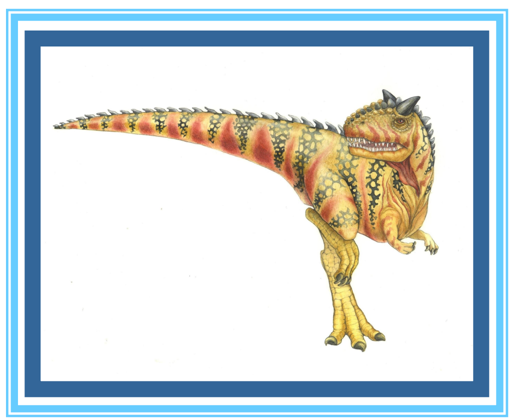
Chapter 6: Synchronization Tools



Outline

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

Objectives

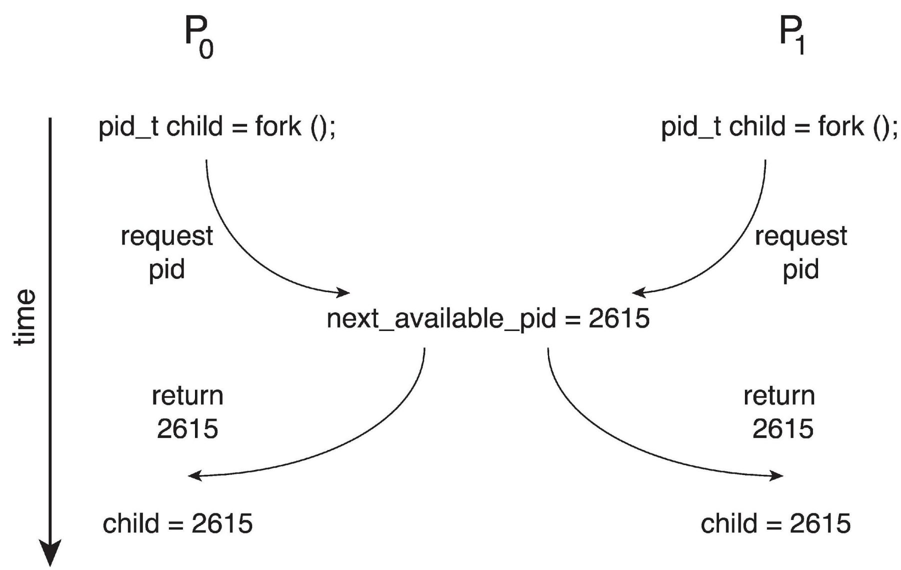
- Describe the critical-section problem and illustrate a race condition
- Illustrate hardware solutions to the critical-section problem using memory barriers, compare-and-swap operations, and atomic variables
- Demonstrate how mutex locks, semaphores, monitors, and condition variables can be used to solve the critical section problem
- Evaluate tools that solve the critical-section problem in low-, Moderate-, and high-contention scenarios

Background

- A system typically consists of several (perhaps hundreds or even thousands) of threads running either concurrently or in parallel. Threads often share user data.
- 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
- Several processes access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place, is called a race condition.
- Solution: Ensure that only one process at a time can be manipulating the variable count.

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 $\{p_0, p_1, \ldots p_{n-1}\}$
- Each process has **critical section** segment of code
  - Process may be changing common variables, updating table, writing file, etc.
  - When one process in critical section, no other may be in its critical section
- ***Critical section problem is to design a protocol that the processes can use to synchronize their activity so as to cooperatively share data.***
- Each process must ask permission to enter critical section in **entry section**, may follow critical section with **exit section**, then **remainder section**

Critical Section Problem

- Each process has a segment of code called a **critical section** : in which the process may be accessing — and updating — data that is shared with at least one other process.
- The section of code implementing request is the **entry section.**
- The critical section may be followed by an **exit section**.
- The remaining code is the **remainder section**.
- General structure of process ***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 the selection of the process 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

Interrupt-based Solution

- Entry section: disable interrupts

Before entering the critical section, interrupts are disabled. This ensures that no interrupt handling routines are executed while the critical section is being executed. Thus, it prevents interruption of the critical section by other interrupts.

- Exit section: enable interrupts

After the critical section is executed, interrupts are enabled again. This allows interrupt handling routines to resume their normal operation.

