G52CON:
Concepts of Concurrency

Lecture 7: Semaphores I

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Outline of this lecture

- problems with Peterson's algorithm
- semaphores
- implementing semaphores
- using semaphores
  - for Mutual Exclusion
  - for Condition Synchronisation
- semaphores and Java

Peterson's algorithm

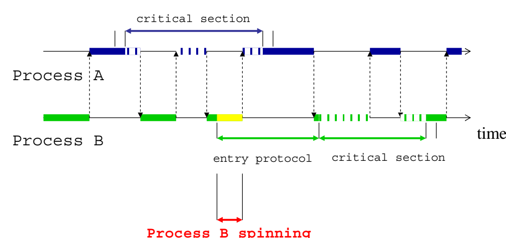
```
// Process 1                      // Process 2
init1;                            init2;
while(true) {                     while(true) {
    // entry protocol                 // entry protocol
    c1 = true;                        c2 = true;
    turn = 2;                         turn = 1;
    while (c2 && turn == 2) {};       while (c1 && turn == 1) {};
    crit1;                            crit2;
    // exit protocol                  // exit protocol
    c1 = false;                       c2 = false;
    rem1;                             rem2;
}                                 }

                    // shared variables
                    bool c1 = c2 = false;
                    integer turn == 1;
```


Problems with Peterson's algorithm

Peterson's algorithm is *correct*, however it is complex and inefficient:

- solutions to the Mutual Exclusion problem for *n* processes are quite complex
- it uses busy-waiting (spin locks) to achieve synchronisation, which is often unacceptable in a multiprogramming environment

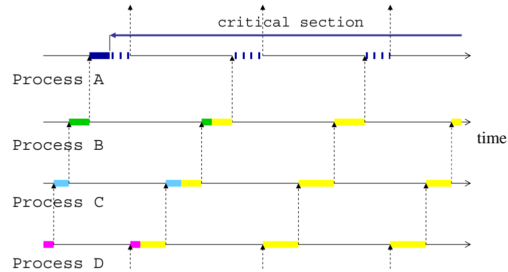
Overhead of spin locks



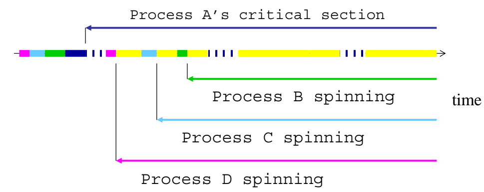
Overhead of spin locks

- time spent spinning is necessary to ensure mutual exclusion
- it is also wasted CPU—Process B can do no useful work while Process A is in its critical section
- however, the scheduler doesn't know this, and will (repeatedly) try to run Process B even while process A is in its critical section
- if the critical sections are large relative to the rest of the program, or there are a large number of processes contending for access to the critical section, this will slow down your concurrent program
- e.g., with 10 processes competing to access their critical sections, in the worst case we could end up wasting 90% (or more) of the CPU

Overhead of spin locks



Overhead of spin locks



Semaphores

A *semaphore s* is an integer variable which can take only non-negative values. Once it has been given its initial value, the only permissible operations on s are the atomic actions:

P(s) : if $s > 0$ then $s = s - 1$, else *suspend* execution of the process that called ***P***(s)

V(s) : if some process p is suspended by a previous ***P***(s) on this semaphore then resume p, else $s = s + 1$

A *general semaphore* can have any non-negative value; a *binary semaphore* is one whose value is always 0 or 1.

Semaphores as abstract data types

A semaphore can be seen as an **abstract data type**:

- a set of permissible values; and
- a set of permissible operations on instances of the type.

However, unlike normal abstract data types, we require that the ***P*** and ***V*** operations on semaphores be implemented as *atomic actions*.

P and *V* as atomic actions

Reading and writing the semaphore value is itself a *critical section*:

- ***P*** and ***V*** operations must be *mutually exclusive*
- e.g., suppose we have a semaphore, s, which has the value 1, and two processes simultaneously attempt to execute ***P*** on s:
  - only one of these operations will be able to complete before the next ***V*** operation on s;
  - the other process attempting to perform a ***P*** operation is suspended.
- Semaphore operations on distinct semaphores need not be mutually exclusive.

