CMSC 412
Fall 2004
Implementing Synchronization

Review

- What is synchronization and why do we need it?
- What is deadlock?
- How are synchronization and deadlock related?

- Reading: chapter 7.
Race Condition

- **Race condition**: The situation where several processes access and manipulate shared data concurrently. The final value of the shared data depends upon which process finishes last.

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

The Critical-Section Problem

- *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.
- Problem - ensure that when one process is executing in its critical section, no other process is allowed to execute in its (related) critical section.
Implementing Critical-Section

1. **Mutual Exclusion.** If process $P_i$ is executing in its critical section, then no other processes can be executing in their critical sections.

2. **Progress.** If no process is executing in its critical section and there exist some processes that wish to enter their critical section, then the selection of the processes that will enter the critical section next cannot be postponed indefinitely.

3. **Bounded Waiting.** 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.
   - Assume that each process executes at a nonzero speed
   - No assumption concerning relative speed of the $n$ processes.

Assumptions

- Some instructions are atomic
  - load, store, test instructions cannot be interrupted
- Hardware configuration can vary
  - Single or multiple processors
Simpler Problem

- Only 2 processes, $P_0$ and $P_1$
- General structure of process $P_i$ (other process $P_j$)
  
  \[
  \text{do } \{
  \begin{array}{l}
  \text{entry section} \\
  \text{critical section} \\
  \text{exit section} \\
  \text{remainder section}
  \end{array}
  \} \text{ while (1);}
  \]

- Processes may share some common variables to synchronize their actions.

Algorithm 1

- Shared variables:
  - int turn (initially turn = 0)
  - turn - i $\Rightarrow P_i$ can enter its critical section
- Process $P_i$
  
  \[
  \text{do } \{
  \begin{array}{l}
  \text{while (turn != i) ;} \\
  \text{critical section} \\
  \text{turn = j;} \\
  \text{remainder section}
  \end{array}
  \} \text{ while (1);}
  \]
Algorithm 1

• Satisfies mutual exclusion but not progress.
  - Processes are forced to enter their critical sections alternately.
  - One process not in its critical section thus prevents the other from entering its critical section.

Algorithm 2

• Shared variables
  - boolean flag[2];
    initially flag [0] = flag [1] = false.
  - flag [i] = true ⇒ $P_i$ ready to enter CS
• Process $P_i$

  do {
    flag[i] := true;
    while (flag[j]) ;
    critical section
    flag [i] = false;
    remainder section
  } while (1);
Algorithm 2

- Satisfies mutual exclusion, but not progress requirement.
  - Both processes can end up setting their flag[] variable to true, and thus neither process enters its critical section!

Algorithm 3

- Combined shared variables of algorithms 1 and 2.
- Process P_i
  
  do {
    flag [i] := true;
    turn = j;
    while (flag [j] and turn = j) ;
    critical section
    flag [i] = false;
    remainder section
  } while (1);
Algorithm 3

- Meets all three requirements; solves the critical-section problem for two processes.
  - One process is always guaranteed to get into its critical section.
  - Processes are forced to take turns when they both want to get in.

Bakery Algorithm

Critical section for $n$ processes

- Before entering its critical section, process receives a number. Holder of the smallest number enters the critical section.
- If processes $P_i$ and $P_j$ receive the same number, if $i < j$, then $P_i$ is served first; else $P_j$ is served first.
- The numbering scheme always generates numbers in increasing order of enumeration; i.e., 1,2,3,3,3,3,4,5...
Bakery Algorithm

- Notation $\leq$ lexicographical order (ticket #, process id #)
  - $(a,b) < (c,d)$ if $a < c$ or if $a = c$ and $b < d$
  - $\max(a_0, \ldots, a_{n-1})$ is a number, $k$, such that $k \geq a_i$ for $i = 0, \ldots, n - 1$

- Shared data
  
  ```
  boolean choosing[n];
  int num[n];
  ```

  Data structures are initialized to `false` and `0` respectively

Bakery Algorithm

```java
do {
    choosing[i] = true;
    num[i] = max(num[0], num[1], ..., num[n - 1]) + 1;
    choosing[i] = false;
    for (j = 0; j < n; j++) {
        while (choosing[j]) ;
        while ((num[j] != 0) && (num[j],j) < (num[i],i)) ;
    }
    critical section
    num[i] = 0;
    remainder section
} while (1);
```
Synchronization Hardware

- Uniprocessor machine
  - Disable/enable interrupts:
    Process $P_i$
    
    ```
    do {
        while (!Interrupts_Enabled()) ;
        Disable_Interrupts()
        critical section
        Enable_Interrupts()
        remainder section
    }
    ```

Disabling Interrupts

- Doesn’t work for multiprocessors
- Doesn’t permit different groups of critical sections
Synchronization Hardware

- **Test-and-Set (Tset):**
  - Test and modify the content of a word atomically

  ```java
  boolean TestAndSet(boolean *target) {
    boolean rv = *target;
    *target = true;
    return rv;
  }
  ```

Mutual Exclusion with TSet

- **Shared data:**
  ```java
  boolean lock = false;
  ```

- **Process \( P_i \):**
  ```java
  do {
    while (TestAndSet(lock)) ;
    critical section
    lock = false;
    remainder section
  }
  ```
Synchronization Hardware