- Will this solve the problem?
  - What if the critical section is code that runs for an hour?
  - Can some processes starve – never enter their critical section.
  - What if there are two CPUs?

Software Solution 1

- Two process solution
- Assume that the **`load`** and **`store`** machine-language instructions are atomic (When an operation is atomic, it means that it will be executed completely or not at all, without interruption by other operations ; 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 0 and 1 at the same time

- What about the Progress requirement?
- What about the Bounded-waiting requirement?

Peterson’s Solution

- A classic software-based solution to the critical-section problem..
- Peterson’s solution is restricted to two processes that alternate execution between their critical sections and remainder sections. The processes are numbered P0 and P1. For convenience, when presenting Pi we use Pj to denote the other process; that is, j equals 1 – i.
- Peterson’s solution requires the two processes to share two data items:

```
int turn;
boolean flag[2];
```

- The variable turn indicates whose turn it is to enter its critical section. That is,

  if turn == i, then process Pi is allowed to execute in critical section.

- The flag array is used to indicate if a process is ready to enter its critical section.

For example, if flag[i] is true, Pi is ready to enter its critical section.

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

        /* critical section */

    flag[i] = false;

        /*remainder section */
}
```

Structure of Peterson’s solution

Peterson's Solution

- To enter the critical section, process Pi first sets **flag[i] to be true** and then sets **turn to the value** . thereby asserting that if the other process wishes to enter the critical section, it can do so. If both processes try to enter at the same time, turn will be set to both i and j at roughly the same time. Only one of these assignments will last; the other will occur but will be overwritten immediately.

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

        /* critical section */

    flag[i] = false;

        /*remainder section */
}
```

- The eventual value of turn determines which of the two processes is allowed to enter its critical section first.

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. Ex :Checkbook the actual order in which credit and debit operations are performed is unimportant, because the final balance will still be the same.
- For **multithreaded** the reordering may produce inconsistent or unexpected results as they share data !

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
```

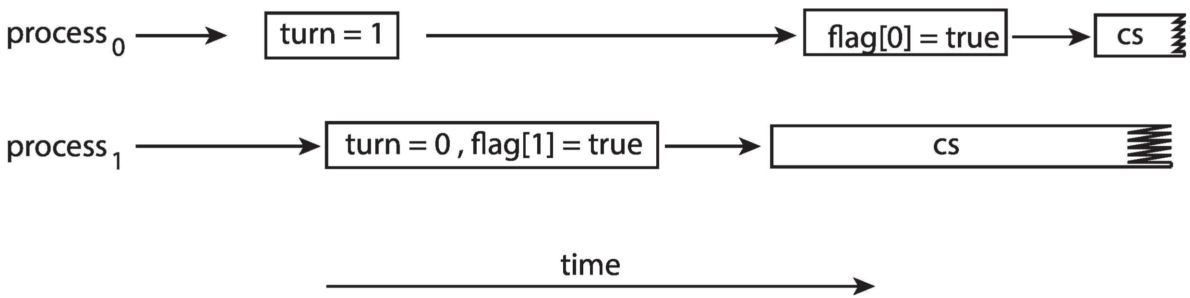
- What is the expected output? **100**
- However, since the variables flag and x are independent of each other, the instructions:

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**.

Hardware Support for Synchronization

- Memory Barriers
- Hardware Instructions
- Atomic Variables

Memory Barrier

- A system may reorder instructions, a policy that can lead to unreliable data states. How a computer architecture determines what memory guarantees it will provide to an application program is known as its **memory model.**
- 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.
- With respect to Peterson's solution, we could place a memory barrier between the first two assignment statements in the entry section to avoid the reordering of operations
- Memory barriers are considered very low-level operations and are typically only used by kernel developers when writing specialized code that ensures mutual exclusion.

Memory Barrier Example

- Returning to the example of slides 6.17 - 6.18
- 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`.

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 If the lock is available, a call to acquire() succeeds, and the lock is then considered unavailable. A process that attempts to acquire an unavailable lock is blocked until the lock is released.
- 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**
  - This lock therefore called a **spinlock**

