CSE 421/521 - Operating Systems
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Lecture - IX
Process Synchronization - II

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Roadmap

- Semaphores
- Classic Problems of Synchronization
  - Bounded Buffer Problem
  - Readers and Writers Problem
  - Dining-Philosophers Problem
- Monitors
- Conditional Variables
- Sleeping Barber Problem

Mutual Exclusion

- Summary of these implementations of mutual exclusion
  - **Impl. 1 — disabling hardware interrupts**
    - NO: race condition avoided, but can crash the system!
  - **Impl. 2 — simple lock variable (unprotected)**
    - NO: still suffers from race condition
  - **Impl. 3 — indivisible lock variable (TSL)**
    - YES: works, but requires hardware

    this will be the basis for "mutexes"
  - **Impl. 4 — no-TSL toggle for two threads**
    - NO: race condition avoided inside, but lockup outside
  - **Impl. 5 — Peterson's no-TSL, no-alternation**
    - YES: works in software, but processing overhead

Mutual Exclusion

- <u>Problem: all implementations (2-5) rely on busy waiting</u>
  - ✓ “busy waiting” means that the process/thread continuously executes a tight loop until some condition changes
  - ✓ busy waiting is bad:
    - **waste of CPU time** — the busy process is not doing anything useful, yet remains “Ready” instead of “Blocked”
    - **paradox of inversed priority** — by looping indefinitely, a higher-priority process B may starve a lower-priority process A, thus preventing A from exiting CR and . . . liberating B! (B is working against its own interest)

--> we need for the waiting process to <u>block</u>, not keep idling!

Semaphores

- Synchronization tool for critical section problem
- Semaphore *S* – integer variable
- Can only be accessed through two standard operations:
  - wait() and signal()
  - (or P() and V())
  - (in dutch: Proberen/test ; Verhogen/increase)

- Classical implementation (using busy-waiting)
  - wait (S) {

```
wait (S) {
        while S <= 0
            ; // no-op
        S--;
    }
```

  - signal (S) {

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

Semaphores without Busy-Waiting

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

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

Semaphores as Synchronization Tool

- Counting semaphore – integer value can range over an unrestricted domain
- Binary semaphore – integer value can range only between 0 and 1; can be simpler to implement
  - Also known as mutex locks

- Provides mutual exclusion
  - Semaphore S;   // initialized to 1
  - wait (S);

```
        Critical Section
 signal (S);
```

Classical Problems of Synchronization

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

Bounded-Buffer Problem

- Shared buffer with N slots to store at most N items
- Producer processes data items and puts into the buffer
- Consumer gets the data items from the buffer
- Variable empty keeps number of empty slots in the butter
- Variable full keeps number of full items in the buffer

Bounded Buffer – 1 Semaphore Soln

- The structure of the producer process

```
int empty=N, full=0;
do {
   //   produce an item
  wait (mutex);
        if (empty> 0){
                // add the item to the  buffer
           empty --; full++;
        }
  signal (mutex);

 } while (true);
```

Bounded Buffer – 1 Semaphore Soln

- The structure of the consumer process

```
do {

     wait (mutex);
          if (full>0){
             //  remove an item from  buffer
             full--; empty++;
          }
      signal (mutex);

     //  consume the removed item

} while (true);
```

consume non-existing item!

Bounded Buffer – 1 Semaphore Soln - II

- The structure of the producer process

```
int empty=N, full=0;
do {
   //   produce an item
  while (empty == 0){}
  wait (mutex);
                    //  add the item to the  buffer
          empty --; full++;
  signal (mutex);

} while (true);
```

Bounded Buffer – 1 Semaphore Soln - II

- The structure of the consumer process

```
do {
    while (full == 0){}
    wait (mutex);
        //  remove an item from  buffer
        full--; empty++;
    signal (mutex);

    //  consume the removed item

} while (true);
```

* Mutual Exclusion not preserved!

Bounded Buffer – 2 Semaphore Soln

- The structure of the producer process

```
do {

        //   produce an item
    wait (empty);
        //  add the item to the  buffer
    signal (full);

} while (true);
```

Bounded Buffer – 2 Semaphore Soln

- The structure of the consumer process

```
do {
    wait (full);
        //  remove an item from  buffer
    signal (empty);

        //  consume the removed item

} while (true);
```

* Mutual Exclusion not preserved!

Bounded Buffer - 3 Semaphore Soln

- Semaphore mutex for access to the buffer, initialized to 1
- Semaphore full (number of full buffers) initialized to 0
- Semaphore empty (number of empty buffers) initialized to N

Bounded Buffer - 3 Semaphore Soln

- The structure of the producer process

```
do {

        //   produce an item

    wait (empty);
    wait (mutex);

        //  add the item to the  buffer

    signal (mutex);
    signal (full);
} while (true);
```

Bounded Buffer - 3 Semaphore Soln

- The structure of the consumer process

```
do {
    wait (full);
    wait (mutex);

        //  remove an item from  buffer

     signal (mutex);
     signal (empty);

         //  consume the removed item

} while (true);
```

Readers-Writers Problem

- Multiple Readers and writers concurrently accessing the same database.

