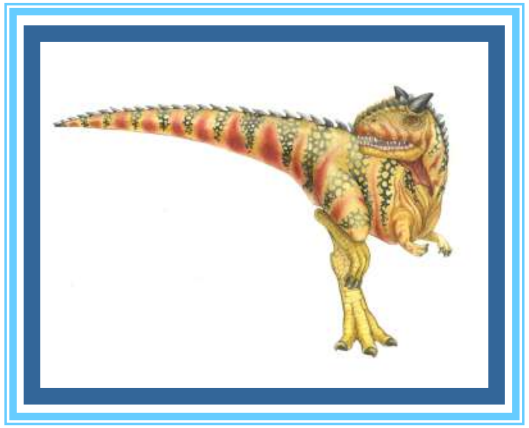
Chapter 5: Process Synchronization



Discussed till now

- Race condition
  - Demonstration through Producer-Consumer problem

- Critical Section Problem
  - Requirements for solutions to the problem

- Solutions to Critical Section Problem
  - Software solution – Peterson's algorithm
  - Hardware solutions (special atomic instructions) -
    - test_and_set( )
    - compare_and_swap( )

Mutex Locks

Mutex Locks

- Previous hardware-based solutions are complicated and generally inaccessible to application programmers
- OS designers build software tools to solve critical section problem
- Simplest such tool is mutex lock

- Protect a critical section by first **`acquire()`** a lock then **`release()`** the lock
  - Boolean variable indicating if lock is available or not

- Calls to **`acquire()`** and **`release()`** must be atomic
  - Usually implemented via hardware atomic instructions

acquire() and release()

- ```
  acquire() {
      while (!available)
          ; /* busy wait */
      available = false;;
  }
  ```

- ```
  release() {
      available = true;
  }
  ```

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

Mutex Locks – adv and disadv

- Disadvantage
  - Requires busy waiting (wastage of CPU cycles that some other process could have used)
  - This type of mutex lock is also called a spinlock (process "spins" while waiting for the lock to become available)

- Advantages
  - No context switch when a process must wait on a lock
  - Useful when locks are expected to be held for short time intervals
  - Can be employed on multiprocessor systems where one thread can "spin" on one processor while another thread performs its critical section on another processor

Mutex Locks for threads

```
int pthread_mutex_init(pthread_mutex_t *mutex,
                       const pthread_mutexattr_t *attr);


int pthread_mutex_lock(pthread_mutex_t *mutex);


int pthread_mutex_unlock(pthread_mutex_t *mutex);


int pthread_mutex_destroy(pthread_mutex_t *mutex);
```

Mutex Locks for threads (contd.)

```
pthread_mutex_t  lock;    // global variable

if (pthread_mutex_init(&lock, NULL) != 0){
   printf("Error");
   return 1;
}
...
...
pthread_mutex_lock(&lock);
<critical section>
pthread_mutex_unlock(&lock);
...
...
pthread_mutex_destroy(&lock);
```

Semaphores

Semaphore

- Synchronization tool that provides more sophisticated ways (than Mutex locks) for process to synchronize their activities.
- Semaphore ***s*** – integer variable
- Can only be accessed via two indivisible / atomic operations (apart from initialization)
  - **`wait()`** and **`signal()`**
  - Originally called **`P()`** and **`V()`**
  - P() possibly from "proberen" (to test)
  - V() possibly from "verhogen" (to increase)

Semaphore operations

- Definition of the wait( ) operation

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

- Definition of the signal( ) operation

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

- Note: both these operations must be atomic (executed indivisibly)

Types of Semaphore

- **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**

Semaphore Usage

- Can solve various synchronization problems
  - Mutual exclusion
  - Process synchronization
  - Resource counting
- Use a binary semaphore ***s*** (value can be 0 or 1)
  - Initialize ***s*** to 1
  - Every cooperating process has this structure:

```
Pi:
    wait(s);
    <Critical section>
    signal(s);
    <Remainder section>
```

Semaphore Usage

- Can solve various synchronization problems
  - Mutual exclusion
  - Process synchronization
  - Resource counting

- Consider P_1 (containing statement S_1) and P_2 (containing statement S_2) that require S_1 to happen before S_2

  Create a semaphore "**synch**" initialized to 0

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

Semaphore Usage

- Can solve various synchronization problems
  - Mutual exclusion
  - Process synchronization
  - Resource counting

- We want to keep track of a given resource with a finite number of instances
- Use a counting semaphore whose value can range over an unrestricted domain
  - Initialize to the number of instances available
  - Each process that wishes to use an instance of the resource performs wait( )
  - When a process releases its instance of the resource, perform signal( )

- Can this be used to solve a problem we have discussed earlier?

