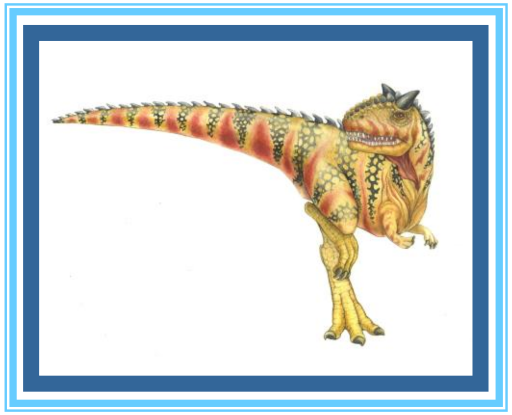
Chapter 6: Synchronization Tools

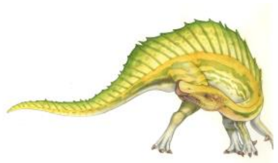


Outline

- Background
- The Critical-Section Problem
- Peterson’s Solution
- Hardware Support for Synchronization
- Mutex Locks
- Semaphores
- Monitors

Objectives

- Describe the critical-section problem and illustrate a race condition
- Illustrate hardware solutions to the critical-section problem using memory barriers, compare-and-swap operations, and atomic variables
- Demonstrate how mutex locks, semaphores, monitors, and condition variables can be used to solve the critical section problem

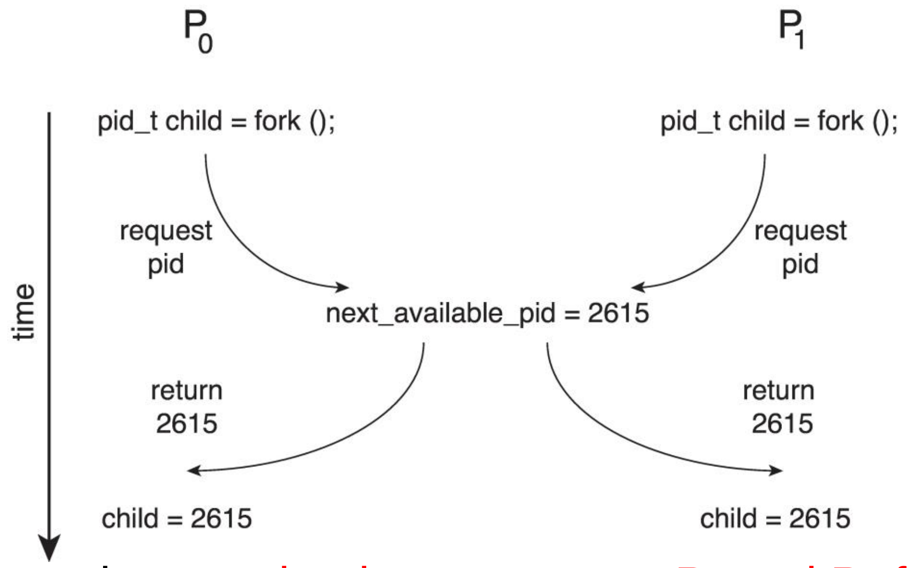


Background

- Processes can execute concurrently
  - May be interrupted at any time, partially completing execution
- Concurrent access to shared data may result in **data inconsistency**
- Maintaining data consistency requires mechanisms to ensure the *orderly execution of cooperating processes*
- We illustrated in chapter 4 the problem when we considered the Bounded Buffer problem with use of a counter that is updated concurrently by the producer and consumer,. Which lead to race condition.

Race Condition

- Processes P_0 and P_1 are creating child processes using the `fork()` system call
- Race condition on kernel variable `next_available_pid` which represents the next available process identifier (pid)



- Unless there is a mechanism to prevent P_0 and P_1 from accessing the variable `next_available_pid` the same pid could be assigned to two different processes!

Critical Section Problem

- Consider system of ***n*** processes {p_0, p_1, … p_{n-1}}
- Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc. (Accessing a shared resource)
  - When one process in critical section, no other may be in its critical section
- ***Critical section problem*** is to design protocol to solve this
  - no two processes are executing in their critical sections at the same time.

