More on Semaphores, and Classic Synchronization Problems

CSCI 3753 Operating Systems
Spring 2005
Prof. Rick Han

Announcements

- HW #3 is due Friday Feb. 25, a week+ from now
- PA #2 is coming, assigned about next Tuesday
- Midterm is tentatively Thursday March 10
- Read chapters 8 and 9

From last time...

- We introduced critical sections, atomic locks, and semaphores
- A semaphore S is an integer variable
  - initialize S to some value $S_{init} = n$
  - P(S) operates atomically on S to decrement S, but only if S>0. Otherwise, the process calling P(S) relinquishes control.
  - V(S) atomically increments S
- A binary semaphore, a.k.a. mutex lock, can be used to provide mutual exclusion on critical sections
  - $S_{init} = 1$
  - value of semaphore varies only between 0 and 1

Semaphores

- Usage example #1: mutual exclusion

```
Semaphore S = 1;  // initial value of semaphore is 1
int counter;            // assume counter is set correctly somewhere in code
```

```
Process P1:                          Process P2:


P(S);                                P(S);
   // execute critical section          // execute critical section
   counter++;                           counter--;
V(S);                                V(S);
```

- Both processes atomically P() and V() the semaphore S, which enables mutual exclusion on critical section code, in this case protecting access to the shared variable counter

Semaphores

- Usage example #2: enforcing *order* of access between two processes
  - Suppose there are two processes P1 and P2, where P1 contains code C1 and P2 contains code C2
  - Want to ensure that code C1 executes before code C2
  - Use semaphores to synchronize the order of execution of the two processes

```
Semaphore S=0;    // initial value of semaphore = 0



Process P1:                                Process P2:


C1;              // execute C1             wait(S);    // P() the semaphore
signal(S);      // V() the semaphore       C2;         // execute C2
```

Semaphores

- In the previous example #2, there are two cases:
  1. if P1 executes first, then
     - C1 will execute first, then P1 will V() the semaphore, increasing its value to 1
     - Later, when P2 executes, it will call wait(S), which will decrement the semaphore to 0 followed by execution of C2
     - Thus C1 executes before C2
  2. If P2 executes first, then
     - P2 will block on the semaphore, which is equal to 0, so that C2 will not be executed yet
     - Later, when P1 executes, it will run through C1, then V() the semaphore
     - This awakens P2, which then executes C2
     - Thus C1 executes before C2

Semaphores

- Let’s revisit the following intuitive implementation of semaphores that uses only disabling and reenabling of interrupts
  - Note that a process that blocks on this kind of semaphore will spin in a busy wait while() loop - this type of semaphore is called a *spinlock*
- Figure 8.25 in the text illustrates a semaphore implemented using a TestandSet instruction that also exhibits spinlock behavior

```
P(S) {
    disableInterrupts();
    while(S==0) {
        enableInt();
        disableInt();
    }
    S--;
    enableInt()
}
```

```
V(S) {
    disableInt();
    S++;
    enableInt()
}
```

Semaphores

- Spinlock implementations of semaphores can occupy the CPU unnecessarily
- Instead, sleep the process until it needs to be woken up by a V()/signal()

```
P(semaphore *S) {
    S->value--;
    if (S->value<0) {
        add this process to S->list;
        block();
    }
}
```

```
V(semaphore *S) {
    S->value++;
    if (S->value<=0) {
        remove a process P from S->list;
        wakeup(P);
    }
}
```

where we have defined the following structure for a semaphore

```
typedef struct {
    int value;
    struct process *list;
} semaphore;
```

Semaphores

- In the previous slide’s redefinition of a semaphore, we are departing from the classic definition of a semaphore
  - Now, the semaphore’s value is allowed to be negative, because the decrement occurs before the test in P()
  - The absolute value of the semaphore’s negative amount can now be used to indicate the number of processes blocked on the semaphore
  - Processes now yield the CPU if the semaphore’s value is negative, rather than busy wait
  - If more than one process is blocked on a semaphore, then use a FIFO queue to select the next process to wake up when a semaphore is V’ed
    - Why is LIFO to be avoided?

Deadlock

- Semaphores provide synchronization, but can introduce more complicated higher level problems like *deadlock*
  - two processes deadlock when each wants a resource that has been locked by the other process
  - e.g. P1 wants resource R2 locked by process P2 with semaphore S2, while P2 wants resource R1 locked by process P1 with semaphore S1

Deadlock

Semaphore Q= 1;   // binary semaphore as a mutex lock

Semaphore S = 1;   // binary semaphore as a mutex lock

Process P1:			*Process P2:*
P(S);	(1)	(2)	P(Q);
P(Q);	(3)	(4)	P(S);
		Deadlock!	
modify R1 and R2;			modify R1 and R2;
V(S);			V(Q);
V(Q);			V(S);

If statements (1) through (4) are executed in that order, then P1 and P2 will be deadlocked after statement (4) - verify this for yourself by stepping thru the semaphore values

Deadlock

- In the previous example,
  - Each process will sleep on the other process’s semaphore
  - the V() signalling statements will never get executed, so there is no way to wake up the two processes from within those two processes
  - there is no rule prohibiting an application programmer from P()’ing Q before S, or vice versa - the application programmer won’t have enough information to decide on the proper order
  - in general, with N processes sharing N semaphores, the potential for deadlock grows

Deadlock

- Other examples:
  - A programmer mistakenly follows a P() with a second P() instead of a V(), e.g.

```
P(mutex)
    critical section
P(mutex)    <---- this causes a deadlock, should have been a V()
```

  - A programmer forgets and omits the P(mutex) or V(mutex). Can cause deadlock if V(mutex) is omitted. Can violate mutual exclusion if P(mutex) is omitted.
  - A programmer reverses the order of P() and V(), e.g.

