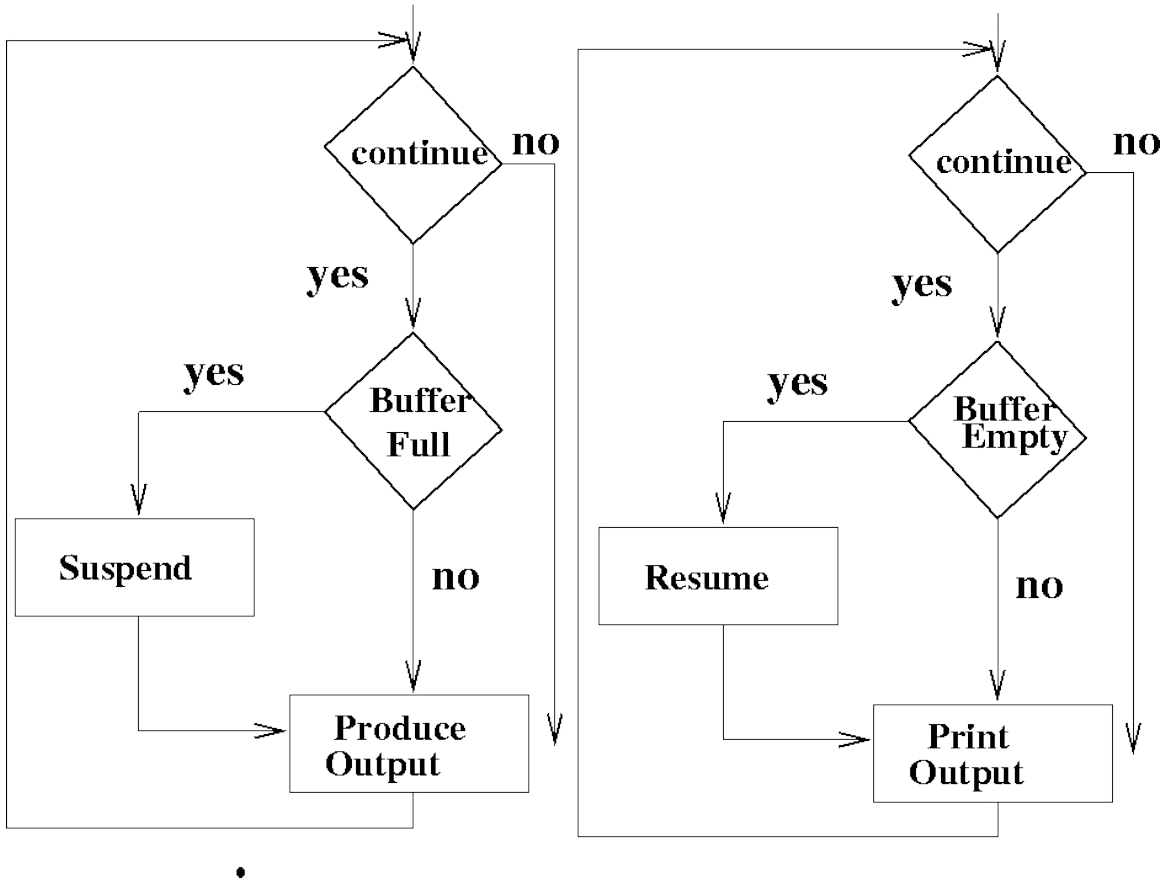
# Outline

- The Critical Section Problem
- Synchronization Hardware
- Semaphores
- Classical Problems of Synchronization
- Critical Regions
- Monitors

# Producer-Consumer Problem

- Paradigm for cooperating processes;
  - producer process produces information that is consumed by a consumer process.
- We need buffer of items that can be filled by producer and emptied by consumer.
    - Unbounded-buffer places no practical limit on the size of the buffer. Consumer may wait, producer never waits.
    - Bounded-buffer assumes that there is a fixed buffer size. Consumer waits for new item, producer waits if buffer is full.
  - Producer and Consumer must synchronize.

# Producer-Consumer Problem



# Bounded Buffer using IPC (messaging)

- Producer

```
repeat
    ...
    produce an item in nextp;
  ...
  send(consumer, nextp);
until false;
```

- Consumer

```
repeat
    receive(producer, nextc);
    ...
    consume item from nextc;
  ...
until false;
```

# Bounded-buffer - Shared Memory Solution

- Shared data

```
var n;
type item = ….;
var buffer: array[0..n-1] of item;
in, out: 0..n-1;
in :=0; out:= 0; /* shared buffer = circular array */
/* Buffer empty if in == out */
/* Buffer full if (in+1) mod n == out */
/* noop means 'do nothing' */
```

# Bounded Buffer - Shared Memory Solution

- Producer process - creates filled buffers

```
repeat
        ...
   produce an item in nextp
      ...
   while in+1 mod n = out do noop;
   buffer[in] := nextp;
   in := in+1 mod n;
until false;
```

# Bounded Buffer - Shared Memory Solution

- Consumer process - Empties filled buffers

```
repeat
        while in = out do noop;
    nextc := buffer[out] ;
     out:= out+1 mod n;
  …
  consume the next item in nextc
  …
until false
```

# Shared data

- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.
- Shared memory solution to the bounded-buffer problem allows at most (n-1) items in the buffer at the same time.

