Module 6: Process Synchronization

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

Background

- 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 bounded-butter problem (Chapter 4) allows at most *n* – 1 items in buffer at the same time. A solution, where all *N* buffers are used is not simple.
  – Suppose that we modify the producer-consumer code by adding a variable *counter*, initialized to 0 and incremented each time a new item is added to the buffer

Bounded-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;
```

- Producer process

```
repeat
      …
    produce an item in nextp
      …
    while counter = n do no-op;
    buffer [in] := nextp;
    in := in + 1 mod n;
    counter := counter +1;
until false;
```

Bounded-Buffer (Cont.)

- Consumer process

  repeat
      while *counter* = 0 **do** *no-op*;
      nextc := *buffer* [*out*];
      out := *out* + 1 **mod** *n*;
      counter := *counter* – 1;
          …
      consume the item in *nextc*
          …
  until *false*;

- The statements:
  - *counter* := *counter* + 1;
  - *counter* := *counter* - 1;

  must be executed *atomically*.

The Critical-Section Problem

- n processes all competing to use some shared data
- Each process has a code segment, called *critical section*, in which the shared data is accessed.
- Problem – ensure that when one process is executing in its critical section, no other process is allowed to execute in its critical section.
- Structure of process P_i

repeat

entry section

critical section

exit section

reminder section

until *false*;

Solution to Critical-Section Problem

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

Initial Attempts to Solve Problem

- Only 2 processes, P_0 and P_1
- General structure of process P_i (other process P_j)

repeat

$\boxed{\textit{entry section}}$

critical section

$\boxed{\textit{exit section}}$

reminder 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* $\Rightarrow$ P_i can enter its critical section
- Process P_i

repeat

$\boxed{\textbf{while } turn \neq i \textbf{ do } no\text{-}op; \quad \text{critical section}}$

$\boxed{turn := j;}$

reminder section

until *false*;

- Satisfies mutual exclusion, but not progress

Algorithm 2

- Shared variables
  - **var** *flag*: **array** [0..1] **of** *boolean*;
    initially *flag* [0] = *flag* [1] = *false*.
  - *flag* [i] = *true* $\Rightarrow P_i$ ready to enter its critical section
- Process P_i

repeat

$\boxed{\begin{array}{l} \textit{flag}[i] := \textit{true}; \\ \textbf{while } \textit{flag}[j] \textbf{ do } \textit{no-op}; \end{array}}$

critical section

$\boxed{\textit{flag}\ [i] := \textit{false};}$

remainder section

until *false*;

- Satisfies mutual exclusion, but not progress requirement.

Algorithm 3

- Combined shared variables of algorithms 1 and 2.
- Process P_i

repeat

flag [*i*] := *true*;
turn := *j*;
while (*flag* [*j*] and *turn* = *j*) **do** *no-op*;

critical section

flag [*i*] := *false*;

remainder section

until *false*;

- Meets all three requirements; solves the critical-section problem for two processes.

Bakery Algorithm

Critical section for n processes

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

Bakery Algorithm (Cont.)

- Notation <≡ lexicographical 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, …, n – 1
- Shared data

var *choosing*: **array** [0..*n* – 1] **of** *boolean*;

number: **array** [0..*n* – 1] **of** *integer*,

Data structures are initialized to *false* and 0 respectively

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;
```

Synchronization Hardware

- Test and modify the content of a word atomically.

function *Test-and-Set* (**var** target: *boolean*): *boolean*;

begin

Test-and-Set := *target*;
target := *true*;

end;

Mutual Exclusion with Test-and-Set

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

repeat

$\boxed{\textbf{while } \textit{Test-and-Set} \text{ (}\textit{lock}\text{) } \textbf{do } \textit{no-op}\text{;}}$

critical section

$\boxed{\textit{lock} := \textit{false};}$

remainder section

until *false*;

Semaphore

- Synchronization tool that does not require busy waiting.
- Semaphore S – integer variable
- can only be accessed via two indivisible (atomic) operations

wait (S): **while** $S \leq 0$ **do** *no-op*;
$S := S - 1$;

signal (S): $S := S + 1$;

Example: Critical Section of *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 Implementation

- Define a semaphore as a record

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

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

Implementation (Cont.)

- Semaphore operations now defined as

wait(*S*): *S.value* := *S.value* – 1;

if *S.value* < 0

then begin

add this process to *S*.L;
*blo*ck;

end;

signal(*S*): *S.value* := *S.value* = 1;

if *S.value* ≤ 0

then begin

remove a process *P* from *S.L*;
wakeup(*P*);

end;

Semaphore as General Synchronization Tool

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

P_i	P_j
⋮	⋮
A	*wait*(*flag*)
signal(*flag*)	B

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(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; can be simpler to implement.
- Can implement a counting semaphore *S* as a binary semaphore.