Semaphore Implementation

- Must guarantee that no two processes can execute the **wait()** and **signal()** on the same semaphore at the same time

- Applications may spend lots of time in critical sections; hence important to avoid busy waiting in the implementation of **wait()** and **signal()**

Avoiding busy waiting

- With each semaphore there is an associated waiting queue

- If a process executes **wait(s)** and finds that the semaphore **s** value is not positive, process blocks itself
  - Place the process into the waiting queue for **s**
  - Control transfer to CPU scheduler for selecting next process to execute

- If a process executes **signal(s)**
  - A process that is blocked on **s** should be restarted
  - Move this process from waiting queue to ready queue

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

```
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);
   }
}
```

> The block() and wakeup() operations must be provided by the kernel as basic system calls

Some observations

- The list of processes waiting for various semaphores can be easily implemented using a link field in the PCB
  - E.g., as a FIFO queue

- The wait( ) and signal( ) operations must execute atomically
  - Disabling interrupts can be a solution for uniprocessor systems (but difficult for multiprocessor systems)
  - Alternative locking via hardware instructions such as TAS or CAS can be used

- Can the value of a counting semaphore become negative?

Deadlock and Starvation

- **Deadlock** – two or more processes are waiting indefinitely for an event that can be caused only by 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

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.

POSIX Semaphores

- For using semaphores
  - #include semaphore.h
  - Compile the code by linking with -lpthread –lrt

- Declare a sempahore: sem_t mutex;
- Initialize a semaphore:
  - sem_init (sem_t *sem, int pshared, unsigned int value)
  - **sem** - the semaphore to be initialized
  - **pshared -** whether or not the newly initialized semaphore is shared between processes or between threads. Non-zero => the semaphore can be accessed by other processes. Zero => can be shared only by threads belonging to this process
  - **value** - the value to assign to the newly initialized semaphore.
  - E.g., sem_init(&mutex, 0, 1); // initialize to 1

POSIX Semaphores (contd.)

- Wait on a semaphore
  - int sem_wait (sem_t *sem)
  - E.g., sem_wait(&mutex);
- Signal a semaphore
  - int sem_post (sem_t *sem)
  - E.g., sem_post(&mutex);
- Destroy a sempahore
  - sem_destroy(sem_t *sem)
  - E.g., sem_destroy(&mutex);

Classical Problems of Synchronization

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

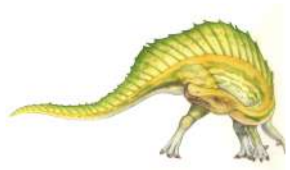
Bounded-Buffer Problem

- Producer and consumer processes share the following data:
  - ***n*** (number of buffers, each of which 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
- Semaphores **empty** and **full** count the number of empty and full buffers
- Semaphore **mutex** provides mutual exclusion in accessing buffer

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);
```

Dining-Philosophers Problem

- Philosophers spend their lives alternating thinking and eating
  - Don't interact with their neighbors
  - When hungry, try to pick up 2 chopsticks (one at a time) to eat from bowl
  - Need both chopsticks to eat, then release both when done
- In the case of 5 philosophers and 5 single chopsticks
  - Shared data
    - Semaphore chopstick [5] all initialized to 1

Dining-Philosophers Problem Algorithm

- The structure of Philosopher *i*:

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

             /* eat for a while */

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

             /* think for a while */

} while (TRUE);
```

- What is the problem with this algorithm?

Dining-Philosophers Problem Algorithm (Cont.)

- Can cause deadlock --> all philosophers can starve to death

- Deadlock handling
  - Allow at most 4 philosophers to be sitting simultaneously at the table
  - Allow a philosopher to pick up the chopsticks only if both are available
  - 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

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 –
  - Multiple readers can be allowed to read at the same time
  - A writer must have exclusive access to the shared data while writing

Readers-Writers Problem Variations

- Several variations of how readers and writers are considered – all involve some form of priorities
- **First** variation – no reader is kept waiting unless writer has already obtained permission to use shared dataset
  - No reader should wait for other readers to finish, simply because a writer is waiting
  - Readers have priority, Writers may starv*e*
- **Second** variation – once writer is ready, it performs the write ASAP
  - Writer has priority
- Both may have starvation leading to even more variations
- We discuss a solution to the first readers-writers problem

Readers-Writers Problem

- Readers and Writers share the following data:
  - Data set
  - Semaphore **rw_mutex** initialized to 1
  - Semaphore **mutex** initialized to 1
  - Integer **read_count** initialized to 0
- Semaphore **rw_mutex** used as mutual exclusion semaphore for writers
- Semaphore **mutex** is used to ensure mutual exclusion when **read_count** is updated

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);
```

If a writer is in the critical section, and *n* readers are waiting:

Which readers are queued up on which sempahore?

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);
```

If a writer is in the critical section, and *n* readers are waiting:
- one reader is queued on **rw_mutex**
- the rest *n*-1 readers are queued on **mutex**

Summary

- Race condition
  - Demonstration through Producer-Consumer problem
- Critical Section Problem
  - Requirements for solutions to the problem
- Solutions to Critical Section Problem
  - Software solution – Peterson's algorithm
  - Hardware solutions (special atomic instructions) -
    - test_and_set( )
    - compare_and_swap( )
  - Mutex locks
  - Semaphores
    - Handling classical problems of synchronization
    - POSIX semaphores