# Bounded Buffer

- A solution that uses all N buffers is not that simple.
  - Modify producer-consumer code by adding a variable *counter*, initialized to 0, incremented each time a new item is added to the buffer
- Shared data

```
type item = ….;
var buffer: array[0..n-1] of item;
in, out: 0..n-1;
counter: 0..n;
in, out, counter := 0;
```

# Bounded Buffer

- **Producer process - creates filled buffers**

```
repeat
        ...
   produce an item in nextp
      ...
   while counter = n do noop;
   buffer[in] := nextp;
   in := in+1 mod n;
   counter := counter+1;
until false;
```

# Bounded Buffer

- **Consumer process - Empties filled buffers**

```
repeat
        while counter = 0 do noop;
    nextc := buffer[out] ;
    out:= out+1 mod n;
    counter := counter - 1;
        ...
    consume the next item in nextc
        ...
until false;
```

- The statements

```
counter := counter + 1;
counter := counter - 1;
```

must be executed *atomically*.

- **Atomic Operations**
  - An operation that runs to completion or not at all.

# 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 (**we expect count = 5 in the end too**):

  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 !!}

# Problem is at the lowest level

- If threads are working on separate data, scheduling doesn't matter:

  | Thread A | Thread B |
  |---|---|
  | x = 1; | y = 2; |

- However, What about (Initially, y = 12):

  | Thread A | Thread B |
  |---|---|
  | x = 1; | y = 2; |
  | x = y+1; | y = y*2; |

  - What are the possible values of x?
- Or, what are the possible values of x below?

  | Thread A | Thread B |
  |---|---|
  | x = 1; | x = 2; |

  - X could be non-deterministic (1, 2??)

# The Critical-Section Problem

- N processes all competing to use shared data.
  - Structure of process $P_i$ ---- Each process has a code segment, called the critical section, in which the shared data is accessed.

```
repeat
        entry section    /* enter critical section */
       critical section  /* access shared variables */
   exit  section      /* leave critical section */
       remainder section  /* do other work */
until false
```

- Problem
  - Ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.

# Solution: Critical Section Problem - Requirements

- **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 exists 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.

# Solution: Critical Section Problem - Requirements

- Assume that each process executes at a nonzero speed in the critical section. That is, assume that each process finishes executing the critical section once entered
- No assumption concerning relative speed of the n processes.
- Assume that a process can get stuck in its remainder section indefinitely, e.g., in a non-terminating while loop

# Solution: Critical Section Problem -- Initial Attempt

- Only 2 processes, P0 and P1
- General structure of process Pi (Pj)

```
repeat
        entry section
                critical section
        exit  section
                remainder section
until false
```

- Processes may share some common variables to synchronize their actions.

# Algorithm 1

- Shared Variables:
  - **var** *turn*: (0..1);
    initially *turn* = 0;
  - *turn* = *i* ☐ P*i* can enter its critical section
- Process *Pi*

```
repeat
        while turn <> i do no-op;
          critical section
        turn := j;
          remainder section
until false
```

Satisfies mutual exclusion, but not progress.

# Algorithm 1

- Satisfies mutual exclusion
  - The turn is equal to either i or j and hence one of Pi and Pj can enter the critical section
- Does not satisfy progress
  - Example: Pi finishes the critical section and then gets stuck indefinitely in its remainder section. Then Pj enters the critical section, finishes, and then finishes its remainder section. Pj then tries to enter the critical section again, but it cannot since turn was set to i by Pj in the previous iteration. Since Pi is stuck in the remainder section, turn will be equal to i indefinitely and Pj can't enter although it wants to. Hence no process is in the critical section and hence no progress.
- We don't need to discuss/consider bounded wait when progress is not satisfied

# Algorithm 2

- Shared Variables
  - **var** *flag*: **array** (0..1) **of** boolean;
    initially *flag[0] = flag[1]* = false;
  - *flag[i] = true* ☐ Pi ready to enter its critical section
- Process $P_i$

```
repeat
        flag[i] := true;
        while flag[j] do no-op;
          critical section
        flag[i]:= false;
          remainder section
until false
```

Satisfies mutual exclusion, but not progress.