```
while (true) {
      acquire lock

          critical section

      release lock

   remainder section
}
```

Hardware Instructions

- Many systems provide hardware support for implementing the critical section code.
- Many modern computer systems provide special hardware instructions that allow either to test and modify the content of a word or to swap the contents of two words atomically
  - **Test-and-Set** instruction
  - **Compare-and-Swap** instruction
- Uniprocessors – could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- We will look at three forms of hardware support:

1. Hardware instructions
2. Atomic variables

The test_and_set Instruction

- Definition

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

Ex : | Lock=F add=10 0 | Target =100 | rv = F | Now Lock=T |

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

Solution Using test_and_set()

- If the machine supports the test and set() instruction, then we can implement mutual exclusion by declaring a 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.

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.
- 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));
}
```

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** **(Running on Entry code)**

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

- Definition of the **`signal()` operation** **(Running on exit code)**

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

Busy Wait: It means the loop will continue running indefinitely until the condition is false

Semaphore (Cont.)

- **Counting semaphore** – integer value can range over an unrestricted domain
- **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
- With semaphores we can solve various synchronization problems

Semaphore Usage Example

- Solution to the CS Problem
  - Create a semaphore "**mutex**" initialized to 1 (Which kind Semaphore?)

```
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

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;
      block();
   }
}

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

Problems with Semaphores

- Incorrect use of semaphore operations:
  - **signal(mutex) …. wait(mutex)**

    In correct usage, processes acquire the semaphore before entering a critical section (using wait(mutex)) and release it afterward (using signal(mutex)).

  - **wait(mutex) … wait(mutex)**

    Multiple wait(mutex) operations without corresponding signal(mutex): This scenario leads to a **deadlock** situation. Each wait(mutex) operation decrements the semaphore value, and if the semaphore's value becomes negative, the process will block. However, without any corresponding signal(mutex) operation to increment the semaphore value, the blocked processes will remain stuck indefinitely, resulting in a deadlock.

  - **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.

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:

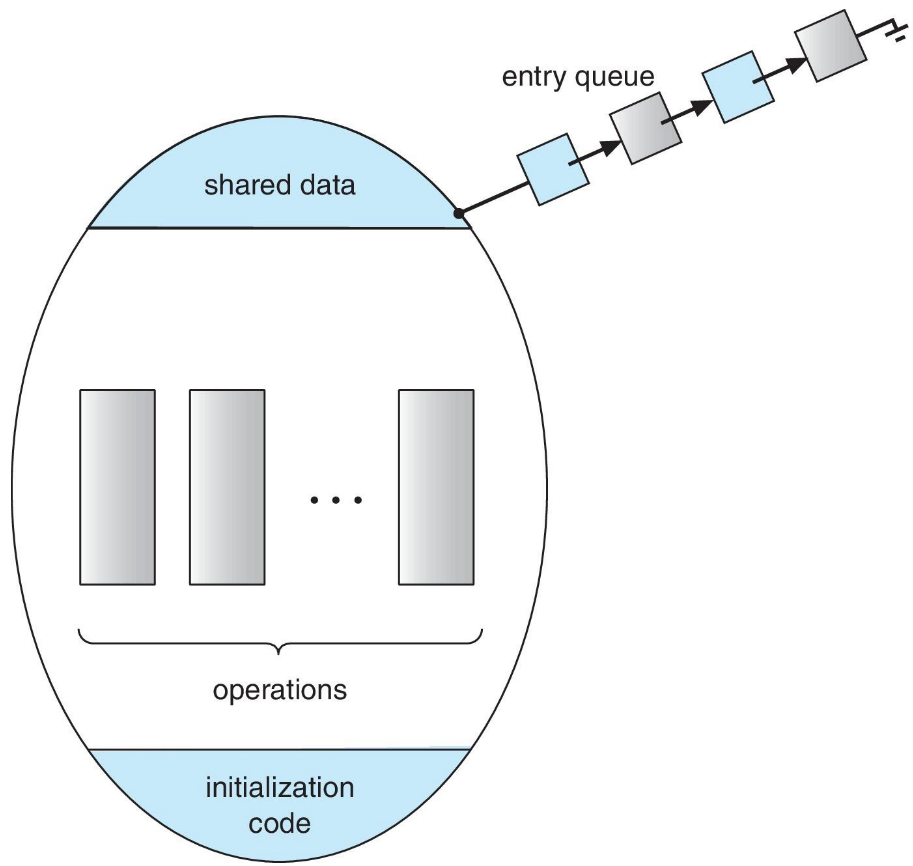
```
monitor monitor-name
{
  // shared variable declarations
  procedure P1 (…) { …. }

