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 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


Software Solution: Peterson's Algorithm

- Good algorithmic software solution
- Two process solution
- 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]`
- 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 P_i is ready!


Algorithm for Process P_i

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

              critical section

        flag[i] = false;

              remainder section

} while (true);
```


Peterson's Solution (Cont.)

- 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
- What about a solution to N > 2 processes


Busy Waiting

- All the software solutions we presented employ “busy waiting”
  - A process interested in entering the critical-section is stuck in a loop asking continuously

    “can I get into the critical-section”
- Busy waiting is a pure waste of CPU cycles

Solution to Critical-section Problem Using Locks

- Many systems provide hardware support for implementing the critical section code.
- All solutions are based on idea of **locking**
  - Two processes can not have a lock simultaneosly.
- Code:

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

Synchronization Hardware

- Modern machines provide special atomic hardware instructions to implement locks
  - **Atomic** = non-interruptible
- Two types instructions:
  - Test memory word and set value
  - Swap contents of two memory words


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
- Each process, wishing to execute critical-section code:

```
do {
        while (test_and_set(&lock))
        ; /* do nothing */
            /* critical section */
    lock = false;
            /* remainder section */

} while (true);
```

- What about bounded waiting?
- Solution results in busy waiting.


Bounded-waiting Mutual Exclusion with test_and_set

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


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 “value” to “new_value ” but only if “value” == “expected”.

That is, the swap takes place only under this condition.


Solution using compare_and_swap

- Shared integer "lock" initialized to 0;
- Solution:

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

- What about bounded waiting?
- Solution results in busy waiting.


Mutex Locks

- Previous solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest tools is the **Mutex lock,** which has a Boolean variable "available" associated with it to indicate if the lock is available or not.
- Two operations available to access a Mutex Lock:
  - ```
    acquire() {
       while (!available)
              ; /* busy wait */
       available = false;
    }
    ```
  - ```
    release() {
       available = true;
    }
    ```


Mutex Locks (Cont.)

- Calls to `acquire()` and `release()` are atomic
  - Usually implemented via hardware atomic instructions
- Usage:

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

- Solution requires **busy waiting**
  - This lock is therefore called a **spinlock**


Semaphores

- 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 = S - 1;
}
```

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

```
signal(S) {
   S = S + 1;
}
```


Semaphore Usage

Can solve various synchronization problems

- A solution to the CS problem.
  - Create a semaphore "**synch**" initialized to 1

```
wait(synch)
    CS
signal(synch);
```

- Consider P_1 and P_2 that require code segment S_1 to happen before code segment S_2
  - Create a semaphore "**synch**" initialized to 0

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


Types of Semaphores

- **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

Counting Semaphores Example

- Allow at most two process to execute in the CS.
- Create a semaphore "**synch**" initialized to 2

```
wait(synch)
    CS
signal(synch);
```


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
- This implementation is based on **busy waiting** in critical section implementation (that is, the code for `wait()` and `signal()`)
  - But implementation code is short
  - Little busy waiting if critical section rarely occupied
- Can we implement semaphores with no busy waiting?


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

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

- Two operations:
  - **block ()** – place the process invoking the operation on the appropriate waiting queue
  - **wakeup (P)** – remove one of processes in the waiting queue and place it in the ready queue