# Algorithm 2

- Satisfies mutual exclusion
  - If Pi enters, then flag[ i ] = true, and hence Pj will not enter.
- Does not satisfy progress
  - Can block indefinitely…. Progress requirement not met
  - Example: There can be an interleaving of execution in which Pi and Pj both first set their flags to true and then both check the other process' flag. Therefore, both get stuck at the entry section
- We don't need to discuss/consider bounded wait when progress is not satisfied

# Algorithm 3

- Shared Variables
  - **var** *flag*: **array** (0..1) **of** boolean;
    initially *flag[0] = flag[1]* = false;
  - *flag[i] = true* ☐ Pi ready to enter its critical section
- Process $P_i$

```
repeat
        while flag[j] do no-op;
        flag[i] := true;
          critical section
        flag[i]:= false;
          remainder section
until false
```

# Algorithm 3

- ***Does not satisfy mutual exclusion***
  - Example: There can be an interleaving of execution in which both first check the other process' flag and see that it is false. Then they both enter the critical section.
- We don't need to discuss/consider progress and bounded wait when mutual exclusion is not satisfied

# Algorithm 4

- Combined Shared Variables of algorithms 1 and 2
- Process Pi

```
repeat
        flag[i] := true;
        turn := j;
        while (flag[j] and turn=j) do no-op;
          critical section
        flag[i]:= false;
          remainder section
until false
```

YES!!! Meets all three requirements, solves the critical section problem for 2 processes.

Also called "Peterson's solution"

# Algorithm 4

- Satisfies mutual exclusion
  - If one process enters the critical section, it means that either the other process was not ready to enter or it was this process' turn to enter. In either case, the other process will not enter the critical section
- Satisfies progress
  - If one process exits the critical section, it sets its ready flag to false and hence the other process can enter. Moreover, there is no interleaving in the entry section that can block both.
- Satisfies bounded wait
  - If a process is waiting in the entry section, it will be able to enter at some point since the other process will either set its ready flag to false or will set to turn to this process.

# Bakery Algorithm

- Critical section for n processes
  - Before entering its critical section, process receives a number. Holder of the smallest number enters critical section.
  - If processes Pi and Pj receive the same number,
    - if i <= j, then Pi is served first; else Pj is served first.
  - The numbering scheme always generates numbers in increasing order of enumeration; i.e. 1,2,3,3,3,3,4,4,5,5

# Bakery Algorithm (cont.)

- Notation -
  - Lexicographic order(ticket#, process id#)
    - $(a,b) < (c,d)$ if $(a<c)$ or if $((a=c)$ and $(b < d))$
    - $\max(a_0,....a_{n-1})$ is a number, $k$, such that $k >= a_i$ for $i = 0,\ldots,n-1$
- Shared Data

  **var** *choosing*: **array**[0..*n*-1] **of** *boolean*;(initialized to *false*)

  *number*: **array**[0..*n*-1] **of** *integer*; (initialized to 0)

# Bakery Algorithm (cont.)

```
repeat
    choosing[i] := true;
    number[i] := max(number[0], number[1],…,number[n-1]) +1;
    choosing[i] := false;
    for j := 0 to n-1
      do begin
      while choosing[j] do no-op;
            while number[j] <> 0
                  and (number[j] ,j) < (number[i],i) do no-op;
      end;
       critical section
     number[i]:= 0;
       remainder section
until false;
```

# Supporting Synchronization

| | |
|---|---|
| *Programs* | *Shared Programs* |
| *Higher-level API* | *Locks Semaphores Monitors Send/Receive CCregions* |
| *Hardware* | *Load/Store Disable Ints Test&Set Comp&Swap* |

- We are going to implement various synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide inherent support for synchronization at the hardware level
  - Need to provide primitives useful at software/user level

# Hardware Solutions for Synchronization

- Load/store - Atomic Operations required for synchronization
  - Showed how to protect a critical section with only atomic load and store ⇒ pretty complex!
- Mutual exclusion solutions presented depend on memory hardware having read/write cycle.
  - If multiple reads/writes could occur to the same memory location at the same time, this would not work.
  - Processors with caches but no cache coherency cannot use the solutions
- In general, it is impossible to build mutual exclusion without a primitive that provides some form of mutual exclusion.
  - How can this be done in the hardware???
  - How can this be simplified in software???

