Chapter 5: Synchronization
Mutual Exclusion & Semaphores

CSCI 3753 Operating Systems

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Announcements

- PA1 & PS1 due **Today**
  - Add a system call to the linux kernel
- PA2 & PS2 have been released
  - Add a device driver to Linux using kernel modules
  - Both are due June 26th

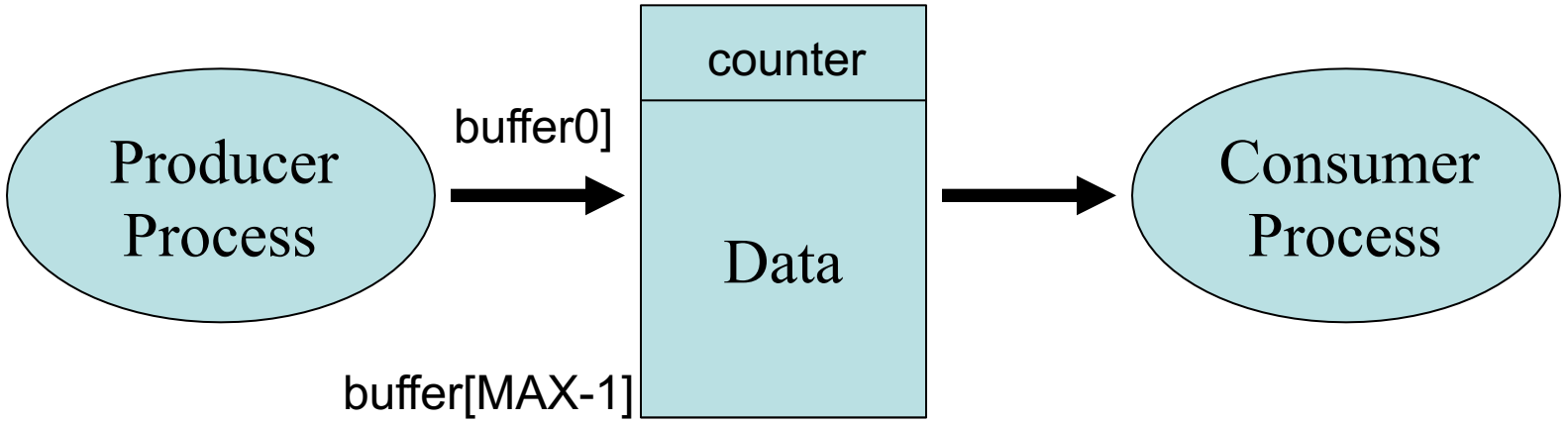
- