Operating Systems: Synchronization Tools and Examples – Part II

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Semaphore

- Semaphores is a synchronization tool that provides more sophisticated ways (other than Mutex locks) for processes to synchronize their activities.
- Semaphore ***S*** – integer variable (usually initialized with a +ve integer)
- Can only be accessed via two indivisible (**atomic**) operations
  - **`wait()`** and **`signal()`**
    - Originally called **`P()`** and **`V()`**

Semaphore – Wait(S) and Signal() Operations

- **Wait() operation:** Decreases the Semaphore (S) value only if S > 0

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

- **Signal() operation:** Increases the Semaphore (S) value.

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

Semaphore Usage

- Semaphores can solve various synchronization problems
  - Used as locks (*binary semaphores*)
  - Used to control access to a given resource consisting of a finite number of instances (*counting semaphore*)
  - To solve synchronization problems (may or may not access shared data)

Binary Semaphore

- **Binary semaphore** – integer value (S) can range only between 0 and 1
  - Initially, semaphore S = 1 (lock is available), S = 0 (lock is unavailable).
  - Behaves like a mutex lock.

```
do {
      wait(S);
      /*critical section*/
      Signal(S);
      /*remainder section*/
} while (TRUE);
```

Counting Semaphore

- **Counting semaphore** – integer value (`S`) can range over an unrestricted domain.
  - Used to control access to finite instances (`N`) of a resource.
  - Initially, `S = N` *(all instances of resource available)*
  - *To* acquire the resource: processes perform `wait(S)`
  - *To* release the resource (after use) - processes perform `signal(S)`
  - `S = 0`, *implies all instances of the resource are being used*
  - Waiting processes *block or is busy waiting* until `S > 0` *(an instance of resource is available)*

Semaphores – synchronization problems

Question 1: Consider two concurrently running processes $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ that require $\boldsymbol{P_1}$ to execute before $\boldsymbol{P_2}$ (here $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$ may or may not access/modify shared variables.). Use semaphores to synchronize processes $\boldsymbol{P_1}$ and $\boldsymbol{P_2}$.

Semaphores – synchronization problems

Solution to Question 1:

- Create a semaphore.
- Initialize `synch = 0`

P1:

```
S1;
signal(synch);
```

P2:

```
wait(synch);
S2;
```

Semaphores – synchronization problems Example

Question 2: Illustrate how you would use semaphores to synchronize processes P_1, P_2, P_3, P_4 where P_1 is executed before P_2, P_2 is executed before P_3, P_3 is executed before P_4.

Semaphores – synchronization problems Example

Solution to Question 2: Initialize $synch_1$, $synch_2$, $synch_3 = 0$

P_1:

```
S1;
signal(synch1);
```

P_2:

```
wait(synch1);
S2;
signal(synch2)
```

P_3:

```
wait(synch2);
S3;
signal(synch3);
```

P_4:

```
wait(synch3);
S4;
```

Semaphores studied so far suffer from busy waiting!

Semaphore Implementation with no Busy waiting

- With each semaphore there is an associated waiting queue
- Each semaphore has two data items:
  - value (of type integer)
  - pointer to the list of processes waiting
- **Semaphore Structure**

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

- **`wait()`** and **`signal()`** operations are atomic.
- Two additional operations: **`block()`** and **`wakeup()`**

Semaphore Implementation with no Busy waiting

Wait Operation:

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

block() – places the process invoking the operation on the appropriate waiting queue

Signal Operation:

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

wakeup() – removes a processes in the waiting queue and places it in the ready queue

Semaphore Implementation with no Busy waiting

- Note that in this implementation, semaphore values may be negative
- If a semaphore value is negative, its magnitude is the number of processes waiting on that semaphore.
- Implementation of semaphores using waiting queues <u>may</u> result in **Deadlock and/or starvation**.

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

Semaphores in C

- Semaphores are not part of Pthread standards and instead they belong to the POSIX SEM extension.
- To use semaphores in C on a Linux machine include ‘semaphore.h’ header file:
    - `#include <semaphore.h>`
  - `sem_t` data type for semaphores.
  - semaphores created with `sem_init()` function.
    - `Sem_init()` - Takes 3 arguments:
      1. Pointer to the semaphore
      2. Flag indicating the level of sharing
      3. The semaphore’s initial value
  - `sem_wait();`
  - `sem_post();`

Semaphores in C

```
/*Declaring Semaphore*/

Sem_t sem;

/*Initialize Semaphore*/

if (sem_init(&sem, 0, n) !=0){

     printf("Error in initializing empty semaphore \n"

}

/* acquire the semaphore */

sem_wait(&sem);

/* critical section */

/* release the semaphore */

Sem_post(&sem);
```

sem_init arguments
1. pointer to the semaphore
2. flag indicating the level of sharing
3. The semaphore’s initial value

Returns 0 when semaphore created with no errors, otherwise returns non zero value.

Problems with Semaphores

- Incorrect use of semaphore operations could result in mutual exclusion being violated, deadlock and/or starvation.
- Consider the following situation:
  - Processes share a Semaphore **`mutex,`** which is initialized to 1.
- Suppose that a process interchanges the order in which the `wait()` and `signal()` operations on the semaphore `mutex` are executed. That is, it executes

```
signal(mutex);

...

critical section

...

wait(mutex);
```

- **What is the problem with the above code?**

Problems with Semaphores

- Suppose that a process replaces `signal(mutex)` with `wait(mutex)`.

  That is, it executes

```
wait(mutex);

...

critical section

...

wait(mutex);
```

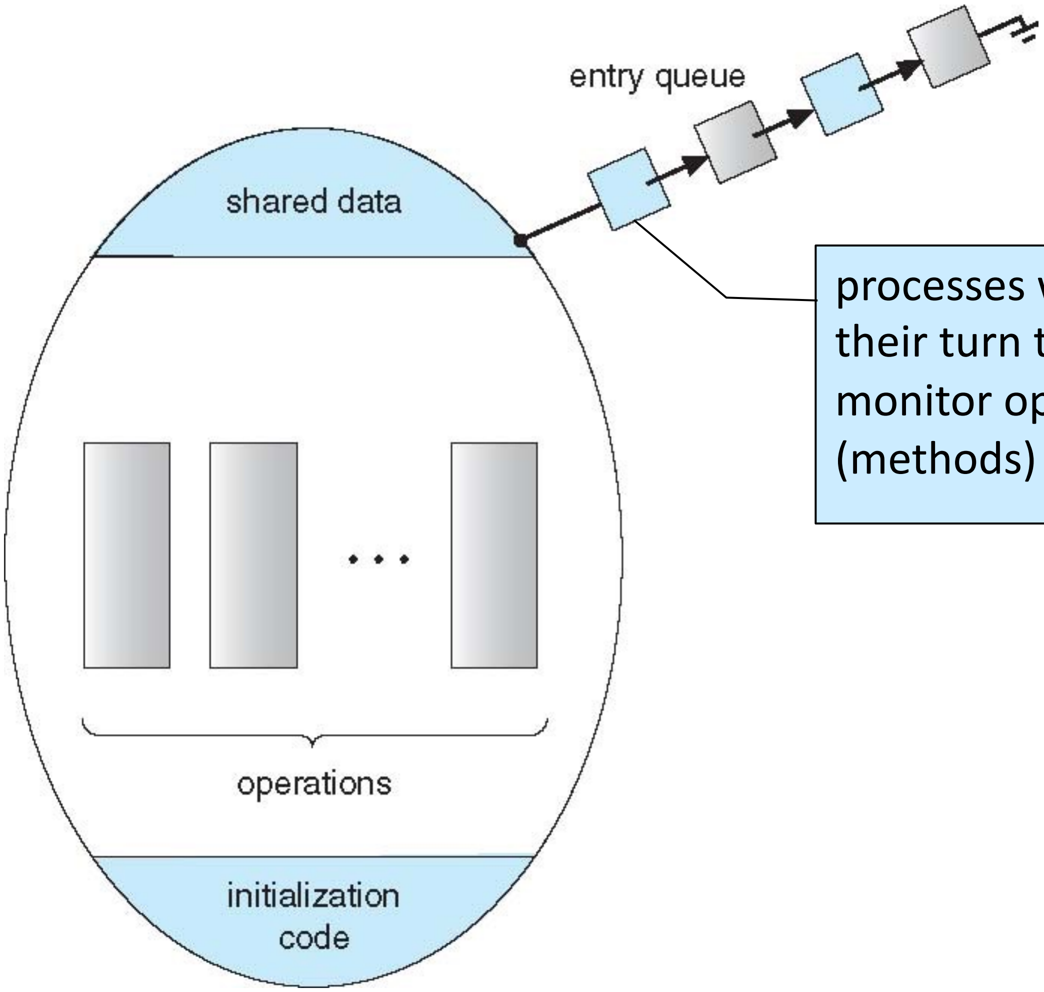
What is the problem here?

- Omitting of `wait(mutex)` or `signal(mutex)` (or both)
  - Deadlock and starvation are possible.

Monitors

- **Monitor** is a high-level abstraction that provides a convenient and effective mechanism for process synchronization.
- A **monitor type** is an ADT has
  - Private data members
  - Public functions that are implicitly executed with mutual exclusion.
    - For each monitor instance there exists a mutual exclusion lock.
    - To enter the monitor, a process acquires the mutual exclusion lock
    - While exiting the monitor, a process releases the lock, and therefore the monitor, for other threads.

Schematic view of a Monitor



processes waiting their turn to execute monitor operations (methods)

Syntax of Monitor

```
monitor monitor-name
{
    shared variable declarations

    procedure P1 (…) { … }
    .
    .
    .
    procedure Pn (…) {……}

    initialization code (…) { … }

}
```

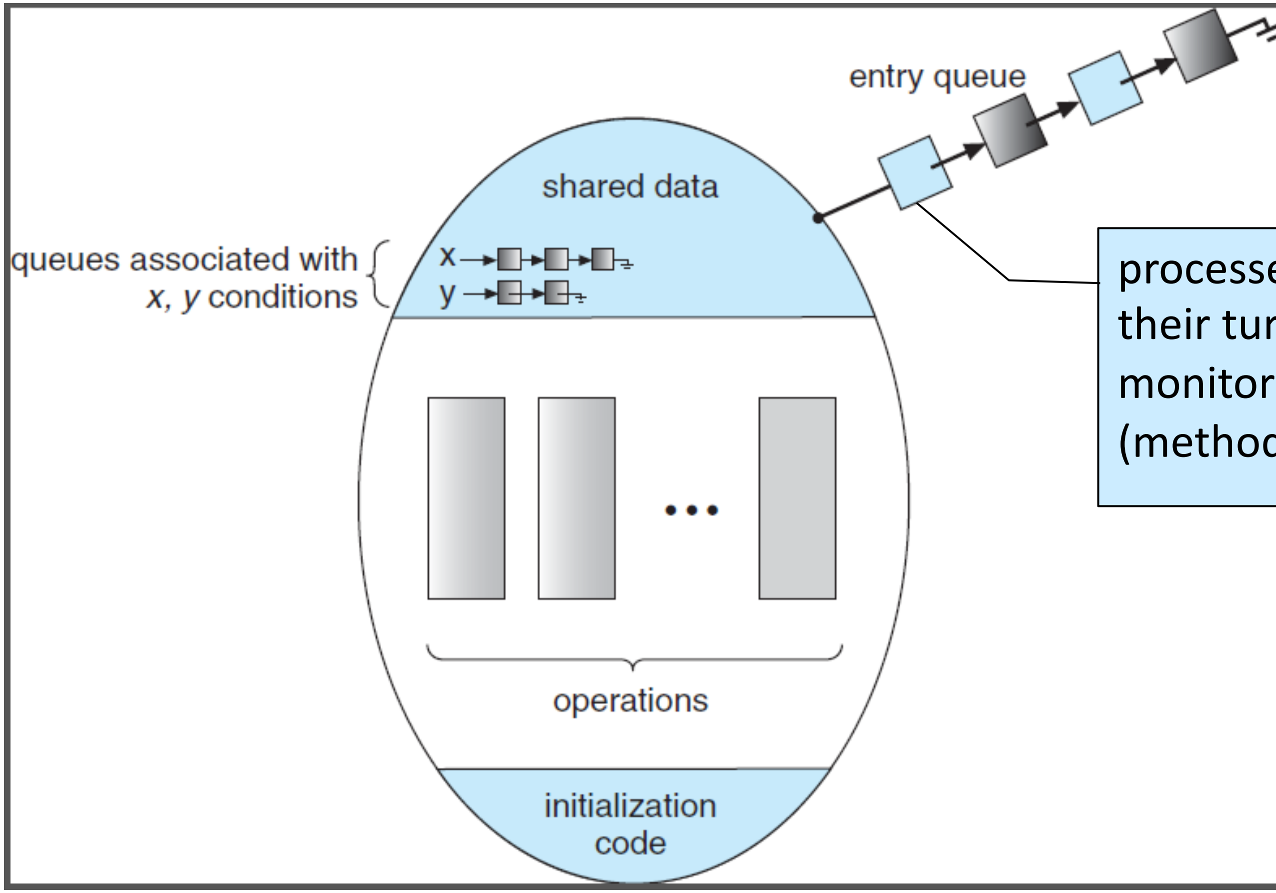
Monitor Example

```
monitor BankAccount {
      private: int amount;
      void BankAccount_init(){
            amount = 0;
      }
      void withdraw(int value){
            amount = amount - value;
      }
      void deposit(int value){
            amount = amount + value;
      }
};
```

Condition Variables

- Monitor construct defined so far is not powerful for modelling some synchronization schemes.
- Condition variables (CV) are additional mechanisms to achieve the above and defined as: **`condition x, y;`**
- They have legal atomic operations: `wait() and signal()`
- Operations accessed as `x.wait(), x.signal()`
- **`x.wait()`** – blocks the process and adds it to a queue associated with x.
- **`x.signal()`** – wakes up exactly one process from x's queue of waiting processes.
  - ➢ If no processes waiting, then does nothing.