# Synchronization Hardware

- Test and modify the content of a word atomically - Test-and-set instruction

```
function Test-and-Set (var target: boolean): boolean;
  begin
     Test-and-Set := target;
      target := true;
  end;
```

- Similarly "SWAP" instruction

# Mutual Exclusion with Test-and-Set

- Shared data: var lock: boolean (initially false)
- Process Pi

```
repeat
        while Test-and-Set (lock) do no-op;
                critical section
              lock := false;
                remainder section
    until false;
```

# Bounded Waiting Mutual Exclusion with Test-and-Set

```
var j : 0..n-1;
      key : boolean;
repeat
     waiting [i]  := true; key := true;
       while waiting[i] and key do key := Test-and-Set(lock);
     waiting [i ] := false;
 critical section
      j := i+1 mod n;
      while (j <> i )  and (not waiting[j]) do j := j + 1 mod n;
       if j = i  then lock := false;
                 else waiting[j] := false;
  remainder section

until false;
```

# Hardware Support: Other examples

- **Swap (&address, register)** { /* x86 */
  temp = M[address];
  M[address] = register;
  register = temp;
  }
- **compare&swap (&address, reg1, reg2)** { /* 68000 */
  if (reg1 == M[address]) {
  M[address] = reg2;
  return success;
  } else {
  return failure;
  }
  }
- **load-linked&store conditional(&address)** {
  /* R4000, alpha */
  loop:
  ll r1, M[address];
  movi r2, 1; /* Can do arbitrary comp */
  sc r2, M[address];
  beqz r2, loop;
  }

# 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
- Protect a critical section by first **acquiring** a lock and then **releasing** the lock
  - 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()

**Semantics of** `acquire`

```
acquire(mutex_lock) {
    while Test&Set(mutex_lock)) ; /* busy wait */
          }
```

**Semantics of** `release`

```
release(mutex_lock) {
   mutex_lock = 0;
}
```

**Critical section implementation**

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

# Semaphore

- Semaphore *S* - integer variable (non-negative)
  - used to represent number of abstract resources
- Can only be accessed via two indivisible (atomic) operations

  *wait* (*S*): **while** *S* <= 0 **do** no-op

  *S* := *S*-1;

  *signal* (S): *S* := *S*+1;
  - *P* or *wait* used to acquire a resource, waits for semaphore to become positive, then decrements it by 1
  - *V* or *signal* releases a resource and increments the semaphore by 1, waking up a waiting P, if any
  - If *P* is performed on a *count* <= 0, process must wait for *V* or the release of a resource.

**P():"*proberen*" (to test) ; V() "*verhogen*" (to increment) in Dutch**

# Example: Critical Section for n Processes

- Shared variables

  **var** *mutex*: semaphore
  initially *mutex* = 1

- Process $P_i$

```
repeat
        wait(mutex);
           critical section
        signal (mutex);
           remainder section
until false
```

# Semaphore as a General Synchronization Tool

- Execute *B* in $P_j$ only after *A* execute in $P_i$
- Use semaphore *flag* initialized to 0
- Code:

| $P_i$ | $P_j$ |
| --- | --- |
| ⋮ | ⋮ |
| *A* | *wait*(*flag*) |
| *signal*(*flag*) | *B* |

# Problem...

- Locks prevent conflicting actions on shared data
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
- All Synchronization involves waiting
  - **Busy Waiting,** uses CPU that others could use. This type of semaphore is called a *spinlock*.
    - Waiting thread may take cycles away from thread holding lock (no one wins!)
    - OK for short times since it prevents a context switch.
    - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock ⇒ no progress!
  - Should *sleep* if waiting for a long time
- For longer runtimes, need to modify P and V so that processes can *block* and *resume.*

# Semaphore Implementation

- Define a semaphore as a record

```
type semaphore = record
                    value: integer;
                    L: list of processes;
                 end;
```

- Assume two simple operations
  - *block* suspends the process that invokes it.
  - *wakeup*(*P*) resumes the execution of a blocked process *P*.

# Semaphore Implementation(cont.)

- Semaphore operations are now defined as

```
wait (S):  S.value := S.value -1;
           if S.value < 0
             then begin
                    add this process to S.L;
                    block;
                  end;

signal (S):  S.value := S.value +1;
           if S.value <= 0
             then begin
                    remove a process P from S.L;
                    wakeup(P);
                  end;
```

# Block/Resume Semaphore Implementation

- If process is blocked, enqueue PCB of process and call scheduler to run a different process.
- Semaphores are executed atomically;
  - no two processes execute *wait* and *signal* at the same time.
  - Mutex can be used to make sure that two processes do not change count at the same time.
    - If an interrupt occurs while mutex is held, it will result in a long delay.
    - Solution: Turn off interrupts during critical section.