Implementing *S* 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* (Cont.)

- *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(S)1;

Classical Problems of Synchronization

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

Bounded-Buffer Problem

- Shared data

type *item* = …
var *buffer* = …
full, empty, mutex: semaphore;
nextp, nextc: item;
full :=0; *empty* := *n*; *mutex* :=1;

Bounded-Buffer Problem (Cont.)

- Producer process

```
repeat
        …
    produce an item in nextp
        …
    wait(empty);
    wait(mutex);
        …
    signal(mutex);
    signal(full);
until false;
```

Bounded-Buffer Problem (Cont.)

- Consumer process

repeat

wait(*full*)

wait(*mutex*);

…

remove an item from *buffer* to *nextc*

…

signal(*mutex*);

signal(*empty*);

…

consume the item in *nextc*

…

until *false*;

Readers-Writers Problem

- Shared data

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

  readcount : *integer* (=0);

- Writer process

  wait(*wrt*);

  …

  writing is performed

  …

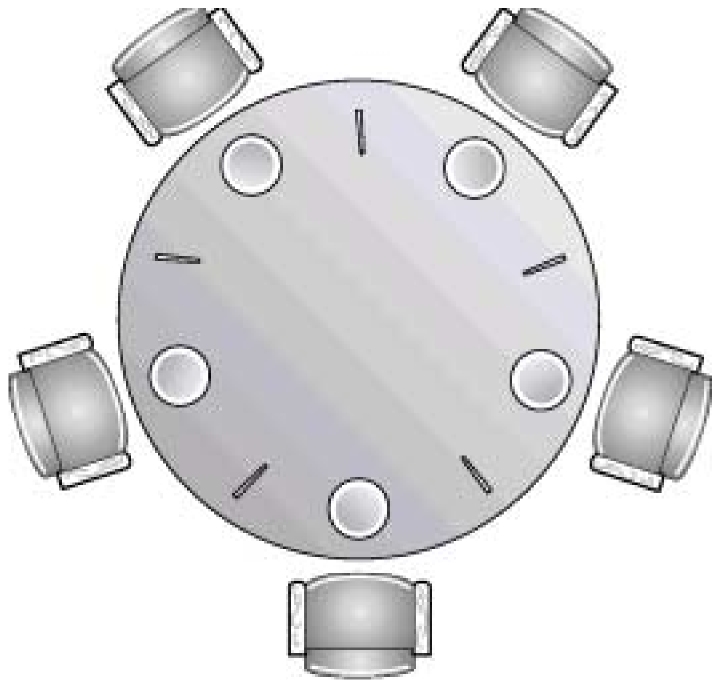
  signal(*wrt*);

Readers-Writers Problem (Cont.)

- 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 (Cont.)

- 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;
```

Critical Regions

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

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

- Variable *v* 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, 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 (Cont.)

- 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;

Implementation: region *x* when *B* do *S*

- Associate with the shared variable *x*, the following variables:

  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 (Cont.)

- 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 queuing of processes for a semaphore.
- For an arbitrary queuing discipline, a more complicated implementation is required.