Monitor with Condition Variables



processes waiting their turn to execute monitor operations (methods)

Monitor Example with Condition Variables

- How to ensure the following two conditions are met:
  - Deposits do not take place if amount >= 500
  - Withdrawals do not take place if amount <=0
- Assume that the value deposited/withdrawn is the same.

```
monitor BankAccount {
        int amount;
        condition c1, c2;

        void BankAccount_init(){
                amount = 0;
        }
        void withdraw(int value){
                if(amount <=0){c1.wait();}
                amount = amount - value;
                c2.signal();
        }
        void deposit(int value){
                if(amount >=500){c2.wait();}
                amount = amount + value;
                c1.signal();
        }
};
```

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 in the monitor. If Q is resumed, then P must wait
- Options include
  - **Signal and wait** – P waits until Q either leaves the monitor or it waits for another condition
  - **Signal and continue** – Q waits until P either leaves the monitor or it waits for another condition
  - Both have pros and cons – language implementer can decide

Resuming Processes within a Monitor

- If several processes queued on condition x, and `x.signal()` executed, which should be resumed?
  - FCFS (first come first serve) frequently not adequate
- **conditional-wait** construct of the form `x.wait(c)`
  - where c is **priority number**
  - process with ***lowest number*** (highest priority) is scheduled next

Classical Problems of Synchronization

- Bounded-Buffer Problem (Producer - Consumer Problem) (discussed in part I)
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded-Buffer Problem – Semaphore Solution

- ***n*** buffers, each can hold one item
- Semaphore **`mutex`** initialized to the value 1
  - `mutex = 1 =>` indicates that `mutex` lock is available
  - `mutex = 0 =>` indicates that `mutex` lock is unavailable
- Semaphore **`full`** initialized to the value 0, as initially the number of filled slots in the buffers is zero.
- Semaphore **`empty`** initialized to the value n, as initially the number of empty slots in the buffer is n.

Bounded Buffer Problem – Semaphore Solution (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);
```

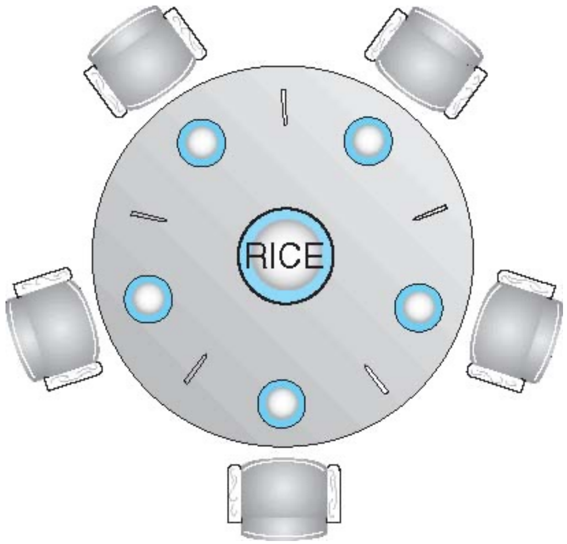
Bounded Buffer Problem Semaphore Solution (Cont.)

- 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);
```

Dining-Philosophers Problem

- Philosophers spend their lives alternating between thinking and eating
- Don't interact with their neighbors
- Occasionally try to pick up 2 chopsticks (one at a time) to eat from a bowl
- Need both chopsticks to eat, then release both when done



Dining-Philosophers Problem Semaphore Solution

In the case of 5 philosophers

- Shared data
  - Bowl of rice (data set) – assumed infinite
  - Semaphore chopstick [5] initialized to 1 (indicates its available)

Dining-Philosophers Problem Algorithm Semaphore Solution

The structure of Philosopher *i*:

```
do {
    wait (chopstick[i] );
    wait (chopstick[ (i + 1) % 5]);

            // eat

    signal (chopstick[i] );
    signal (chopstick[ (i + 1) % 5]);

                    // think
} while (TRUE);
```

What is the problem with this algorithm?

Dining-Philosophers Problem Algorithm

- Consider the following scenario in which all the philosophers are hungry and try to eat at the same time.
- Each philosopher grabs the chopstick to their right (`chopstick[i]`).
- Each semaphore `chopstick[i]=0`, where `0<=i<=4`.
- When each philosopher tries to grab her left chopstick (`chopstick[i+1]% 5`), she will be delayed forever. Thus resulting in a *deadlock*.

Dining-Philosophers Problem Algorithm (Cont.)

- Deadlock can be handled by
  - Allowing at most 4 philosophers to be sitting simultaneously at the table.
  - Allow a philosopher to pick up the forks only if both are available (picking must be done in a critical section).
  - Use an asymmetric solution -- an odd-numbered philosopher picks up first the left chopstick and then the right chopstick. Even-numbered philosopher picks up first the right chopstick and then the left chopstick.