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);
        }
    }
  ```


Implementation with no Busy waiting (Cont.)

- Does the implementation ensure the “progress” requirement?
- Does implementation ensure the “bounded waiting” requirement?

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
- **Priority Inversion** – Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Solved via **priority-inheritance protocol**


Problems with Semaphores

- Incorrect use of semaphore operations:
  - signal (mutex) …. wait (mutex)
  - wait (mutex) … wait (mutex)
  - Omitting of wait (mutex) or signal (mutex) (or both)
- Deadlock and starvation are possible.
- Solution – create high-level programming language constructs


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

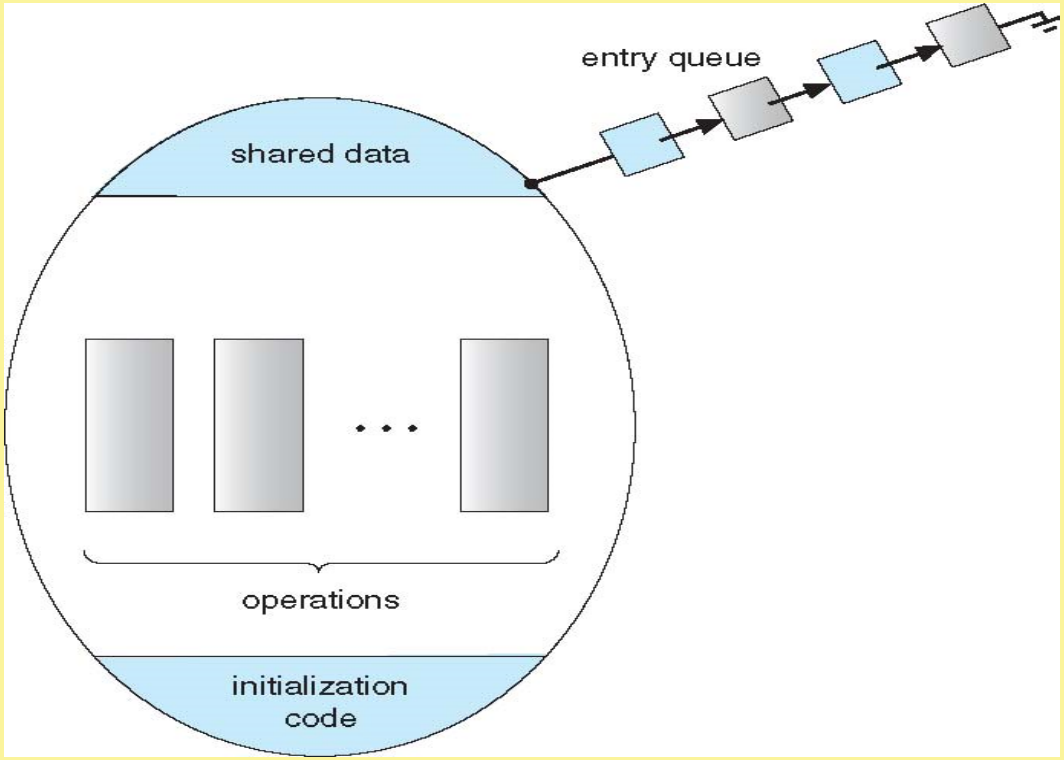
```
monitor monitor-name
{
  // shared variable declarations
  procedure P1 (…) { …. }

