High-level Synchronization

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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 $P_i$:
- `wait(mutex);`
- critical section
- `signal(mutex);`
- remainder section

Semaphore Implementation

- Define a semaphore as a record
  ```
  typedef struct {
    int value;
    proc_list *L;
  } semaphore;
  ```
- 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;
    ... 
  }
  ```

### 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 
    }
  }
  ```

### Deadlock?

- Deadlock?
Condition Variables in Monitors

- To allow a process to wait within the monitor, a condition variable must be declared, as
  
  ```c
  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:
  
  - If `p0` executes `signal` while `p1` is waiting, then `p0` immediately yields the monitor to `p1`
  
  - The logical condition holds when `P1` gets to run if
    ```c
    if (resourceNotAvailable()) Condition.wait();
    /* now available ... continue ... */
    ```

- Brinch Hansen (“Mesa”) semantics:
  
  - `p0` executes `signal` while `p1` is waiting, then when `p0` exits the monitor `p1` can receive the signal
  
  - The logical condition may not hold when `P1` gets to run

Dining Philosophers Example

```c
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

Address Space for p0

Info to be shared

write(pipe[1], ...);

System Call Interface

Pipe for p0 and p1

write function

read function

Address Space for p1

Info copy

read(pipe[0]);

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

```c
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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