Critical Section

- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**
- General structure of process $\boldsymbol{P_i}$

```
while (true) {

        entry section

            critical section

        exit section

            remainder section

}
```

Critical-Section Problem (Cont.)

Requirements for solution to critical-section problem

1. **Mutual Exclusion** - If process P_i is executing in its critical section, then no other processes can be executing in their critical sections
2. **Progress** - If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then only those processes that are not executing in their remainder sections can participate in deciding which will enter its critical section next, and this selection cannot be postponed indefinitely.
   - if no process is in critical section, can decide quickly who enters
   - only one process can enter the critical section so in practice, others are put on the queue

Critical-Section Problem (Cont.)

Requirements for solution to critical-section problem

3. **Bounded Waiting** - There exists a bound, or limit, 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.
   - In practice, once a process enters its critical section, it does not get another turn until a waiting process gets a turn (managed as a queue)

Software Solution 1

- Two process solution
- Assume that the **`load`** and **`store`** machine-language instructions are atomic; that is, cannot be interrupted
- The two processes share one variable:
  - **`int turn;`**
- The variable **`turn`** indicates whose turn it is to enter the critical section
- initially, the value of **`turn`** is set to *i*

Algorithm for Process P_i

```
while (true){

        while (turn = = j);

        /* critical section */

        turn = j;

        /* remainder section */

}
```

Correctness of the Software Solution

- Mutual exclusion is preserved

  P_i enters critical section only if:

  `turn = i`

  and **`turn`** cannot be both i and j at the same time
- What about the Progress requirement?
- What about the Bounded-waiting requirement?

Peterson's Solution

- Two process solution
  - alternate execution between their critical sections and remainder sections.
- Assume that the **`load`** and **`store`** machine-language instructions are atomic; that is, cannot be interrupted
- The two processes share two variables:
  - **`int turn;`**
  - **`boolean flag[2] //`** Initialized to FALSE
- 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 $\mathbf{P_i}$ is ready!

Algorithm for Process P_i

```
while (true){

      flag[i] = true;
      turn = j;
      while (flag[j] && turn = = j)
               ;

         /* critical section */

      flag[i] = false;

      /* remainder section */

}
```

Correctness of Peterson’s Solution

- Provable that the three CS requirement are met:
  1. Mutual exclusion is preserved

     P_i enters CS only if:

     either **`flag[j] = false`** or **`turn = i`**
  2. Progress requirement is satisfied
  3. Bounded-waiting requirement is met

Peterson's Solution and Modern Architecture

- Although useful for demonstrating an algorithm, Peterson's Solution is not guaranteed to work on modern architectures.
  - To improve performance, processors and/or compilers may reorder operations that have no dependencies
- Understanding why it will not work is useful for better understanding race conditions.
- For single-threaded this is ok as the result will always be the same.
- For multithreaded the reordering may produce inconsistent or unexpected results!

Modern Architecture Example

- Two threads share the data:

```
boolean flag = false;
int x = 0;
```

- Thread 1 performs

```
while (!flag)
  ;
print x
```

- Thread 2 performs

```
x = 100;
flag = true
```

- What is the expected output?

100

Modern Architecture Example (Cont.)

- However, since the variables `flag` and `x` are independent of each other, the instructions:

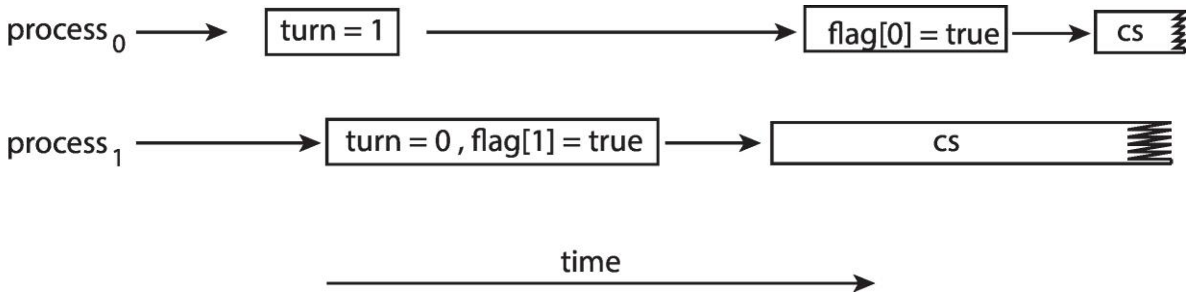
```
flag = true;
 x = 100;
```

  for Thread 2 may be reordered

- If this occurs, the output may be 0!