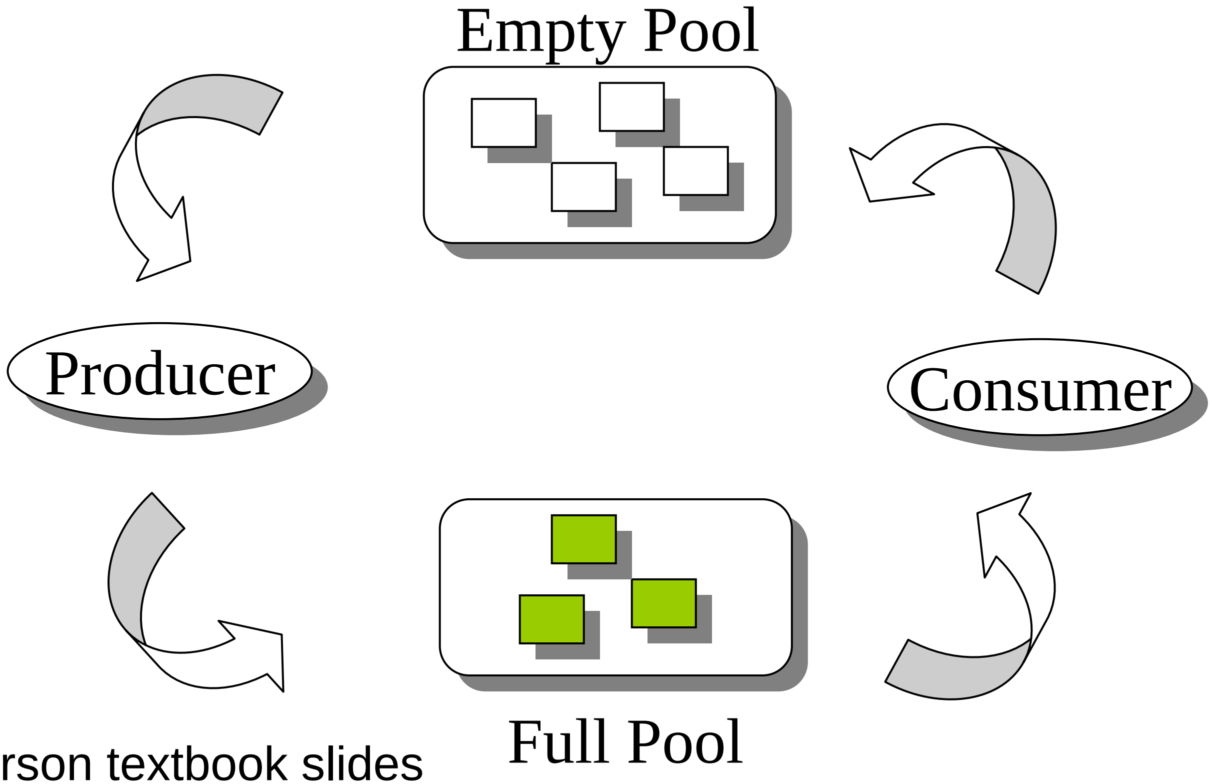
```
V(mutex)
    critical section    <---- this violates mutual exclusion, but is not an
P(mutex)                      example of deadlock
```

Classic Synchronization Problems

- Bounded Buffer Producer-Consumer Problem
- Readers-Writers Problem
  - First Readers Problem
- Dining Philosophers Problem
- These are not just abstract problems
  - They are representative of several classes of synchronization problems commonly encountered when trying to synchronize access to shared resources among multiple processes

Bounded Buffer
Producer/Consumer Problem

- Pool of *n* buffers, each capable of holding 1 item
- producer takes an empty buffer and produces a full buffer
- consumer takes a full buffer and produces an empty buffer



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Bounded Buffer Producer/Consumer Problem

- Synchronization setup:
  - Use a mutex semaphore to protect access to buffer manipulation, $mutex_{init} = 1$
  - Use two counting semaphores *full* and *empty* to keep track of the number of full and empty buffers, where the values of $full + empty = n$
    - $full_{init} = 0$
    - $empty_{init} = n$

Bounded Buffer Producer/Consumer Problem

- Why do we need counting semaphores? Why do we need two of them? Consider the following:

Producer:

```
while(1) {
    // need code here to keep track of
     number of empty buffers
    P(mutex)
        obtain empty buffer and add
     next item, creating a full buffer
    V(mutex)
    ...
}
```