  procedure Pn (…) {……}

     Initialization code (…) { … }
  }
}
```

- Mutual exclusion is guaranteed by the operating system.

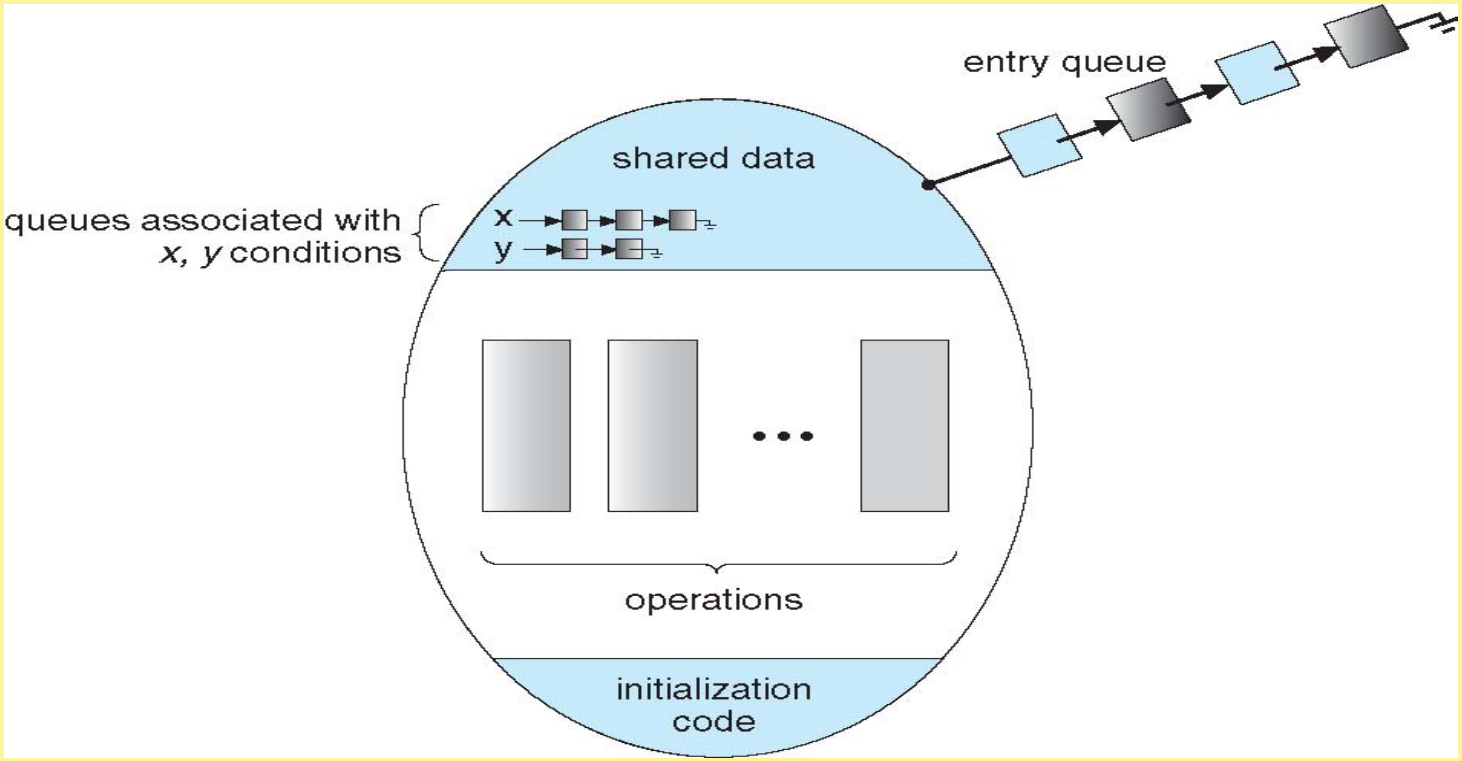

Schematic view of a Monitor



Condition Variables

- Need mechanism to allow a process wait within a monitor
- Provide condition variables.
- A condition variable (say **`x`**) can be accessed only via two operations:
  - **`x.wait()`** – a process that invokes the operation is suspended until another process invoked **`x.signal()`**
  - **`x.signal()`** – resumes one of processes (if any) that invoked **`x.wait()`**
    - If no process is suspended on variable **`x`** , then it has no effect on the variable


Monitor with Condition Variables



Condition Variables Choices

- If process P invokes `x.signal()`, and process Q is suspended in `x.wait()`, what should happen next?
  - Both Q and P cannot execute in parallel. If Q is resumed, then P must wait
- Options include:
  - **Signal and wait** – P either waits until Q leaves the monitor or it waits for another condition
  - **Signal and continue** – Q either waits until P leaves the monitor or it waits for another condition


Condition Variables Choices (Cont.)

- There are reasonable arguments in favor of adopting either option.
  - Since P was already executing in the monitor, the signal-and-continue method seems more reasonable.
  - However, if we allow P to continue, by the time Q is resumed, the logical condition for which Q was waiting may no longer hold.