```
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;
              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);
```

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

Monitors (Cont.)

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

  var *x, y: condition*

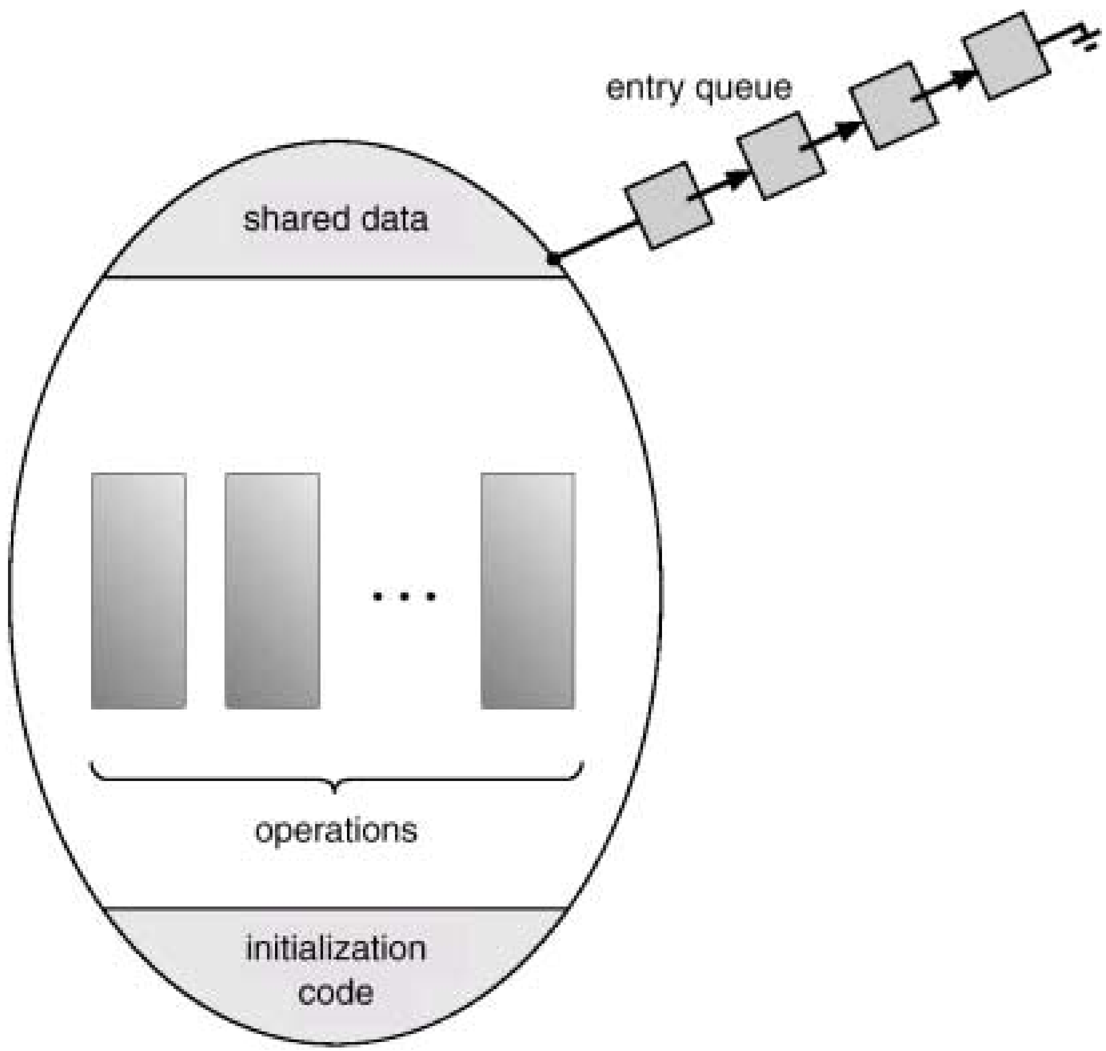
- Condition variable can only be used with the operations *wait* and *signal*.
  - The operation

    x.wait;

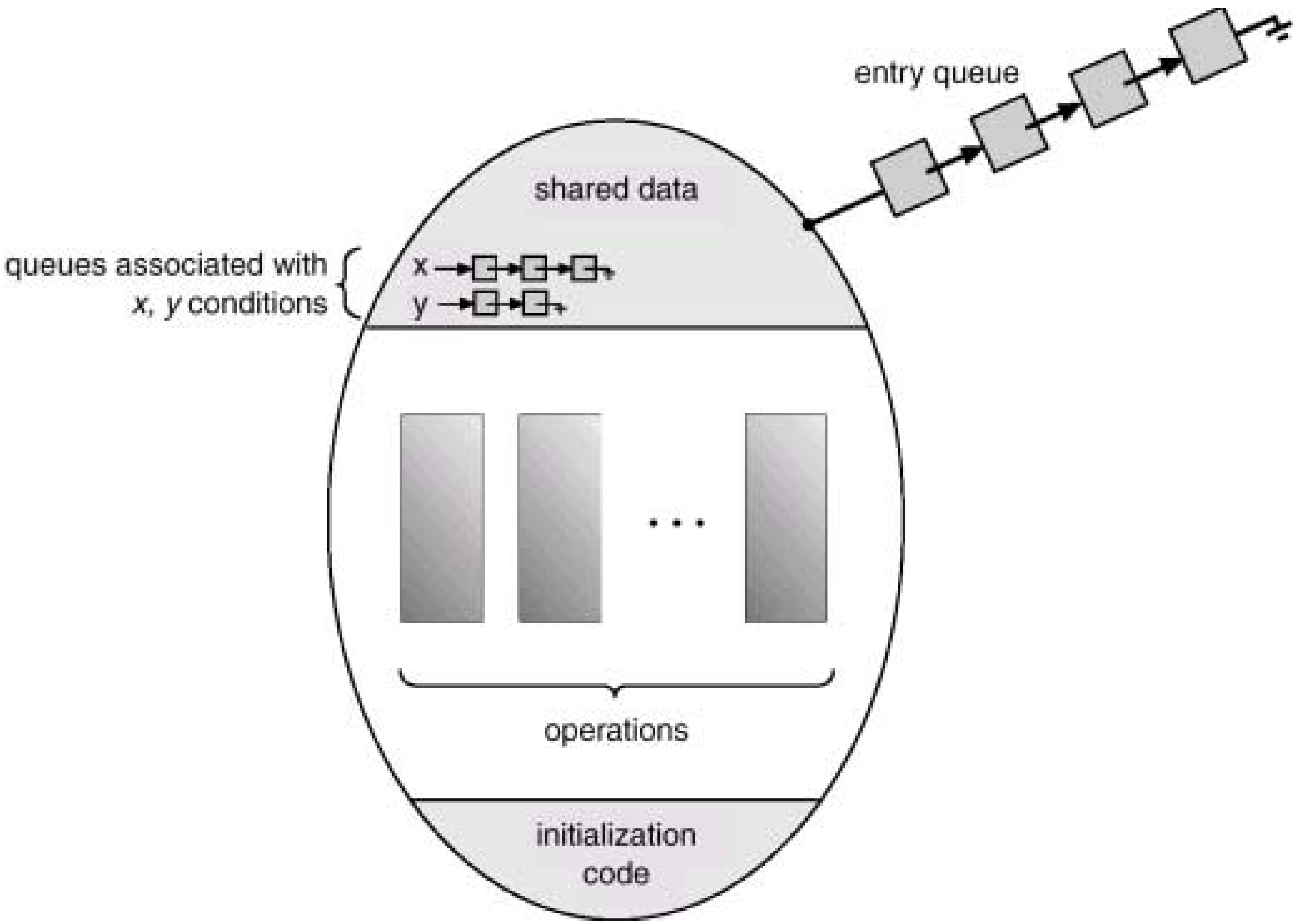
    means that the process invoking this opeation is suspended until another process invokes

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

Schematic view of a monitor



Monitor with condition variables



Dining Philosophers Example

type *dining-philosophers* = **monitor**
var *state* : **array** [0..4] **of** :(*thinking, hungry, eating*);
var *self* : **array** [0..4] **of** *condition*;
procedure entry *pickup* (*i*: 0..4);
begin
state[*i*] := *hungry*,
test (i);
if *state[i]* ≠ *eating* **then** *self[i], wait*,
end;

procedure entry *putdown* (*i*: 0..4);
begin
state[i] := thinking;
test (i+4 **mod** 5);
test (i+1 **mod** 5);
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.
```