# 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 semaphores initialized to 1

| *P0* | *P1* |
|---|---|
| *wait*(*S*); | *wait*(*Q*); |
| *wait*(*Q*); | *wait*(*S*); |
| ⋮ | ⋮ |
| *signal* (*S*) ; | *signal* (*Q*); |
| *signal* (*Q*); | *signal* (*S*); |

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

# Two Types of Semaphores

- Counting Semaphore - integer value can range over an unrestricted domain.
- Binary Semaphore - integer value can range only between 0 and 1; simpler to implement.
- Can implement a counting semaphore S as a binary semaphore.

# Classical Problems of Synchronization

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

# Bounded Buffer Problem

- Shared data

```
type item = ….;
var buffer: array[0..n-1] of item;
full, empty, mutex : semaphore;
nextp, nextc :item;
full := 0; empty := n; mutex := 1;
```

# Bounded Buffer Problem

- Producer process - creates filled buffers

```
repeat
        ...
   produce an item in nextp
      ...
   wait (empty);
   wait (mutex);
    ...
    add nextp to buffer
    ...
    signal (mutex);
    signal (full);
until false;
```

# Bounded Buffer Problem

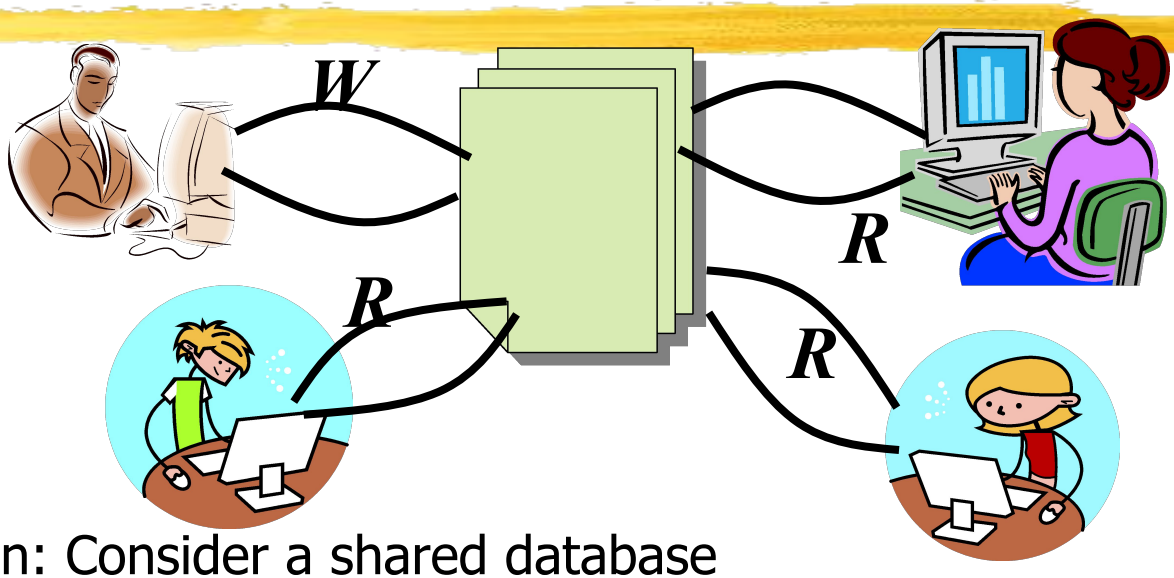
- Consumer process - Empties filled buffers

```
repeat
        wait (full );
    wait (mutex);
      ...
    remove an item from buffer  to  nextc
      ...
    signal (mutex);
    signal (empty);
      ...
      consume the next item in nextc
      ...
until false;
```

# Discussion

- ASymmetry?
  - Producer does: `P(empty), V(full)`
  - Consumer does: `P(full), V(empty)`
- Is order of P's important?
  - Yes!  Can cause deadlock
- Is order of V's important?
  - No, except that it might affect scheduling efficiency

# Readers/Writers Problem




- Motivation: Consider a shared database
  - Two classes of users:
    - Readers – never modify database
    - Writers – read and modify database
  - Is using a single lock on the whole database sufficient?
    - Like to have many readers at the same time
    - Only one writer at a time

# Readers-Writers Problem

- Shared Data

  **var** *mutex, wrt*: *semaphore* (=1);
  *readcount*: *integer* (= 0);

- Writer Process

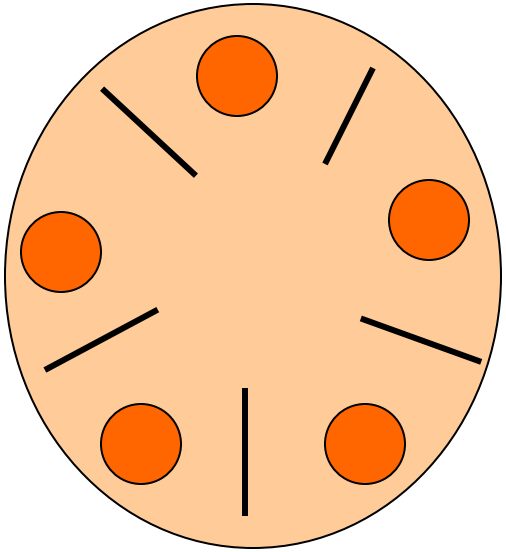
  *wait*(*wrt*);
  ...
  writing is performed
  ...
  *signal*(*wrt*);

