High-level Synchronization

CS 256/456

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Recap of Last Class

- Concurrent access to shared data may result in data inconsistency – race condition.
  - Disabling interrupts
- The Critical-Section problem
  - Pure software solution
  - With help from the hardware
- Synchronization without busy/spin waiting
  - Semaphore
  - Mutex lock

Semaphore

- Synchronization tool that does not require busy waiting.
- Semaphore *S* – integer variable which can only be accessed via two atomic operations
- Semantics (roughly) of the two operations:

```
wait(S) or P(S):
   wait until S>0;
   S--;

signal(S) or V(S):
   S++;
```

- Solving the critical section problem:

Shared data:

```
semaphore mutex=1;
```

Process *Pi:*

```
wait(mutex);
    critical section
signal(mutex);
    remainder section
```


Semaphore Implementation

- Define a semaphore as a record

```
typedef struct {
   int value;
   proc_list *L;
} semaphore;
```

- Assume two simple operations:
  - **block** suspends the process that invokes it.
  - **wakeup(P)** resumes the execution of a blocked process **P**.
- Semaphore operations now defined as (both are atomic):

```
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);
   }
```

Does this completely solve the critical section problem?
How to make sure wait(S) and signal(S) are atomic?
So have we truly removed busy waiting?

Mutex Lock (Binary Semaphore)

- Mutex lock – a semaphore with only two state: locked/unlocked
- Semantics of the two (atomic) operations:

  lock(mutex):
  ```
  wait until mutex==unlocked;
  mutex=locked;
  ```

  unlock(mutex):
  ```
  mutex=unlocked;
  ```

- Can you implement mutex lock using semaphore?
- How about the opposite?

Implement Semaphore Using Mutex Lock

- Data structures:
  ```
  mutex_lock L1, L2;
  int C;
  ```
- Initialization:
  ```
  L1 = unlocked;
  L2 = locked;
  C = initial value of semaphore;
  ```
- *wait* operation:
  ```
  lock(L1);
  C --;
  if (C < 0) {
     unlock(L1);
     lock(L2);
  }
  unlock(L1);
  ```
- *signal* operation:
  ```
  lock(L1);
  C ++;
  if (C <= 0)
     unlock(L2);
  else
     unlock(L1);
  ```


Classical Problems of Synchronization

- Bounded-Buffer Problem
- Dining-Philosophers Problem

Bounded Buffer Problem

- Shared data

```
buffer;
```

- Producer process

```
while (1) {
   ...
   produce an item in nextp;
   ...
   add nextp to buffer;
   ...
}
```

- Consumer process

```
while (1) {
   ...
   remove an item from buffer to nextc;
   ...
   consume nextc;
   ...
}
```

- Protecting the critical section for safe concurrent execution.
- Synchronizing producer and consumer when buffer is empty/full.

Bounded Buffer Solution

- Shared data

```
buffer;
semaphore full=0;
semaphore empty=n;
semaphore mutex=1;
```

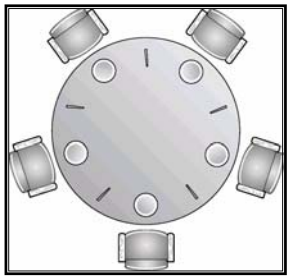
- Producer process

```
while (1) {
   ...
   produce an item in nextp;
   ...
   wait(empty);
   wait(mutex);
   add nextp to buffer;
   signal(mutex);
   signal(full);
   ...
}
```

- Consumer process

```
while (1) {
   ...
   wait(full);
   wait(mutex);
   remove an item from buffer to nextc;
   signal(mutex);
   signal(empty);
   ...
   consume nextc;
   ...
}
```


Dining-Philosophers Problem



- Philosopher i (1 ≤ i ≤ 5):

```
while (1) {
   ...
   eat;
   ...
   think;
   ...
}
```

- eating needs both chopsticks (the left and the right one).

Dining-Philosophers Solution

- Shared data:

```
semaphore chopstick[5];
```

Initially all values are 1;

- Philosopher i:

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

Deadlock?

