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.
- The Critical-Section problem
  - Pure software solution
  - With help from the hardware
- Problems with busy-waiting-based synchronization
  - Waste CPU, particularly when context switch occurs while a process is inside critical section
- Solution
  - Avoid busy wait as much as possible (yield the processor instead).
  - If you can’t avoid busy wait, you must prevent context switch during critical section (disable interrupts while in the kernel)

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:
    - 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); unlock(L2); 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**

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

**Consumer process**

```c
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):**

```c
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:**

```c
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
}
```
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:
  - `p0` executes `signal` while `p1` is waiting \( \Rightarrow \) `p0` immediately yields the monitor to `p1`
  - The logical condition holds when `P1` gets to run
    ```
    if (resourceNotAvailable()) Condition.wait();
    /* now available ... continue ... */
    ```

- Brinch Hansen (“Mesa”) semantics:
  - `p0` executes `signal` while `p1` is waiting \( \Rightarrow \) `p0` continues to execute,
    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

- User program synchronization
  - for threads
  - for processes

- OS kernel synchronization
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
  - still has the risk of context switch in the middle of critical section
- 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

Spin or Block in Synchronization

- Multi-processor synchronization.
- A process is waiting for an event, triggered by another process.
- Should it spin wait or yield the processor?
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