Peterson’s Solution Revisited

- The effects of instruction reordering in Peterson’s Solution



- This allows both processes to be in their critical section at the same time!
- To ensure that Peterson’s solution will work correctly on modern computer architecture we must use **Memory Barrier**.

Memory Barrier

- **Memory model** are the memory guarantees a computer architecture makes to application programs.
- Memory models may be either:
  - **Strongly ordered** – where a memory modification of one processor is immediately visible to all other processors.
  - **Weakly ordered** – where a memory modification of one processor may not be immediately visible to all other processors.
- A **memory barrier** is an instruction that forces any change in memory to be propagated (made visible) to all other processors.

Memory Barrier Instructions

- When a memory barrier instruction is performed, the system ensures that all loads and stores are completed before any subsequent load or store operations are performed.
- Therefore, even if instructions were reordered, the memory barrier ensures that the store operations are completed in memory and visible to other processors before future load or store operations are performed.

Memory Barrier Example

- Returning to the previous example
- We could add a memory barrier to the following instructions to ensure Thread 1 outputs 100:
- Thread 1 now performs

```
 while (!flag)
   memory_barrier();
print x
```

- Thread 2 now performs

```
 x = 100;
memory_barrier();
flag = true
```

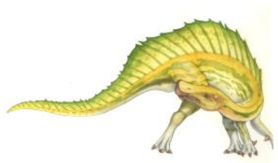
- For Thread 1 we are guaranteed that that the value of `flag` is loaded before the value of `x`.
- For Thread 2 we ensure that the assignment to `x` occurs before the assignment `flag`.
- Wrt Peterson's solution where should we place memory_barrier()?

Synchronization Hardware

- Many systems provide hardware support for implementing the critical section code.
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable

Hardware Instructions

- Special hardware instructions that allow us to either *test-and-modify* the content of a word, or to *swap* the contents of two words atomically (uninterruptedly.)
  - **Test-and-Set** instruction
  - **Compare-and-Swap** instruction



The test_and_set Instruction

- Definition

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

- Properties
  - Executed atomically
  - Returns the original value of passed parameter
  - Set the new value of passed parameter to `true`

Solution Using test_and_set()

- Shared boolean variable **`lock`**, initialized to **`false`**
- Solution:

```
do {
        while (test_and_set(&lock))
         ; /* do nothing */

              /* critical section */

    lock = false;
              /* remainder section */
 } while (true);
```

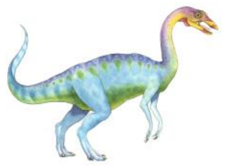
- Does it solve the critical-section problem?

The compare_and_swap Instruction

- Definition

```
int compare_and_swap(int *value, int expected, int new_value)
 {

   int temp = *value;

   if (*value == expected)

       *value = new_value;

    return temp;

  }
```

- Properties
  - Executed atomically
  - Returns the original value of passed parameter **`value`**
  - Set the variable **`value`** the value of the passed parameter **`new_value`** but only if **`*value == expected`** is true. That is, the swap takes place only under this condition.
- If two CAS instructions are executed simultaneously (each on a different core), they will be executed sequentially in some arbitrary order.



Solution using compare_and_swap

- Shared integer **`lock`** initialized to 0;
- Solution:

```
while (true){
    while (compare_and_swap(&lock, 0, 1) != 0)
          ; /* do nothing */

    /* critical section */

    lock = 0;

    /* remainder section */
}
```

- Does it solve the critical-section problem?