Monitor Implementation Using Semaphores

- Variables

  var *mutex: semaphore* (init = 1)
  next: semaphore (init = 0)
  next-count: integer (init = 0)

- Each external procedure *F* will be replaced by

  wait(*mutex*);
  …
  body of *F*;
  …
  if next-count > 0
  then signal(next)
  else signal(mutex);

- Mutual exclusion within a monitor is ensured.

Monitor Implementation (Cont.)

- For each condition variable x, we have:

  var *x-sem*: *semaphore* (init = 0)
  x-count: integer (init = 0)

- The operation x.wait can be implemented as:

  x-count := *x-count* + 1;
  if *next-count* >0
  then *signal(next)*
  else *signal(mutex);*
  wait(x-sem);
  x-count := *x-count* – 1;

Monitor Implementation (Cont.)

- The operation x.signal can be implemented as:

  if *x-count* > 0
      then begin
          next-count := *next-count* + 1;
          signal(x-sem);
          wait(next);
          next-count := *next-count* – 1;
      end;

Monitor Implementation (Cont.)

- *Conditional-wait* construct: *x.wait(c);*
  - *c* – integer expression evaluated when the wait opertion is executed.
  - value of *c* (*priority number*) stored with the name of the process that is suspended.
  - when *x.signal* is executed, process with smallest associated priority number is resumed next.
- Check tow conditions to establish correctness of system:
  - User processes must always make their calls on the monitor in a correct sequence.
  - Must ensure that an uncooperative process does not ignore the mutual-exclusion gateway provided by the monitor, and try to access the shared resource directly, without using the access protocols.

Solaris 2 Operating System

- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing.
- Uses adaptive mutexes for efficiency when protecting data from short code segments.
- Uses condition variables and readers-writers locks when longer sections of code need access to data.