CSE 3221.3
Operating System Fundamentals

No.6

Process Synchronization(2)

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Semaphores

- Problems with the software solutions.
  - Complicated programming, not flexible to use.
  - Not easy to generalize to more complex synchronization problems.
- *Semaphore* (a.k.a. *lock*): an easy-to-use synchronization tool
  - An integer variable *S*
  - *wait(S)* {
    while (*S*<=0) ;
    S-- ;
    }
  - *signal(S)* {
    S++ ;
    }

Semaphore usage (1): the n-process critical-section problem

- **The n processes share a semaphore,**
  Semaphore *mutex ;* *// mutex* **is initialized to 1**.

Process P_i

```
do {
        wait(mutex);
           critical section of Pi
        signal(mutex);
           remainder section of Pi
} while (1);
```

Semaphore usage (2): as a General Synchronization Tool

- **Execute** ***B*** **in** P_j **only after** ***A*** **executed in** P_i
- **Use semaphore** ***flag*** **initialized to 0**

P_i	P_j
…	**…**
A	*wait* **(flag) ;**
signal **(flag) ;**	**B**
…	**…**

Spinlock vs. Sleeping Lock

- **Previous definition of semaphore requires busy waiting.**
  - **It is called** *spinlock.*
  - *spinlock* **does not need context switch, but waste CPU cycles in a continuous loop.**
  - *spinlock* **is OK only for lock waiting is very short.**
- **Semaphore without busy-waiting, called** *sleeping lock*:
  - **In defining** *wait()*, **rather than busy-waiting, the process makes system calls to block itself and switch back to waiting state, and put the process to a waiting queue associated with the semaphore. The control is transferred to CPU scheduler.**
  - **In defining** *signal(),* **the process makes system calls to pick a process in the waiting queue of the semaphore, wake it up by moving it to the ready queue to wait for CPU scheduling.**
  - **Sleeping Lock is good only for long waiting.**

Spinlock Implementation(1)

- **In uni-processor machine, disabling interrupt before modifying semaphore.**

```
wait(S) {

  do {

     if(S>0) {
        S-- ;

        return ;
     }

  }  while(1) ;
}
```

```
signal(S) {


   S++ ;

   return ;

}
```

Spinlock Implementation(1)

- In uni-processor machine, disabling interrupt before modifying semaphore.

```
wait(S) {

  do {
    Disable_Interrupt;
    if(S>0) {
      S-- ;
      Enable_Interrupt ;
      return ;
    }
    Enable_Interrupt ;
  } while(1) ;
}
```

```
signal(S) {

  Disable_Interrupt ;
  S++ ;
  Enable_Interrupt ;
  return ;

}
```

Spinlock Implementation(2)

- In multi-processor machine, inhibiting interrupt of all processors is not easy and efficient.
- Use software solution to critical-section problems
  - e.g., bakery algorithm.
  - Treat *wait()* and *signal()* as critical sections.
- Or use hardware support if available:
  - *TestAndSet()* or *Swap()*
- Example: implement spinlock among two processes.
  - Use Peterson's algorithm for protection.
  - Shared data:

Semaphore ***S ;*** **Initially *S*=1**

*boolean flag[2]****;*** **initially** *flag [0] = flag [1] = false*.
int turn; **initially** *turn = 0* **or** *1*.

Spinlock Implementation(3)

```
wait(S) {
    int i=process_ID(); //0→P0, 1→P1
    int j=(i+1)%2 ;
  do {
    flag [ i ]:= true; //request to enter
    turn = j;
    while (flag [ j ] and turn = j) ;
    if (S >0) {  //critical section
        S--;
        flag [ i ] = false;
        return ;
     } else {
       flag [ i ] = false;
     }
   } while (1);
}
```

```
signal(S) {
    int i=process_ID(); //0→P0, 1→P1
    int j=(i+1)%2 ;

    flag [ i ]:= true; //request to enter
    turn = j;
    while (flag [ j ] and turn = j) ;

      S++; //critical section

      flag [ i ] = false;

      return ;
}
```

Spinlock Implementation(2)

- **In multi-processor machine, inhibiting interrupt of all processors is not easy and efficient.**
- **Use software solution to critical-section problems**
  - **e.g., bakery algorithm.**
  - **Treat** *wait()* **and** *signal()* **as critical sections.**
- **Or use hardware support if available:**
  - *TestAndSet()* **or** *Swap()*
- **Example: implement spinlock between N processes.**
  - **Use Bakery algorithm for protection.**
  - **Shared data:**

Semaphore ***S*** **; Initially** ***S*****=1**

boolean choosing[N]; (**Initially** *false*)

int number[N]; (**Initially** *0*)