- Multiple Readers accessing at the same time --> OK

- When there is a Writer accessing, there should be no other process accessing at the same time.

Readers-Writers Problem

- The structure of a writer process

```
do {
      wait (wrt) ;

        //    writing is performed

      signal (wrt) ;
  } while (true)
```

Readers-Writers Problem (Cont.)

- The structure of a reader process

```
do  {
      wait (mutex) ;
      readercount ++ ;
      if (readercount == 1)  wait (wrt) ;
      signal (mutex) ;

            // reading is performed

      wait (mutex) ;
      readercount  - - ;
      if readercount  == 0)  signal (wrt) ;
      signal (mutex) ;
 } while (true)
```

Dining Philosophers Problem

• Five philosophers spend their time eating and thinking.

• They are sitting in front of a round table with spaghetti served.

•There are five plates at the table and five chopsticks set between the plates.

• Eating the spaghetti requires the use of two chopsticks which the philosophers pick up one at a time.

•Philosophers do not talk to each other.

•Semaphore chopstick [5] initialized to 1

Dining-Philosophers Problem (Cont.)

- 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) ;
```

- Ensures mutual exclusion, but may result in deadlock!

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.

To Prevent Deadlock

- Allow philosopher to pick up his chopsticks only if both chopsticks are available (i.e. in critical section)
- Use an asymmetric solution: an odd philosopher picks up first his left chopstick and then his right chopstick; and vice versa

- Exercise: Write the algorithms for the above solutions

Problems with Semaphores

- Wrong use of semaphore operations:
  - semaphores *A* and *B*, initialized to 1

P_0	P_1
wait (A);	*wait(B)*
wait (B);	*wait(A)*

  ➔ Deadlock

  - signal (mutex) …. wait (mutex)

  ➔ violation of mutual exclusion

  - wait (mutex) … wait (mutex)

  ➔ Deadlock

  - Omitting of wait (mutex) or signal (mutex) (or both)

  ➔ violation of mutual exclusion or deadlock

Semaphores

- inadequate in dealing with deadlocks
- do not protect the programmer from the easy mistakes of taking a semaphore that is already held by the same process, and forgetting to release a semaphore that has been taken
- mostly used in low level code, eg. operating systems
- the trend in programming language development, though, is towards more structured forms of synchronization, such as monitors

Monitors

- A high-level abstraction that provides a convenient and effective mechanism for process synchronization
- Only one process may be active within the monitor at a time

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

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

- A monitor procedure takes the lock before doing anything else, and holds it until it either finishes or waits for a condition

Monitor - Example

As a simple example, consider a monitor for performing transactions on a bank account.

```
monitor account {
   int balance := 0

  function withdraw(int amount) {
    if amount < 0 then error "Amount may not be negative"
    else if balance < amount then error "Insufficient funds"
    else balance := balance - amount
  }

  function deposit(int amount) {
    if amount < 0 then error "Amount may not be negative"
    else balance := balance + amount
  }
}
```

.. implements the following:

```
class Account {
 private lock myLock;

 private int balance := 0
 invariant balance >= 0

 public method boolean withdraw(int amount)
    precondition amount >= 0
 {
   myLock.acquire();
   try:
     if balance < amount then return false
     else { balance := balance - amount ; return true
}
   finally:
     myLock.release();
 }

 public method deposit(int amount)
    precondition amount >= 0
 {
   myLock.acquire();
   try:
     balance := balance + amount
   finally:
     myLock.release();
 }
```

<-- by hiding the details of the synchronization code from the programmer

* mutual exclusion is inherently provided by monitors, so programmer does not need to manage these locks manually

Condition Variables

- For many applications, mutual exclusion is not sufficient
- A thread may need to wait until some condition holds true
- We don't want to use busy waiting...

- Condition variables queue threads until a certain condition is met (non-blocking, non-busy-waiting)
- condition x, y;

- Two operations on a condition variable:
  - x.wait () – a thread invoking this operation is suspended
  - x.signal () – resumes one of the threads (if any) that invoked x.wait ()

If no thread was suspended, x.signal() operation has no effect.

Solution to Dining Philosophers using Monitors

```
monitor DP
  {
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5];       //to delay philosopher when he is
          hungry but unable to get chopsticks

initialization_code() {
         for (int i = 0; i < 5; i++)
                    state[i] = THINKING;
    }
```

```
void pickup (int i) {
         state[i] = HUNGRY;
         test(i);//only if both neighbors are not eating
         if (state[i] != EATING) self [i].wait;
    }
```

Solution to Dining Philosophers (cont)

```
    void test (int i) {
            if ((state[i] == HUNGRY) &&
               (state[(i + 1) % 5] != EATING) &&
               (state[(i + 4) % 5] != EATING) ) {
                    state[i] = EATING ;
                    self[i].signal () ;
             }
     }
```