# Readers-Writers Problem

- Reader process

```
wait(mutex);
   readcount := readcount +1;
   if readcount = 1 then wait(wrt);
signal(mutex);
            ...
              reading is performed
            ...
wait(mutex);
   readcount := readcount - 1;
   if readcount = 0 then signal(wrt);
signal(mutex);
```

# Dining-Philosophers Problem



Shared Data

**var** *chopstick*: **array** [0..4] **of** *semaphore* (=1 initially);

# Dining Philosophers Problem

- Philosopher *i* :

```
repeat
        wait (chopstick[i]);
    wait (chopstick[i+1 mod 5]);
        ...
        eat
        ...
    signal (chopstick[i]);
    signal (chopstick[i+1 mod 5]);
        ...
        think
        ...
until false;
```

# Higher Level Synchronization

- Timing errors are still possible with semaphores
  - Example 1

    *signal* (*mutex*);
    ...
    critical region
    ...
    *wait* (*mutex*);
  - Example 2

    *wait*(*mutex*);
    ...
    critical region
    ...
    *wait* (*mutex*);
  - Example 3

    *wait*(*mutex*);
    ...
    critical region
    ...
    Forgot to signal

# Motivation for Other Sync. Constructs

- Semaphores are a huge step up from loads and stores
  - Problem is that semaphores are dual purpose:
    - They are used for both mutex and scheduling constraints
    - Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?
- Idea: allow manipulation of a shared variable only when condition (if any) is met – ***conditional critical region***
- Idea : Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
  - ***Monitor:*** a lock (for mutual exclusion) and zero or more condition variables (for scheduling constraints ) to manage concurrent access to shared data
    - Some languages like Java provide this natively

# Conditional Critical Regions

- High-level synchronization construct
- A shared variable *v* of type *T* is declared as:

  **var** *v*: **shared** *T*

- Variable v is accessed only inside statement

  **region** *v* when *B* **do** *S*

  where *B* is a boolean expression.

  While statement *S* is being executed, no other process can access variable *v*.

# Critical Regions (cont.)

- Regions referring to the same shared variable exclude each other in time.
- When a process tries to execute the region statement,

  **region** *v* when *B* **do** *S*

  - the Boolean expression *B* is evaluated.
    - If *B* is true, statement *S* is executed.
    - If it is false, the process is delayed until *B* becomes true and no other process is in the region associated with *v*.

# Example - Bounded Buffer

- Shared variables

```
var buffer: shared record
                pool:array[0..n-1] of item;
                count,in,out: integer;
            end;
```

- Producer Process inserts *nextp* into the shared buffer

```
region buffer when count < n
        do begin
            pool[in] := nextp;
            in := in+1 mod n;
            count := count + 1;
        end;
```

# Bounded Buffer Example

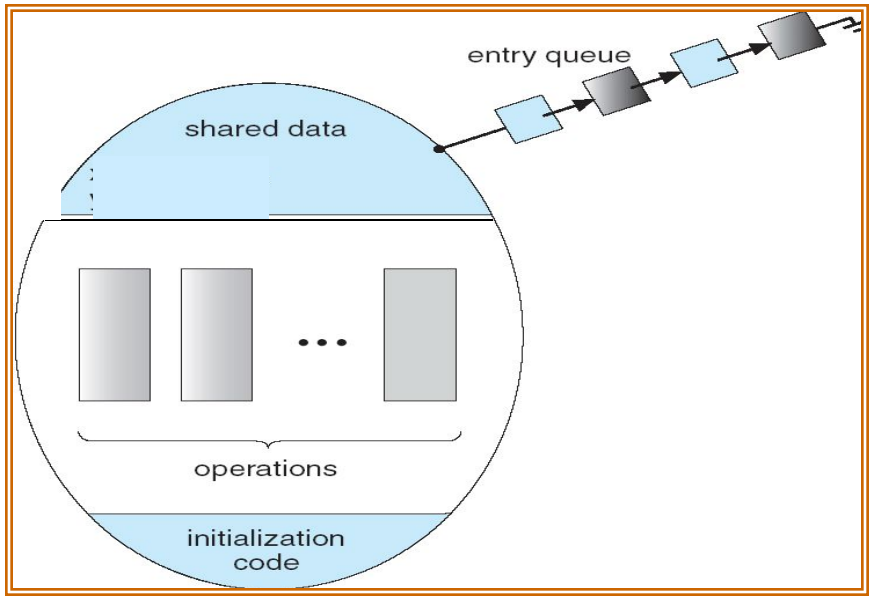
- Consumer Process removes an item from the shared buffer and puts it in *nextc*

```
region buffer  when count > 0
            do begin
                  nextc := pool[out];
                  out := out+1 mod n;
                 count := count -1;
               end;
```