Spinlock Implementation(3)

```
wait(S) {
    int i=process_ID();

    choosing[ i ] = true;
    number[ i ] = max(number[0], number[1],
    …, number [N – 1])+1;
    choosing[ i ] = false;
    for (j = 0; j < N; j++) {
      while (choosing[ j ]) ;
      while ((number[ j ] != 0) &&
              (number[ j ],j)< (number[ i ],i)) ;
    }
   if (S >0) {  //critical section
       S--;
      number[i] = 0;
      return ;
   }
   number[i] = 0;
 } while (1);
}
```

```
signal(S) {
    int i=process_ID();

   choosing[ i ] = true;
   number[ i ] = max(number[0], number[1],
     …, number [N – 1])+1;
   choosing[ i ] = false;
   for (j = 0; j < N; j++) {
        while (choosing[ j ]) ;
        while ((number[ j ] != 0) &&
                (number[ j ],j)< (number[ i ],i)) ;
    }

    S++; //critical section

    number[i] = 0;

    return ;
}
```

Sleeping Lock (I)

- **Define a sleeping lock as a structure:**

```
typedef struct {
   int value;   // Initialized to 1
   struct process *L;
} semaphore;
```

- **Assume two system calls:**
  - *block()* **suspends the process that invokes it.**
  - *wakeup(P)* **resumes the execution of a blocked process** P**.**
- **Equally applicable to multiple threads in one process.**

Sleeping Lock (II)

- **Semaphore operations now defined as:**

***wait*(*S*):**

```
S.value--;
if (S.value < 0) {
        add this process to S.L;
        block();
}
```

***signal*(*S*):**

```
S.value++;
if (S.value <= 0) {
        remove a process P from S.L;
        wakeup(P);
}
```

Two Types of Semaphores: Binary vs. Counting

- ***Binary*** **semaphore (a.k.a. mutex lock) – integer value can range only between 0 and 1; simpler to implement by hardware.**
- ***Counting*** **semaphore – integer value can range over an unrestricted domain.**
- **We can implement a counting semaphore *S* by using two binary semaphore.**
- **Binary semaphore is normally used as mutex lock.**
- **Counting semaphore can be used as shared counter, load controller, etc…**

Implementing counting semaphore with two Binary Semaphores

- **Data structures:**

  binary-semaphore S1, S2;
  int C:

- **Initialization:**

  S1 = 1
  S2 = 0
  C = **initial value of semaphore** *S*

Implementing *S*

- ***wait(S)*** **operation:**

```
wait_binary(S1);
C--;
if (C < 0) {
    signal_binary(S1);
    wait_binary(S2);
}
signal_binary(S1);
```

- ***signal(S)*** **operation:**

```
wait_binary(S1);
C ++;
if (C <= 0)
    signal_binary(S2);
else
    signal_binary(S1);
```

Classical Synchronization Problems

- The Bounded-Buffer P-C Problem
- The Readers-Writers Problem
- The Dining-Philosophers Problem

Bounded-Buffer P-C Problem

- A producer produces some data for a consumer to consume. They share a bounded-buffer for data transferring.
- Shared memory:
  A buffer to hold at most *n* items
- Shared data (three semaphores)

  *Semaphore filled, empty; /*counting*/*
  Semaphore mutex;   /* binary */

  Initially:

  filled = 0, empty = n, mutex = 1

Bounded-Buffer Problem: Producer Process

```
do {
        …
    produce an item in nextp
        …
    wait(empty);
    wait(mutex);
        …
    add nextp to buffer
        …
    signal(mutex);
    signal(filled);

} while (1);
```

Bounded-Buffer Problem: Consumer Process

```
do {
    wait(filled)
    wait(mutex);
      …
    remove an item from buffer to nextc
      …
    signal(mutex);
    signal(empty);
      …
    consume the item in nextc
      …
} while (1);
```

The Readers-Writers Problem

- Many processes concurrently access a data object
  - Readers: only read the data.
  - Writers: update and may write the data object.
- Only writer needs exclusive access of the data.
- The first readers-writers problem:
  - Unless a writer has already obtained permission to use the shared data, readers are always allowed to access data.
  - May starve a writer.
- The second readers-writer problem:
  - Once a writer is ready, the writer performs its write as soon as possible.
  - May starve a reader.

The 1st Readers-Writers Problem

- Use semaphore to implement 1st readers-writer problem
- Shared data:

int readcount = 0 ; // keep track the number of readers
// accessing the data object

Semaphore *mutex = 1 ;* // mutually exclusive access to
// *readcount* among readers

Semaphore *wrt = 1 ;* // mutual exclusion to the data object
// used by every writer
//also set by the 1st reader to read the data
// and clear by the last reader to finish reading

The 1st Readers-Writers Problem

Writer Process

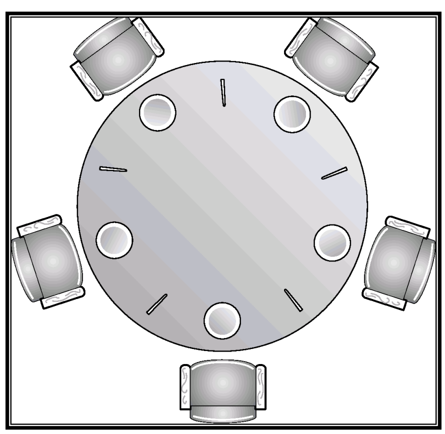
```
 …
wait(wrt);
 …
writing is performed
 …
signal(wrt);
…
```