Bounded-waiting with compare-and-swap

```
while (true) {
   waiting[i] = true;
   key = 1;
   while (waiting[i] && key == 1)
      key = compare_and_swap(&lock,0,1);
   waiting[i] = false;
   /* critical section */
   j = (i + 1) % n;
   while ((j != i) && !waiting[j])
      j = (j + 1) % n;
   if (j == i)
      lock = 0;
   else
      waiting[j] = false;
   /* remainder section */
}
```

Atomic Variables

- Typically, instructions such as compare-and-swap are used as building blocks for other synchronization tools.
- One tool is an **atomic variable** that provides *atomic* (uninterruptible) updates on basic data types such as integers and booleans.
- Most systems that support atomic variables provide special atomic data types as well as functions for accessing and manipulating atomic variables
- For example:
  - Let **`sequence`** be an atomic variable
  - Let **`increment()`** be operation on the atomic variable **`sequence`**
  - The Command:

```
increment(&sequence);
```

ensures **`sequence`** is incremented without interruption:

Atomic Variables

- The `increment()` function can be implemented as follows:

```
void increment(atomic_int *v)
{
    int temp;
    do {
        temp = *v;
    }
    while (temp != (compare_and_swap(v,temp,temp+1));
}
```

- Although atomic variables provide atomic updates, they do not entirely solve race conditions in all circumstances.
    - For example count variable in bounded-buffer problem.
        - producer and consumer processes also have while loops whose condition depends on the value of count.
            - See the situation for one producer and two consumers.

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
  - Boolean variable indicating if lock is available or not
- Protect a critical section by
  - First **`acquire()`** a lock
  - Then **`release()`** the lock
- Calls to **`acquire()`** and **`release()`** must be **atomic**
  - Usually implemented via hardware atomic instructions such as compare-and-swap.
- But this solution requires **busy waiting**

Solution to CS Problem Using Mutex Locks

- If the lock is available, a call to acquire() succeeds and the lock is then considered unavailable.

```
while (true) {
        acquire lock

            critical section

        release lock

remainder section
}
```

Mutex Locks

- The main disadvantage of the implementation given here is that it requires **busy waiting**.
  - While a process is in its critical section, other process tries to enter its critical section must loop continuously in the call to acquire().
    - Busy waiting wastes CPU cycles
    - Solution (??)
- mutex lock we have been describing is also called a **spinlock** because the process "spins" while waiting for the lock to become available.
  - Spinlocks do have an advantage specially for multicore systems. (How??)

Semaphore

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for processes to synchronize their activities.
- Semaphore ***S*** – integer variable
- Can only be accessed via two indivisible (atomic) operations
  - **`wait()`** and **`signal()`**
    - Originally called **`P()`** and **`V()`**
- Definition of the **`wait() operation`**

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

- Definition of the **`signal() operation`**

```
signal(S) {
    S++;
}
```

Semaphore (Cont.)

- **Counting semaphore** – integer value can range over an unrestricted domain
- When the count for the semaphore goes to 0. All processes that wish to use a resource will block until the count becomes greater than 0
- **Binary semaphore** – integer value can range only between 0 and 1
  - Same as a **mutex lock**
  - Can implement a counting semaphore ***S*** as a binary semaphore

Semaphore Usage Example

- Solution to the CS Problem
  - Create a semaphore "**`mutex`**" initialized to 1

```
wait(mutex);
    CS
signal(mutex);
```

- Consider ***P_1*** and ***P_2*** that with two statements ***S_1*** and ***S_2*** and the requirement that ***S_1*** to happen before ***S_2***
  - Create a semaphore "**`synch`**" initialized to 0

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

Semaphore Implementation

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

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue
- Each entry in a waiting queue has two data items:
  - Value (of type integer)
  - Pointer to next record in the list
- Two operations:
  - **block** – place the process invoking the operation on the appropriate waiting queue
  - **wakeup** – remove one of processes in the waiting queue and place it in the ready queue (CPU may or may not be assigned??)

Implementation with no Busy waiting (Cont.)