Monitors

- High-level synchronization construct that allows the safe sharing of an abstract data type among concurrent processes.
- Native support for mutual exclusion.

```
monitor monitor-name
{
    shared variable declarations
    procedure body P1 (...) {
      . . .
    }
    procedure body Pn (...) {
       . . .
    }
    {
      initialization code
    }
}
```

Condition Variables in Monitors

- To allow a process to wait within the monitor, a **condition** variable must be declared, as

  ```
  condition x, y;
  ```

- Condition variable can only be used with the operations **wait** and **signal**.
  - The operation

    ```
    x.wait();
    ```

    means that the process invoking this operation is suspended until another process invokes

    ```
    x.signal();
    ```
  - The **x.signal** operation resumes exactly one suspended process. If no process is suspended, then the **signal** operation has no effect.
- Unlike semaphore, there is no counting in condition variables

Two Semantics of Condition Variables

- Hoare semantics:
  - p_0 executes signal while p_1 is waiting ⇒ p_0 immediately yields the monitor to p_1
  - The logical condition holds when P_1 gets to run

```
if (resourceNotAvailable()) Condition.wait();
/* now available ... continue ... */
. . .
```

- Brinch Hansen ("Mesa") semantics:
  - p_0 executes signal while p_1 is waiting ⇒ p_0 continues to execute, then when p_0 exits the monitor p_1 can receive the signal
  - The logical condition may not hold when P_1 gets to run

Dining Philosophers Example

```
monitor dp {
   enum {thinking, eating} state[5];
   condition cond[5];

   void pickup(int i) {
      while (state[(i+4)%5]==eating || state[(i+1)%5]==eating)
        cond[i].wait();
      state[i] = eating;
   }

   void putdown(int i) {
      state[i] = thinking;
      cond[(i+4)%5].signal();
      cond[(i+1)%5].signal();
   }

   void init() {
      for (int i=0; i<5; i++)
        state[i] = thinking;
   }
}
```


Synchronization in Practice

- OS kernel synchronization
- User program synchronization
  - for threads
  - for processes

OS Kernel Synchronization

- There are multiple threads in the kernel
  - all threads in kernel share the same address space
  - these threads are different from "kernel threads" we discussed earlier
- When only need to protect a short critical section
  - busy waiting is OK
  - disabling interrupts, software/hardware spin locks
- For complex synchronization
  - busy waiting is not OK
  - semaphore, mutex lock, …
  - may need to yield the CPU or wake up a previously suspended thread

User Program Synchronization for Threads

- All threads share the same address space
- When only need to protect a short critical section (busy waiting is OK)
  - software/hardware spin locks
  - need any help from the kernel?
- For complex synchronization (busy waiting is not OK)
  - semaphore, mutex lock, condition variable, …
  - may need kernel help
- In pthreads
  - mutex lock and condition variable
  - condition variable must be used together with a mutex lock

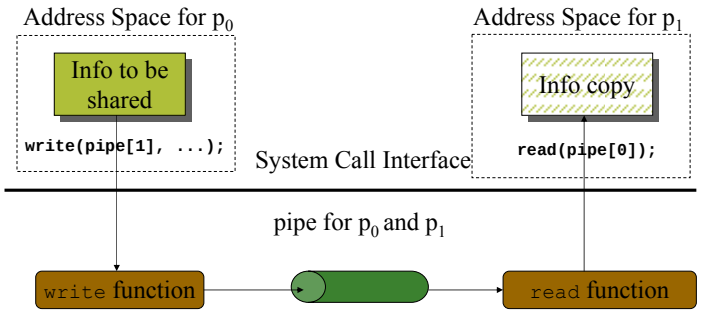
Synchronization Primitives in Pthreads

- Mutex lock
  - pthread_mutex_init
  - pthread_mutex_destroy
  - pthread_mutex_lock
  - pthread_mutex_unlock
- Condition variable (used in conjunction with a mutex lock)
  - pthread_cond_init
  - pthread_cond_destroy
  - pthread_cond_wait
  - pthread_cond_signal
  - pthread_cond_broadcast

User Program Synchronization for Processes

- Processes naturally do not share the same address space
- Process synchronization:
  - semaphore
  - shared memory
  - pipes

UNIX Pipes



UNIX Pipes (cont)

- The pipe interface is intended to look like a file interface
  - Analog of open is to create the pipe
  - File read/write system calls are used to send/receive information on the pipe
- What is going on here?
  - Kernel creates a buffer when pipe is created
  - Processes can read/write into/out of their address spaces from/to the buffer
  - Processes just need a handle to the buffer

UNIX Pipes (cont)

- File handles are copied on fork
- … so are pipe handles

```
int pipeID[2];
. . .
pipe(pipeID);
. . .
if(fork() == 0) { /* the child */
  . . .
  read(pipeID[0], childBuf, len);
  <process the message>;
  . . .
} else { /* the parent */
  . . .
  write(pipeID[1], msgToChild, len);
  . . .
}
```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