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
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

- 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

Problem:

- all implementations (2-5) rely on busy waiting

  “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 inverted 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 block, not keep idling!
Synchronization Hardware

- Many systems provide hardware support for critical section code
- Uniprocessors - could disable interrupts
  - Currently running code would execute without preemption
  - Generally too inefficient on multiprocessor systems
    - Operating systems using this not broadly scalable
- Modern machines provide special atomic hardware instructions
  - Atomic = non-interruptable
  - Either test memory word and set value
  - Or swap contents of two memory words

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())
- Classical implementation (using busy-waiting)
  - wait (S) {
    while S <= 0
      ; // no-op
      S--;  
  }
  - signal (S) {
    S++;
  }
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);

Semaphores without Busy-Waiting

```c
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);
    }
}
```
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
  
  $P_0$
  
  wait ($S$); wait ($Q$);
  
  .
  
  wait ($Q$); wait ($S$);
  
  .
  
  signal ($S$); signal ($Q$);

- **Starvation**: indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.

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 buffer
- Variable full keeps number of full items in the buffer

Bounded Buffer - 1 Semaphore Soln

- The structure of the producer process
  ```c
  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

```c
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

```c
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

```c
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**

```c
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**

```c
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 processes accessing at the same time.

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Readers-Writers Problem

- The structure of a writer process

```c
#include <semaphore.h>

int main()
{
    int wrt = 0;
    sem_init(&wrt, 0, 1);

    while (true) {
        sem_wait(&wrt);
        // writing is performed
        sem_post(&wrt);
    }
    return 0;
}
```
Readers-Writers Problem (Cont.)

- The structure of a reader process

```c
    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 $i$:

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

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

    // think
}
```

To Prevent Deadlock

• Ensures mutual exclusion, but does not prevent deadlock
• Allow philosopher to pick up her chopsticks only if both chopsticks are available (i.e. in critical section)
• Use an asymmetric solution: an odd philosopher picks up first her left chopstick and then her 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

```plaintext
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.

```plaintext
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
    }
}
```
Condition Variables

- **Provide additional synchronization mechanism**
- **condition x, y;**

- **Two operations on a condition variable:**
  - `x.wait()` - a process invoking this operation is suspended
  - `x.signal()` - resumes one of processes (if any) that invoked `x.wait()`

If no process suspended, `x.signal()` operation has no effect.

Solution to Dining Philosophers using Monitors

```c
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)**

```c
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);
}
```

➡ No two philosophers eat at the same time
➡ No deadlock
➡ But starvation can occur!

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**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, leaves.
- 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
+ Semaphore Barber
+ Semaphore accessSeats (mutex)
+ 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 his 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
- HW-2 out next Tuesday!
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