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 *signal* (flag) ; …	… *wait* (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

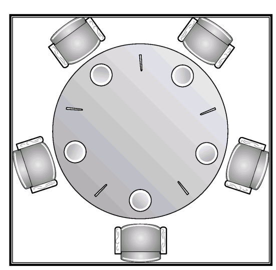
```
…
wait(wrt);
…
writing is performed
…
signal(wrt);
…
```

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 */
};
```