- A compromise between these two choices was adopted in the language Concurrent Pascal. When P executes the signal operation, it immediately leaves the monitor. Hence, Q is immediately resumed.


Languages Supporting the Monitor Concept

- Many programming languages have incorporated the idea of the monitor as described in this section, including Java and C#.
- Other languages such as Erlang provide concurrency support using a similar mechanism.

Monitor Implementation

- For each monitor, a semaphore **`mutex`** is provided.
- A process must execute **`wait(mutex)`** before entering the monitor and must execute **`signal(mutex)`** after leaving the monitor. This is ensured by the compiler.
  - We use the "signal and wait" mechanism to handle the signal operation.
- Since a signaling process must wait until the resumed process either leaves or it waits, an additional semaphore, **`next`**, is used.
- The signaling processes can use **`next`** to suspend themselves.
- An integer variable **`next_count`** is provided to count the number of processes suspended on **`next`**


Monitor Implementation (Cont.)

- Variables

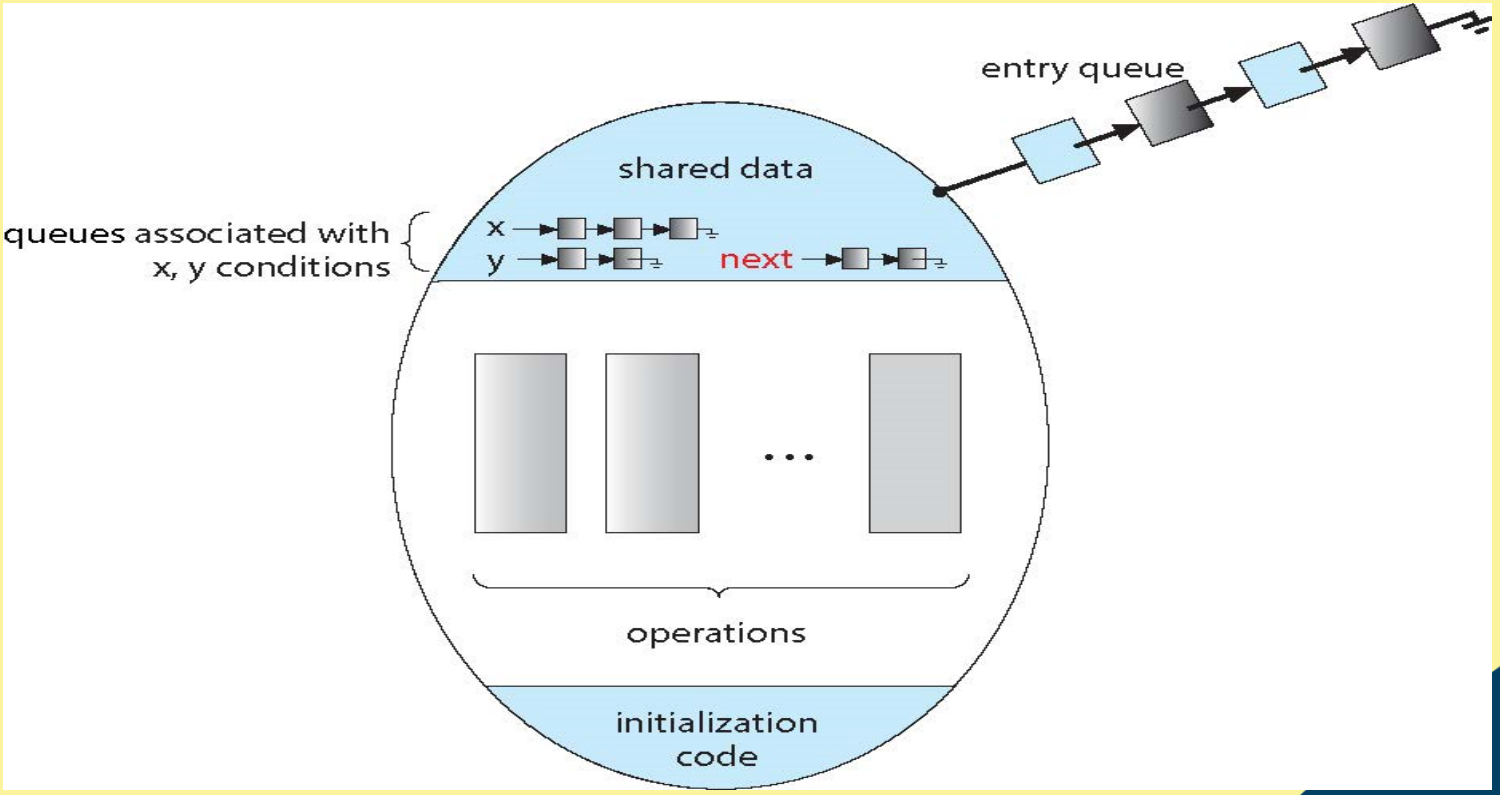
```
semaphore mutex;  // (initially  = 1)
semaphore next;   // (initially  = 0)
int next_count = 0;
```

- Each procedure ***F*** will be replaced by

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

- Mutual exclusion within a monitor is ensured


Monitor with Next Semaphore



Condition Variables Implementation

- 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--;
```