- Waiting queue

```
typedef struct {
   int value;
   struct process *list;
} semaphore;
```

Implementation with no Busy waiting (Cont.)

```
wait(semaphore *S) {
   S->value--;
   if (S->value < 0) {
      add this process to S->list;
      sleep ();
   }
}

signal(semaphore *S) {
   S->value++;
   if (S->value > 0) {
      remove a process P from S->list;
      wakeup(P);
   }
}
```

Semaphore values may be negative

Problems with Semaphores

- Incorrect use of semaphore operations:
  - **`signal(mutex)`** …. **`wait(mutex)`**
  - **`wait(mutex)`** … **`wait(mutex)`**
  - Omitting of **`wait (mutex)`** and/or **`signal (mutex)`**
- These – and others – are examples of what can occur when semaphores and other synchronization tools are used incorrectly.

Class Assignment

Consider the following set of processes, with the length of the CPU burst given in milliseconds:

Process	Burst Time	Priority
P_1	5	4
P_2	3	1
P_3	1	2
P_4	7	2
P_5	4	3

The processes are assumed to have arrived in the order P_1, P_2, P_3, P_4, P_5, all at time 0.

a. Draw four Gantt charts that illustrate the execution of these processes using the following scheduling algorithms: FCFS, SJF, non-preemptive priority (a larger priority number implies a higher priority), and RR (quantum = 2).

b. What is the turnaround time of each process for each of the scheduling algorithms in part a?

c. What is the waiting time of each process for each of these scheduling algorithms?

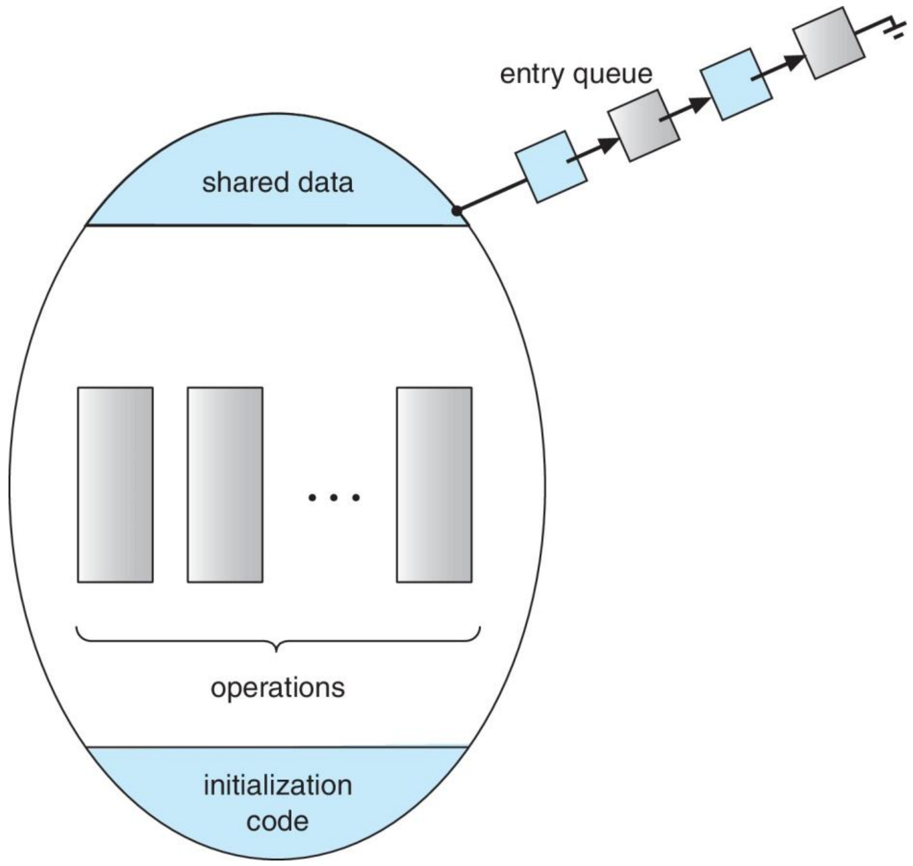
d. Which of the algorithms results in the minimum average waiting time (over all processes)?