- **Swap**
  - Atomically swap two variables.

```c
void Swap(boolean *a, boolean *b) {
    boolean temp = *a;
    *a = *b;
    *b = temp;
}
```

Mutual Exclusion with Swap

- Shared data (initialized to false):
  ```c
  boolean lock;
  boolean waiting[n];
  ```
- Process $P_i$
  ```c
  do {
      key = true;
      while (key == true) Swap(lock, key);
      critical section
      lock = false;
      remainder section
  }
  ```
Semaphores

- Synchronization tool
- Semaphore $S$ - integer variable
- can only be accessed via two indivisible (atomic) operations:
  
  \[
  \text{wait } (S):
  \]
  
  while $S \leq 0$ do \textit{no-op};
  
  $S--;
  
  \]

  \[
  \text{signal } (S):
  \]
  
  $S++;
  
  

Critical Section of $n$ Processes

- Shared data:
  
  \[
  \text{semaphore mutex; } //\text{initially } \text{mutex} = 1
  \]

- Process $P_i$:
  
  \[
  \text{do } \{
  \text{wait(mutex)};
  \text{critical section}
  \text{signal(mutex)};
  \text{remainder section}
  \} \text{ while (1);}
  \]
Semaphore Implementation

- To avoid busy-waiting, define a semaphore as a record
  
  ```c
  typedef struct {
    int value;
    struct process *L;
  } semaphore;
  ```

- Assume two simple operations:
  - `block` suspends the process that invokes it.
  - `wakeup(P)` resumes the execution of a blocked process P.

Implementation

- Semaphore operations now defined as

  `wait(S):`
  
  ```c
  S.value--;
  if (S.value < 0) {
    add this process to S.L;
    block();
  }
  ```

  `signal(S):`
  
  ```c
  S.value++;
  if (S.value <= 0) {
    remove a process P from S.L;
    wakeup(P);
  }
  ```
Two Types of Semaphores

- **Counting semaphore** - integer value can range over an unrestricted domain.
- **Binary semaphore** - integer value can range only between 0 and 1; can be simpler to implement.
- Can implement a counting semaphore $S$ as a binary semaphore.

Implementing $S$ as a Binary Semaphore

Data structures:
- binary-semaphore $S1, S2$;
- int $C$:

Initialization:
- $S1 = 1$
- $S2 = 0$
- $C = \text{initial value of semaphore } S$
Implementing $S$ (wait)

```c
wait(S1);
C--;
if (C < 0) {
    signal(S1);
    wait(S2);
}
signal(S1);
```

Implementing $S$ (signal)

```c
wait(S1);
C ++;
if (C <= 0)
    signal(S2);
else
    signal(S1);
```
Semaphores for Ordering

- Execute B in $P_j$ after A executed in $P_i$
- Use semaphore flag initialized to 0
- Code:

  $P_i$  $P_j$
  $\vdots$  $\vdots$
  A       wait(flag)
  signal(flag)  B

Classical Synchronization Problems

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem
Bounded-Buffer Problem

- Shared data

    semaphore full, empty, mutex;

Initially:

    full = 0, empty = n, mutex = 1

where $n$ is the size of the buffer.

Producer Process

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

do {
    wait(full)
    wait(mutex);
    ... remove an item from buffer
    signal(mutex);
    signal(empty);
    ... consume removed item
} while (1);

Readers-Writers Problem

• Shared data

    semaphore mutex, wsem;

Initially

    mutex = 1, wsem = 1, readcount = 0
Writer Process

wait(wsem);
... writing is performed
signal(wsem);

Reader Process

wait(mutex);
readcount++;
if (readcount == 1)
  wait(wsem);
signal(mutex);
... reading is performed
wait(mutex);
readcount--;
if (readcount == 0)
  signal(wsem);
signal(mutex);
Comments

- Readers have priority - a writer can gain access to the data only if there are no readers (i.e. when readcount is zero, signal(wsem) executes)
- Possibility of starvation - writers may never gain access to data

Reader Process

wait(rsem);
wait(x);
readcount++;
if (readcount == 1) then
    wait(wsem);
signal(x);
signal(rsem);

Read here

wait(x);
readcount--;
if (readcount == 0) then
    if (readcount == 0) then
        signal(wsem)
signal(x)
Writer Process

wait(y);
writecount++:
if writecount == 1 then
    wait(rsem);
signal(y);
wait(wsem);

Write here

signal(wsem);
wait(y);
writecount--;
if (writecount == 0) then
    signal(rsem);
signal(y);

Dining-Philosophers Problem

• Shared data
  
  semaphore chopstick[5];

Initially all values are 1
Dining-Philosophers Problem

• Philosopher $i$:
  do {
    wait(chopstick[i])
    wait(chopstick[(i+1) % 5])
    ... eat
    signal(chopstick[i]);
    signal(chopstick[(i+1) % 5]);
    ... think
  } while (1);

Comments

• This solution can deadlock
  - Imagine each philosopher grabbing one chopstick (wait()), and then being context-switched. None can make progress
  - Can you draw a wait-graph to show this situation?