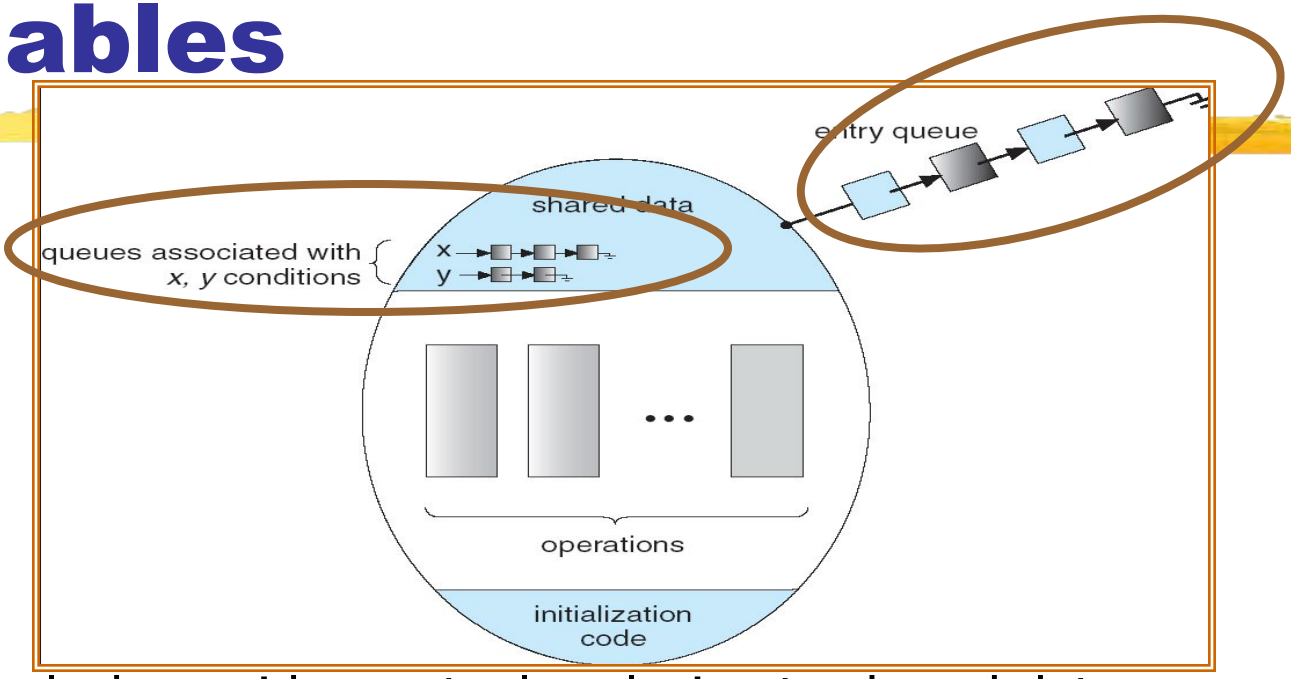
# Monitors

High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.

```
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.
```



# Monitor with Condition Variables




- Lock: the lock provides mutual exclusion to shared data
  - Always acquire before accessing shared data structure
  - Always release after finishing with shared data
  - Lock initially free
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep

# Monitors with condition variables

- To allow a process to wait within the monitor, a condition variable must be declared, as:

  **var** *x,y*: *condition*

  - Condition variable can only be used within the operations *wait* and *signal*. Queue is associated with condition variable.
    - The operation

      x.wait;

    means that the process invoking this operation is suspended until another process invokes

      x.signal;

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

# Dining Philosophers

```
type dining-philosophers= monitor
    var state: array[0..4] of (thinking, hungry, eating);
    var self:   array[0..4] of condition;
    // condition where philosopher I can delay himself when hungry but
    //    is  unable to obtain chopstick(s)
     procedure entry pickup (i :0..4);
        begin
           state[i] := hungry;
           test(i); //test that your left and right neighbors are not eating
           if state [i] <> eating then self [i].wait;
        end;
     procedure entry putdown (i:0..4);
        begin
            state[i] := thinking;
            test (i + 4 mod 5 );  // signal one neighbor
            test (i + 1 mod 5 );  // signal other neighbor
        end;
```