Reader Process

```
…
wait(mutex);
readcount++;
if (readcount == 1)   wait(wrt);
signal(mutex);
  …
reading is performed
…
wait(mutex);
readcount--;
if (readcount == 0)   signal(wrt);
signal(mutex);
…
```

The Dining-Philosophers Problem

- **Five philosophers are thinking or eating**
- **Using only five chopsticks**
- **When thinking, no need for chopsticks.**
- **When eating, need two closest chopsticks.**
- **Can pick up only one chopsticks**
- **Can not get the one already in the hand of a neighbor.**



The Dining-Philosophers Problem: Semaphore Solution

- Represent each chopstick with a semaphore

  Semaphore *chopstick[5]*; **// Initialized to** *1*

Philosopher i (i=0,1,2,3,4)

```
do {
    wait(chopstick[i]) ;
    wait(chopstick[(i+1) % 5]) ;
      …
      eat
      …
    signal(chopstick[i]);
    signal(chopstick[(i+1) % 5]);
      …
      think
      …
} while (1);
```

Incorrect Semaphore Usage

Mistake 1:

```
…
signal(mutex) ;
…
Critical Section
…
wait(mutex) ;
```

Mistake 2:

```
…
wait(mutex) ;
…
Critical Section
…
wait(mutex) ;
```

Mistake 3:

```
…
wait(mutex) ;
…
Critical Section
…
```

Mistake 4:

```
…
Critical Section
…
signal(mutex) ;
```

Starvation and Deadlock

- *Starvation* – infinite blocking. A process may never be removed from the semaphore queue in which it is suspended.
- *Deadlock* – two or more processes are waiting infinitely 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***);

double_rq_lock() in Linux Kernel

```
double_rq_lock(struct runqueue *rq1,
  struct runqueue *rq2)
{
   if (rq1 == rq2)
      spinlock(&rq1->lock);
   else {
         if (rq1 < rq2) {
           spin_lock(&rq1->lock);
           spin_lock(&rq2->lock);
         } else {
           spin_lock(&rq2->lock);
           spin_lock(&rq1->lock);
          }
    }
}
```

Why not?

```
double_rq_lock(struct runqueue *rq1,
  struct runqueue *rq2)
{
    spin_lock(&rq1->lock);
    spin_lock(&rq2->lock);
}
```

```
struct runqueue *RdQ, *DevQ1, *DevQ2, …
```

P1	P2
…	…
double_rq_lock(RdQ,DevQ1);	double_rq_lock(DevQ1,RdQ);
…	…

double_rq_unlock() in Linux Kernel

```
double_rq_unlock(struct runqueue *rq1,
  struct runqueue *rq2)
{
   spin_unlock(&rq1->lock);
     if (rq1 != rq2)
          spin_unlock(&rq2->lock);
}
```

Pthread Semaphore

- Pthread semaphores for multi-threaded programming in Unix/Linux:
  - Pthread Mutex Lock (binary semaphore)
  - Pthread Semaphore (general counting semaphore)

Pthread Mutex Lock

```
#include <pthread.h>
/*declare a mutex variable*/
pthread_mutex_t  mutex ;

/* create a mutex lock */
pthread_mutex_init (&mutex, NULL) ;

/* acquire the mutex lock  */
pthread_mutex_lock(&mutex) ;

/* release the mutex lock  */
pthread_mutex_unlock(&mutex) ;
```

Using Pthread Mutex Locks

- Use mutex locks to solve critical section problems:

```
#include <pthread.h>
pthread_mutex_t  mutex ;
…
pthread_mutex_init(&mutex, NULL) ;
…
pthread_mutex_lock(&mutex) ;

/*** critical section ***/

pthread_mutex_unlock(&mutex) ;
```

Pthread Semaphores

```
#include <semaphore.h>
/*declare a pthread semaphore*/
sem_t sem ;

/* create and initialize a semaphore */
sem_init (&sem, flag, initial_value) ;

/* wait() operation  */
sem_wait(&sem) ;

/* signal() operation  */
sem_post(&sem) ;
```

Using Pthread semaphore

- Using Pthread semaphores for counters shared by multiple threads:

```
#include <semaphore.h>
sem_t  counter ;
…
sem_init(&counter, 0, 0) ;  /* initially 0 */
…
sem_post(&counter) ;    /* increment */
…
sem_wait(&counter) ;    /* decrement */
```

volatile in multithread program

- In multithread programming, a shared global variable must be declared as volatile to avoid compiler's optimization which may cause conflicts:

```
volatile int data ;

volatile char buffer[100] ;
```

Process Synchronization for multiple processes in Unix

- In Unix, a shared global variable must be created with the following systems calls:

```
#include <sys/shm.h>

int shmget(key_t key, size_t size, int shmflg);

void *shmat(int shmid, const void *shmaddr, int shmflg);

int shmdt(const void *shmaddr);

int shmctl(int shmid, int cmd, struct shmid_ds *buf);
```

nanosleep()

```
#include <time.h>

int nanosleep(const struct timespec *req,
              struct timespec *rem);

struct timespec
{
 time_t tv_sec; /* seconds */
 long tv_nsec; /* nanoseconds 0-999,999,999 */
};
```