  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

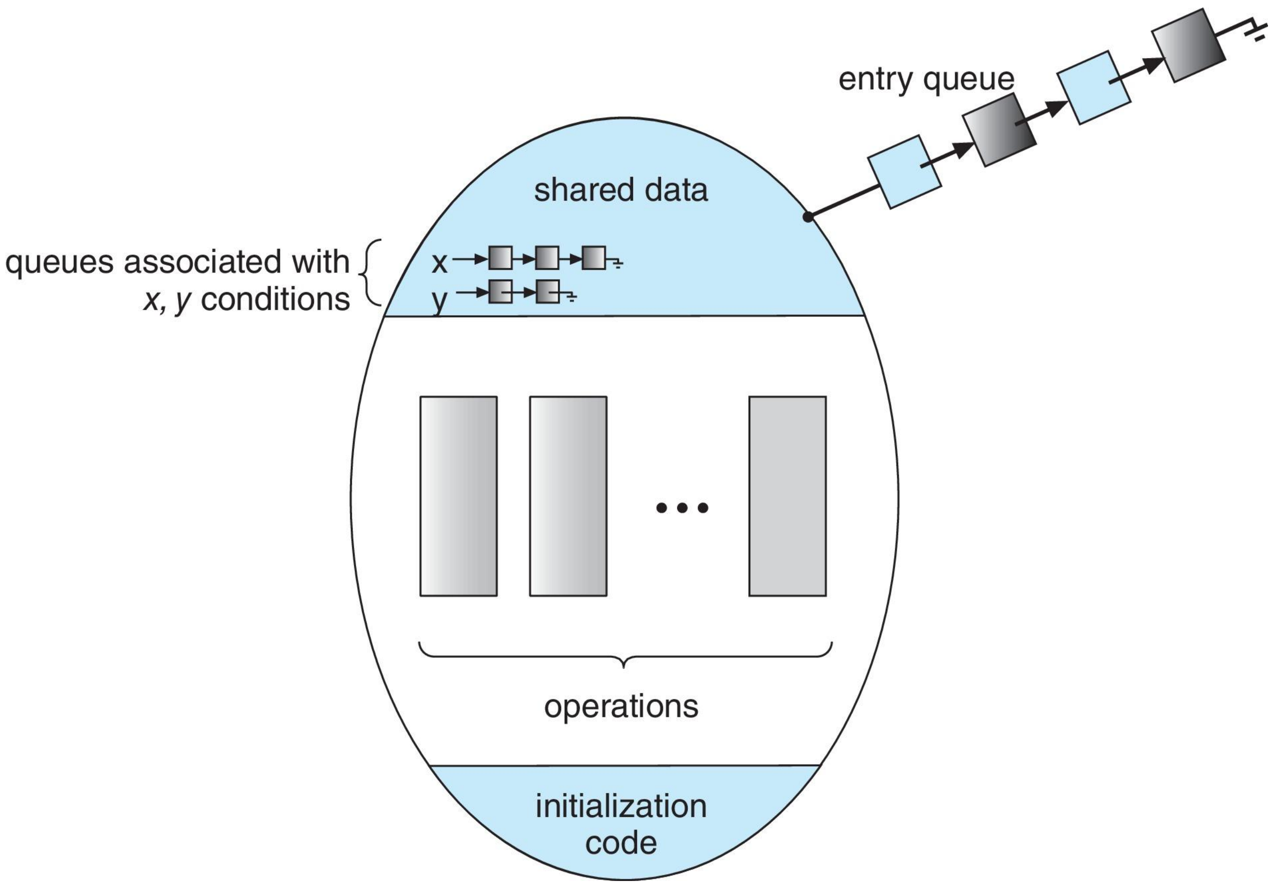
```
wait(mutex);
    …
            body of P;
    …
signal(mutex);
```

- Mutual exclusion within a monitor is ensured
- Ensures that only one procedure can execute its critical section at a time. By encapsulating each procedure with wait(mutex) and signal(mutex), the code guarantees mutual exclusion, preventing race conditions and ensuring that critical sections are executed safely without interference from other processes.

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

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

R.release;
```

- Where R is an instance of type **`ResourceAllocator`**

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