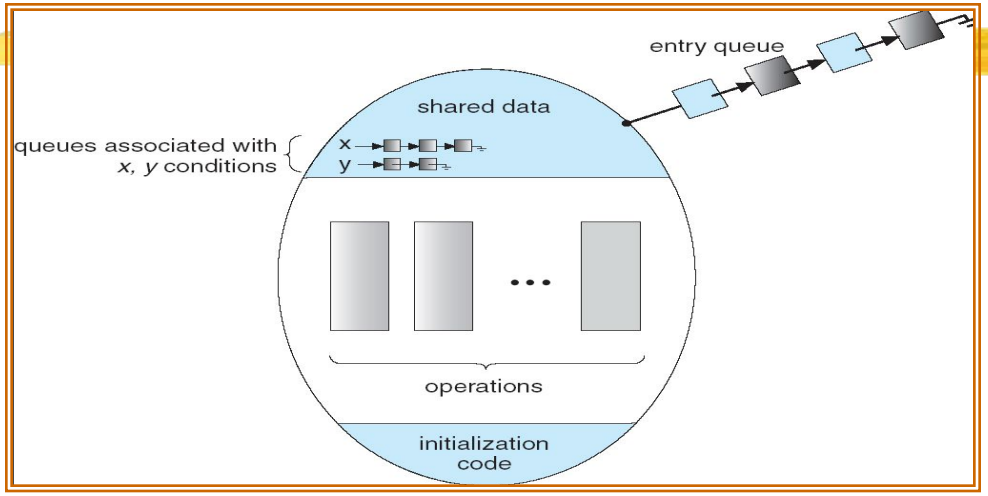
# Dining Philosophers (cont.)

```
procedure test (k :0..4);
        begin
          if state [k + 4 mod 5] <> eating
             and state [k ] = hungry
             and state [k + 1 mod 5] <> eating
             then
                begin
                   state[k] := eating;
                   self [k].signal;
                end;
        end;

begin
   for i := 0 to 4
       do state[i] := thinking;
end;
```

# Additional (extra) slides

# Mesa vs. Hoare monitors




- Who proceeds next – signaler or waiter?
  - Hoare-style monitors(most textbooks):
    - Signaler gives lock, CPU to waiter; waiter runs immediately
    - Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
  - Mesa-style monitors (most real operating systems):
    - Signaler keeps lock and processor
    - Waiter placed on ready queue with no special priority
    - Practically, need to check condition again after wait (condition may no longer be true!)

# Implementing S (counting sem.) as a Binary Semaphore

- Data Structures

  **var** *S1* : *binary-semaphore*;
  *S2* : *binary-semaphore*;
  *S3* : *binary-semaphore;*
  *C*: *integer*;

- Initialization

  *S1* = *S3* =1;
  *S2* = 0;
  *C* = initial value of semaphore *S*;

# Implementing S

## Wait operation

```
wait(S3);
 wait(S1);
 C := C-1;
 if C < 0
 then begin
          signal (S1);
          wait(S2);
      end
 else signal (S1);
 signal (S3);
```

## Signal operation

```
      wait(S1);
  C := C + 1;
 if C <= 0 then signal (S2);
 signal (S1);
```

# Implementing Regions

- Region *x* when *B* do *S*

  **var** *mutex*, *first-delay*, *second-delay*: *semaphore*;

  *first-count*, *second-count*: *integer*;

- Mutually exclusive access to the critical section is provided by mutex.

  If a process cannot enter the critical section because the Boolean expression *B* is false,

  it initially waits on the first-delay semaphore;

  moved to the second-delay semaphore before it is allowed to reevaluate *B*.

# Implementation

- Keep track of the number of processes waiting on *first-delay* and *second-delay*, with *first-count* and *second-count* respectively.
- The algorithm assumes a FIFO ordering in the queueing of processes for a semaphore.
- For an arbitrary queueing discipline, a more complicated implementation is required.

# Implementing Regions

```
wait(mutex);
while not B
   do begin    first-count := first-count +1;
               if second-count > 0
                     then signal (second-delay);
                     else  signal (mutex);
               wait(first-delay);
               first-count := first-count -1;
               second-count := second-count + 1;
               if first-count > 0 then signal (first-delay)
                                  else signal (second-delay);
               wait(second-delay);
               second-count := second-count -1;
     end;
S;
if first-count > 0  then signal (first-delay);
                    else if second-count > 0
                              then signal (second-delay);
                              else  signal (mutex);
```