Resuming suspended processes

Note that the definition of ***V*** doesn't specify which process is woken up if more than one process has been suspended on the same semaphore

- this has implications for the fairness of algorithms implemented using semaphores and properties like Eventual Entry.
- we will come back to this later …

Implementing semaphores

To implement ***P*** and ***V*** as atomic actions, we can use any of the mutual exclusion algorithms we have seen so far:

- Peterson's algorithm
- special hardware instructions (e.g. Test-and-Set)
- disabling interrupts

There are several ways a processes can be suspended:

- busy waiting–this is inefficient
- blocking: a process is *blocked* if it is waiting for an event to occur without using any processor cycles (e.g., a not-runnable thread in Java).

Using semaphores

We can think if ***P*** and ***V*** as controlling access to a resource:

- when a process wants to use the resource, it performs a ***P*** operation:
  - if this succeeds, it decrements the amount of resource available and the process continues;
  - if all the resource is currently in use, the process has to wait.
- when a process is finished with the resource, it performs a ***V*** operation:
  - if there were processes waiting on the resource, one of these is woken up;
  - if there were no waiting processes, the semaphore is incremented indicating that there is now more of the resource free.
  - note that the definition of V doesn't specify *which* process is woken up if more than one process has been suspended on the same semaphore.

Semaphores for mutual exclusion and condition synchronisation

Semaphores can be used to solve mutual exclusion and condition synchronisation problems:

- semaphores can be used to implement the entry and exit protocols of mutual exclusion protocols in a straightforward way
- semaphores can also be used to implement more efficient solutions to the condition synchronisation problem

General form of a solution

We assume that each of the *n* processes have the following form, $i = 1, \ldots, n$

```
// Process i
init_i;
while(true) {
 // entry protocol
 crit_i;
 // exit protocol
 rem_i;
}
```


Mutual exclusion using a binary semaphore

```
binary semaphore s = 1;   // shared binary
                          // semaphore

// Process i
init_i;
while(true) {
 P(s);             // entry protocol
 crit_i;
 V(s);             // exit protocol
 rem_i;
}
```


Other advantages

In addition:

- the semaphore solution works for n processes;
- it is much simpler than an n process solution based on Peterson's algorithm; and
- it avoids busy waiting.

Solving the Ornamental Gardens

```
// East turnstile            // West turnstile

// initialisation            // initialisation
while(true) {                while(true) {
  // wait for turnstile        // wait for turnstile

  count = count + 1;           count = count + 1;

  // other stuff ...           // other stuff ...
}                            }

              integer count == 0
```


Selective mutual exclusion with general semaphores

If we have *n* processes, of which *k* can be in their critical section at the same time:

```
semaphore s = k;      // shared general semaphore

// Process i
init_i;
while(true) {
    P(s);             // entry protocol
    crit_i;
    V(s);             // exit protocol
    rem_i;
}
```


Semaphores and condition synchronisation

Condition synchronisation involves delaying a process until some boolean condition is true.

- condition synchronisation problems can be solved using *busy waiting*:
  - the process simply sits in a loop until the condition is true
  - busy waiting is inefficient
- semaphores are not only useful for implementing mutual exclusion, but can be used for general condition synchronisation.

Producer-Consumer with an infinite buffer

Given two processes, a ***producer*** which generates data items, and a ***consumer*** which consumes them:

- we assume that the processes communicate via an *infinite* shared buffer;
- the producer may produce a new item at any time;
- the consumer may only consume an item when the buffer is not empty; and
- all items produced are eventually consumed.

This is an example of a *Condition Synchronisation* problem: delaying a process until some Boolean condition is true.

Infinite buffer solution

```
// Producer process             // Consumer process
Object v = null;                Object w = null;
integer in = 0;                 integer out = 0;
while(true) {                   while(true) {
    // produce data v               P(n);
    ...                             w = buf[out];
    buf[in] = v;                    out = out + 1;
    in = in + 1;                    // use the data w
    V(n);                           ...
}                               }

         // Shared variables
         Object[] buf = new Object[∞];
         semaphore n = 0;
```


Semaphores in Java

- as of Java 5, Java provides a `Semaphore` class in the package `java.util.concurrent`
- supports *P* and *V* operations (called `acquire()` and `release()` in the Java implementation)
- the constructor optionally accepts a *fairness* parameter
  - if this is false, the implementation makes no guarantees about the order in which threads are awoken following a release()
  - if *fairness* is true, the semaphore guarantees that threads invoking any of the acquire methods are processed first-in-first-out (FIFO)
- Java implementation of semaphores is based on higher-level concurrency constructs called monitors

The next lecture

Semaphores II

Suggested reading:

- Andrews (2000), chapter 4, sections 4.1–4.2;
- Ben-Ari (1982), chapter 4;
- Burns & Davies (1993), chapter 6.