Synchronization Principles

Background
- Concurrent access to shared data may result in data inconsistency.
- Maintaining data consistency requires mechanisms to ensure the orderly execution of cooperating processes.

The Critical-Section Problem
- Pure software solution
- With help from the hardware

Synchronization without busy waiting (with the support of process/thread scheduler)
- Semaphore
- Mutex lock
- Condition variables

Recap of Last Class: CPU Scheduling
- CPU scheduling may take place at:
  - Hardware interrupt/software exception, system calls.

Objectives:
- Minimize completion time; maximize throughput
- Minimize response time
- Maintain fairness

Policies:
- FCFS, SJF, Priority
- Round-Robin
- Earliest Deadline First

Multiple scheduling policies in system
- Linux 2.4 task scheduling

Bounded Buffer

Shared data
typedef struct { ... } item;
item buffer[BUFFERSIZE];
int in = 0, out = 0;
int counter = 0;

Producer process
item nextProduced;
while (1) {
    while (counter==BUFFERSIZE);
    /* do nothing */
    buffer[in] = nextProduced;
    in = (in+1) % BUFFERSIZE;
    counter++;
}

Consumer process
item nextConsumed;
while (1) {
    while (counter==0);
    /* do nothing */
    nextConsumed = buffer[out];
    out = (out+1) % BUFFERSIZE;
    counter--;
}
Bounded Buffer

- The following statements must be performed atomically:
  - `counter++;
  - `counter--;

- Atomic operation means an operation that completes in its entirety without interruption.

- The statement "counter++" may be compiled into the following instruction sequence:
  - `register1 = counter;
  - `register1 = register1 + 1;
  - `counter = register1;

- The statement "counter--" may be compiled into:
  - `register2 = counter;
  - `register2 = register2 - 1;
  - `counter = register2;

Race Condition

- Race condition:
  - The situation where several processes access and manipulate shared data concurrently.
  - The final value of the shared data and/or effects on the participating processes depends upon the order of process execution.

- To prevent race conditions, concurrent processes must be synchronized.

The Critical-Section Problem

- Problem context:
  - n processes all competing to use some shared data
  - Each process has a code segment, called critical section, in which the shared data is accessed.

- Find a solution that satisfies the following:
  1. Mutual Exclusion. No two processes simultaneously in the critical section.
  2. Progress. No process running outside its critical section may block other processes.
  3. Bounded Waiting/Fairness. A bound must exist on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.

Eliminating Concurrency

- First idea: eliminating the chance of context switch when a process runs in the critical section.
  - software exceptions
  - hardware interrupts
  - system calls

- Disabling interrupts?
  - not feasible for user programs since they shouldn't be able to disable interrupts
  - feasible for OS kernel programs
    - for short critical sections
    - on single-processor machines
Critical Section for Two Processes

- Only 2 processes, P₀ and P₁
- General structure of process Pᵢ (other process Pⱼ)
  ```
  do { 
    entry section
    critical section
    exit section
    remainder section
  } while (1);
  ```
- Processes may share some common variables to synchronize their actions.
- Assumption: instructions are atomic and no re-ordering of instructions.

Algorithm 1

- Shared variables:
  ```
  int turn;
  initially turn = 0;
  turn == i \Rightarrow Pᵢ can enter its critical section
  ```
- Process Pᵢ
  ```
  do { 
    while (turn != i) ;  
    critical section
    turn = j;
    remainder section
  } while (1);
  ```
- Satisfies mutual exclusion, but not progress requirement.

Algorithm 2

- Shared variables:
  ```
  boolean flag[2];
  initially flag[0] = flag[1] = false;
  flag[i] == true \Rightarrow Pᵢ ready to enter its critical section
  ```
- Process Pᵢ
  ```
  do { 
    flag[i] = true;
    while (flag[j]) ;  
    critical section
    flag[i] = false;
    remainder section
  } while (1);
  ```
- Satisfies mutual exclusion, but not progress requirement.

Algorithm 3

- Combined shared variables of algorithms 1 and 2.
- Process Pᵢ
  ```
  do { 
    flag[i] = true;
    turn = j;
    while (flag[j] && turn == j) ;  
    critical section
    flag[i] = false;
    remainder section
  } while (1);
  ```
- Meets all three requirements; solves the critical-section problem for two processes. \(\Rightarrow\) called Peterson's algorithm.

⇒ called Peterson's algorithm.
Synchronization Using Special Instruction:
TSL (test-and-set)

**entry_section:**
- TSL R1, LOCK | copy lock to R1 and set lock to 1
- CMP R1, #0 | was lock zero?
- JNE entry_section | if it wasn’t zero, lock was set, so loop
- RET | return; critical section entered

**exit_section:**
- MOV LOCK, #0 | store 0 into lock
- RET | return; out of critical section

- Does it solve the synchronization problem?
- Does it work for multiple (>2) processes?
- What if you have special instruction SWP (swap the value of a register and a memory word)?

Solving Critical Section Problem with Busy Waiting

- In all our solutions, a process enters a loop until the entry is granted ⇒ busy waiting.
- Problems with busy waiting:
  - waste of CPU time
  - priority inversion
- What is the fundamental problem here?
- Develop solutions that do not busy wait. Need cooperation from the thread/process scheduler.

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

- 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;

- Solving the critical section problem:
  Shared data:
  mutex=unlocked;
  Process P:
  lock(mutex);
  critical section
  unlock(mutex);
  remainder section

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