Monitors

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- *Abstract data type*, internal variables only accessible by code within the procedure
- Only one process may be active within the monitor at a time
- Pseudocode syntax of a monitor:

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

  procedure P2 (…) { …. }

  procedure Pn (…) {……}

  initialization code (…) { … }
}
```

Schematic view of a Monitor



Monitor Implementation Using Semaphores

- Variables

```
 semaphore mutex
mutex = 1
```

- Each procedure ***P*** is replaced by

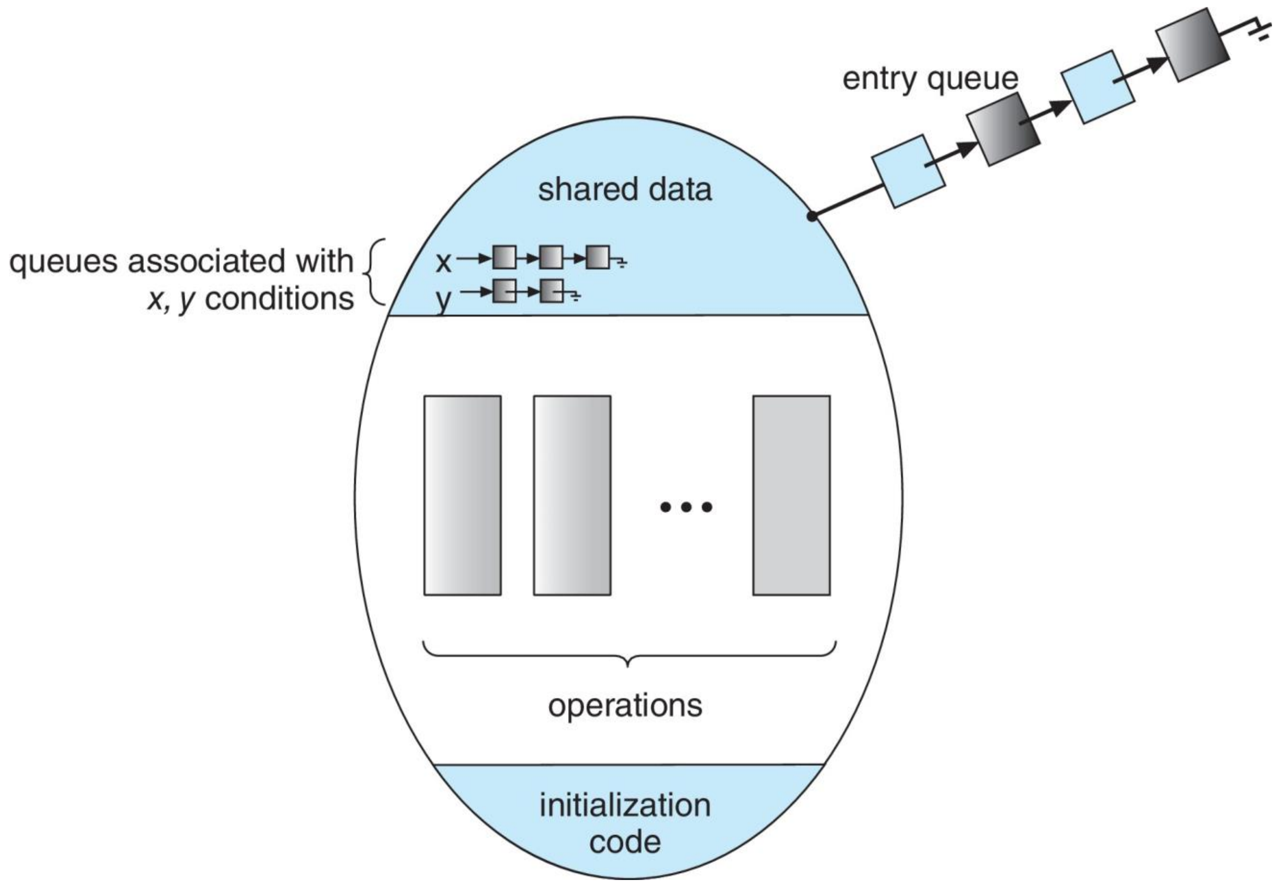
```
                    wait(mutex);
                       …
                        body of P;
                       …
                    signal(mutex);
```

- Mutual exclusion within a monitor is ensured

Condition Variables

- **`condition x, y;`**
- Two operations are allowed on a condition variable:
  - **`x.wait()`** – a process that invokes the operation is suspended until **`x.signal()`**
  - **`x.signal()`** – resumes one of processes (if any) that invoked **`x.wait()`**
    - If no **`x.wait()`** on the variable, then it has no effect on the variable

Monitor with Condition Variables



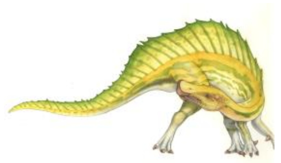
Usage of Condition Variable Example

- Consider P_1 and P_2 that that need to execute two statements S_1 and S_2 and the requirement that S_1 to happen before S_2
  - Create a monitor with two procedures F_1 and F_2 that are invoked by P_1 and P_2 respectively
  - One condition variable “x” initialized to 0
  - One Boolean variable “done”
  - **F1:**