Consumer:

```
while(1) {
    ...

    P(mutex)
        remove item from full buffer,
     create an empty buffer
     V(mutex)
    ...
}
```

Bounded Buffer Producer/Consumer Problem

- If we add an *empty* counting semaphore initialized to n, then a producer calling P(empty) will keep decrementing until 0, replacing n empty buffers with n full ones. If the producer tries to produce any more, P(empty) blocks producer until more empty buffers are available - this is the proper behavior that we want

Producer:

```
while(1) {
    P(empty)

    P(mutex)
        obtain empty buffer and add next item, creating a full buffer
    V(mutex)
    ...
}
```

Consumer:

```
while(1) {
    ...

    P(mutex)
        remove item from full buffer, create an empty buffer
    V(mutex)
    ...
}
```

Bounded Buffer Producer/Consumer Problem

- We also need to add V(*empty*), so that when the consumer is done reading, more empty buffers are produced.
- Unfortunately, this solution does not prevent a consumer from reading even when there are no buffers to read. For example, if the first consumer reads before the first producer executes, then this solution will not work.

Producer:

```
while(1) {
    P(empty)

    P(mutex)
        obtain empty buffer and add
     next item, creating a full buffer
    V(mutex)
    ...
}
```

Consumer:

```
while(1) {
    ...

    P(mutex)
        remove item from full buffer,
     create an empty buffer
     V(mutex)
    V(empty)
}
```

Bounded Buffer Producer/Consumer Problem

- So add a second counting semaphore full, initially set to 0
- Verify for yourself that this solution won’t deadlock, synchronizes properly with mutual exclusion, prevents a producer from writing to a full buffer, and prevents a consumer from reading from an empty buffer

Producer:

```
while(1) {
    P(empty)

    P(mutex)
        obtain empty buffer and add
     next item, creating a full buffer
    V(mutex)
    V(full)
}
```

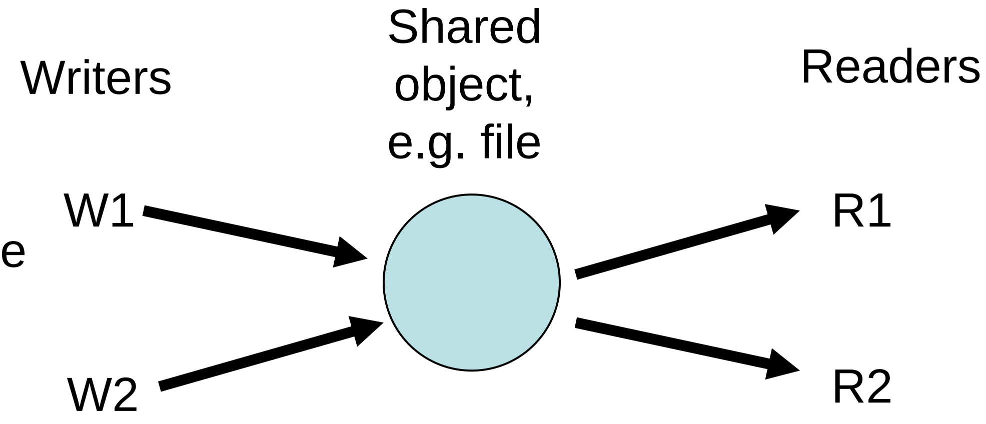
Consumer:

```
while(1) {
    P(full)

    P(mutex)
        remove item from full buffer,
     create an empty buffer
     V(mutex)
    V(empty)
}
```

The Readers/Writers Problem

- There are several writer processes that want to write to a shared object, e.g. a file, and also several reader processes that want to read from the same shared object
- Want to synchronize access



Writers

Shared object, e.g. file

Readers

W1

W2

R1

R2

a writer must have exclusive access

Readers can share with any other reader but not a writer

The “First Readers/Writers Problem”: no reader is kept waiting unless a writer already has seized the shared object. We will implement this in the next slides.

The Readers/Writers Problem

- readers share data structures:
  - semaphore mutex, wrt;   // initialized to 1
  - int readcount;   // initialized to 0, controlled by mutex
- writers also share semaphore wrt

Writer:

```
while(1) {
    wait(wrt);
        // writing
    signal(wrt);
}
```

Reader:

```
while(1) {
    wait(mutex);
    readcount++;
    if (readcount==1) wait(wrt);
    signal(mutex);

    // reading

    wait(mutex);
    readcount--;
    if (readcount==0) signal(wrt);
    signal(mutex);
}
```

The Readers/Writers Problem

- If multiple writers seek to write, then the write semaphore wrt provides mutual exclusion
- If the 1st reader tries to read while a writer is writing, then the 1st reader blocks on wrt
  - if subsequent readers try to read while a writer is writing, they block on mutex
- If the 1st reader reads and there are no writers, then 1st reader grabs the write lock and continues reading, eventually releasing the write lock when done reading
  - if a writer tries to write while the 1st reader is reading, then the writer blocks on the write lock wrt
  - if a 2nd or any subsequent reader tries to read while the 1st reader is reading, then it falls through and is allowed to read