Condition Variables 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 are queued on condition **`x`**, and **`x.signal()`** is executed, which one should be resumed?
- FCFS frequently not adequate
- **conditional-wait** construct of the form x.wait(c)
  - Where c is **priority number**
  - Process with lowest number (low number ➔ highest priority) is scheduled next
- Some languages provide a mechanism to find out the PID of the executing process.
  - In C we have **`getpid()`**, which retunes the PID of the calling process


Resource Allocator Monitor Example

- A monitor to allocate a single resource among competing processes
- Each process, when requesting an allocation of this resource, specifies the maximum time it plans to use the resource. The monitor allocates the resource to the process that has the shortest time-allocation request.

```
monitor ResourceAllocator
{
        boolean busy;
        condition x;

        void acquire(int time) {
             if (busy)
                x.wait(time)
             busy = true;
        }

        void release () {
             busy = false;
             x.signal();
        }

             busy= false;
        }
```


Resource Allocator Monitor Example (Cont.)

- A process that needs to access the resource in question must observe the following sequence:

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

where R is is an instance of type ResourceAllocator

Observation the Resource Allocator Example

- Incorrect use of the operations:
  - R.release …. R.acquire(t)
  - R.acquire(t) …. R.acquire(t)
  - Omitting of acquire and or release (or both)
- Solution exist but not covered in this course


Conclusion

Conclusion:

- Mutual exclusion must be provided between cooperating sequential processes
- User coded solutions are primitive
- Semaphores may be used
- Higher-level primitives like monitors may be used


NPTEL ONLINE CERTIFICATION COURSES

Thank you

Operating System Fundamentals

Santanu Chattopadhyay
Electronics and Electrical Communication Engg.

Synchronization Examples

Concepts Covered:

- Examine classical process-synchronization problems
- Tools used to solve process synchronization problems

Classical Problems of Synchronization

- Classical problems used to test newly-proposed synchronization schemes
  - Bounded-Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem
- We will present solutions using:
  - Semaphores.
  - Monitors
  - Various operating systems

Semaphore Solutions

Bounded-Buffer Problem

- *n* buffers, each can hold one item
- Semaphore `mutex` initialized to the value 1
- Semaphore `full` initialized to the value 0
- Semaphore `empty` initialized to the value *n*

Bounded Buffer Problem (Cont.)

- The structure of the producer process

```
do {
   ...
   /* produce an item in next_produced */
   ...
   wait(empty);
   wait(mutex);
   ...
   /* add next produced to the buffer */
   ...
   signal(mutex);
   signal(full);
} while (true);
```


Bounded Buffer Problem (Cont.)

- The structure of the consumer process

```
do {
    wait(full);
    wait(mutex);
        ...
    /* remove an item from buffer to next_consumed */
        ...
    signal(mutex);
    signal(empty);
        ...
    /* consume the item in next consumed */
        ...
} while (true);
```


Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do ***not*** perform any updates
  - Writers – can both read and write
- Problem – allow multiple readers to read at the same time
  - Only one single writer can access the shared data at the same time
- Several variations of how readers and writers are considered – all involve some form of priorities
- Shared Data
  - Semaphore **`rw_mutex`** initialized to 1
  - Semaphore **`mutex`** initialized to 1
  - Integer **`read_count`** initialized to 0


Readers-Writers Problem (Cont.)

- The structure of a writer process

```
do {
        wait(rw_mutex);
                ...
        /* writing is performed */
                ...
        signal(rw_mutex);
 } while (true);
```


Readers-Writers Problem (Cont.)

- The structure of a reader process

```
do {
    wait(mutex);
    read_count++;
    if (read_count == 1)
       wait(rw_mutex);
    signal(mutex);

        ...
    /* reading is performed */

        ...
    wait(mutex);
    read_count--;
    if (read_count == 0)
       signal(rw_mutex);
    signal(mutex);
} while (true);
```


Readers-Writers Problem Variations

- ***First*** variation – no reader kept waiting unless writer has permission to use shared object
- ***Second*** variation – once writer is ready, it performs the write ASAP
- Both may have starvation leading to even more variations
- Problem is solved on some systems by kernel providing reader-writer locks

Dining-Philosophers Problem

- Philosophers spend their lives alternating thinking and eating
- They do not interact with their neighbors, occasionally try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both to eat, then release both when done
- In the case of 5 philosophers, the shared data:
  - Bowl of rice (data set)
  - Semaphore chopstick [5] initialized to 1