```
    S1;
    done = true;
    x.signal();
```

  - **F2:**

```
    if done = false
        x.wait()
    S2;
```



Monitor Implementation Using Semaphores

- Variables

```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next_count = 0; // number of processes waiting
                              inside the monitor
```

- Each function ***P*** will be replaced by

```
wait(mutex);
     …
   body of P;
     …
if (next_count > 0)
 signal(next)
else
 signal(mutex);
```

- Mutual exclusion within a monitor is ensured

Implementation – Condition Variables

- For each condition variable ***x***, we have:

```
semaphore x_sem; // (initially  = 0)
int x_count = 0;
```

- The operation **`x.wait()`** can be implemented as:

```
x_count++;
if (next_count > 0)
    signal(next);
else
   signal(mutex);
wait(x_sem);
x_count--;
```

Implementation (Cont.)

- The operation **`x.signal()`** can be implemented as:

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

Resuming Processes within a Monitor

- If several processes queued on condition variable **`x`**, and **`x.signal()`** is executed, which process should be resumed?
- FCFS frequently not adequate
- Use the **conditional-wait** construct of the form

```
x.wait(c)
```

where:

- **`c`** is an integer (called the priority number)
- The process with lowest number (highest priority) is scheduled next

Single Resource allocation

- Allocate a single resource among competing processes using priority numbers that specifies the maximum time a process plans to use the resource
- The process with the shortest time is allocated the resource first
- Let R is an instance of type **`ResourceAllocator`** (next slide)
- Access to **`ResourceAllocator`** is done via:

```
R.acquire(t);
     ...
  access the resurce;
     ...
R.release;
```

- Where **`t`** is the maximum time a process plans to use the resource

A Monitor to Allocate Single Resource

```
monitor ResourceAllocator
{
   boolean busy;
   condition x;
   void acquire(int time) {
            if (busy)
               x.wait(time);
            busy = true;
   }
   void release() {
            busy = false;
            x.signal();
   }
   initialization code() {
    busy = false;
   }
}
```

Single Resource Monitor (Cont.)

- Usage:

```
acquire
 ...
release
```

- Incorrect use of monitor operations
  - **`release()`** … **`acquire()`**
  - **`acquire()`** … **`acquire())`**
  - Omitting of **`acquire()`** and/or **`release()`**

Liveness

- Processes may have to wait indefinitely while trying to acquire a synchronization tool such as a mutex lock or semaphore.
- Waiting indefinitely violates the progress and bounded-waiting criteria discussed at the beginning of this chapter.
- **Liveness** refers to a set of properties that a system must satisfy to ensure processes make progress.
- Indefinite waiting is an example of a liveness failure.

Liveness

- **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

```
        P0                    P1
   wait(S);              wait(Q);
   wait(Q);              wait(S);
    ...                   ...
   signal(S);            signal(Q);
   signal(Q);            signal(S);
```

- Consider if P_0 executes wait(S) and P_1 wait(Q). When P_0 executes wait(Q), it must wait until P_1 executes signal(Q)
- However, P_1 is waiting until P_0 execute signal(S).
- Since these signal() operations will never be executed, P_0 and P_1 are **deadlocked**.

Liveness

- Other forms of deadlock:
- **Starvation** – indefinite blocking
  - A process may never be removed from the semaphore queue in which it is suspended
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**

End of Chapter 6