```
 void putdown (int i) {
            state[i] = THINKING;
                  // test left and right neighbors
            test((i + 4) % 5);
            test((i + 1) % 5);
   }
}
```

Solution to Dining Philosophers (cont)

//main thread will run the initialization code

```
....
DiningPhilosophers.initialization_code();
....
```

// each Dining Philosopher thread will run the pickup and putdown functions
// for Philosopher thread i:

```
....
DiningPhilosophers.pickup(i);
....
eat
....
DiningPhilosophers.putdown(i);
....
```

- No two philosophers eat at the same time
- No deadlock
- But starvation can occur! <-- how can we prevent this? HW

Sleeping Barber Problem

- Based upon a hypothetical barber shop with one barber, one barber chair, and a number of chairs for waiting customers
- When there are no customers, the barber sits in his chair and sleeps
- As soon as a customer arrives, he either awakens the barber or, if the barber is cutting someone else's hair, sits down in one of the vacant chairs
- If all of the chairs are occupied, the newly arrived customer simply leaves

Solution

- Use three semaphores: one for any waiting customers, one for the barber (to see if he is idle), and a mutex

- When a customer arrives, he attempts to acquire the mutex, and waits until he has succeeded.
- The customer then checks to see if there is an empty chair for him (either one in the waiting room or the barber chair), and if none of these are empty, the customer checks again later (in a loop).
- Otherwise the customer takes a seat – thus reducing the number available (a critical section).

- The customer then signals the barber to awaken through his semaphore, and the mutex is released to allow other customers (or the barber) the ability to acquire it.
- If the barber is not free, the customer then waits. The barber sits in a perpetual waiting loop, being awakened by any waiting customers. Once he is awoken, he signals the waiting customers through their semaphore, allowing them to get their hair cut one at a time.

Implementation:

+ Semaphore Customers // to wait for available customers
+ Semaphore Barber // to wait for available barber
+ Semaphore accessSeats (mutex) // to change seat availability
+ int NumberOfFreeSeats

The Barber(Thread):

```
while(true) //runs in an infinite loop
{
  Customers.wait() //tries to acquire a customer - if none is available he's going to
     sleep
  accessSeats.wait() //at this time he has been awaken -> want to modify the number
     of available seats
  NumberOfFreeSeats++ //one chair gets free
  Barber.signal() // the barber is ready to cut
  accessSeats.signal() //we don't need the lock on the chairs anymore //here the
     barber is cutting hair
}
```

The Customer(Thread):

```
while (notCut) //as long as the customer is not cut
{
  accessSteats.wait() //tries to get access to the chairs
  if (NumberOfFreeSeats>0) { //if there are any free seats
    NumberOfFreeSeats -- //sitting down on a chair
    Customers.signal() //notify the barber, who's waiting that there is
    a customer
    accessSeats.signal() // don't need to lock the chairs anymore
    Barber.wait() // now it's this customers turn, but wait if the barber
    is busy
    notCut = false
  } else // there are no free seats //tough luck
  accessSeats.signal() //but don't forget to release the lock on the
    seats }
```

Summary

- Semaphores
- Classic Problems of Synchronization
  - Bounded Buffer Problem
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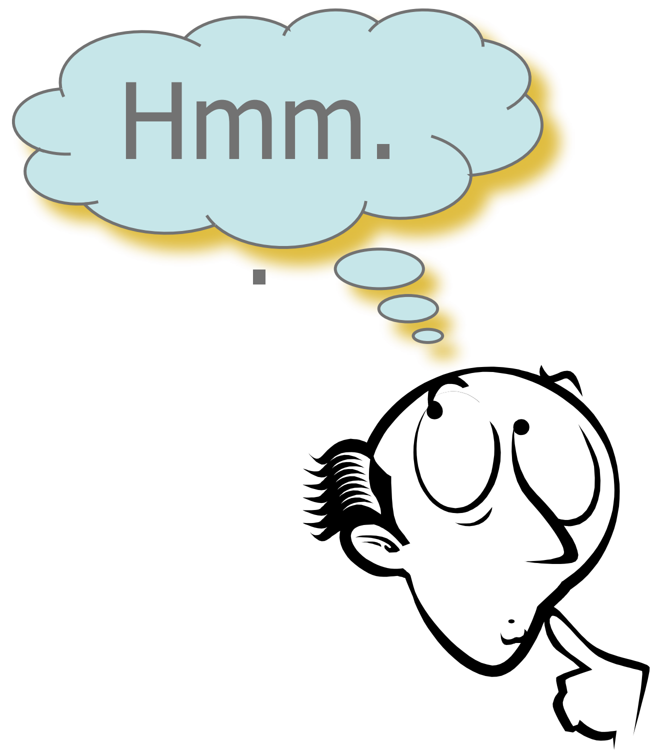
  - Dining-Philosophers Problem
- Monitors
- Conditional Variables
- Sleeping Barber Problem



- Next Lecture: Deadlocks - I
- Reading Assignment: Chapter 7 from Silberschatz.

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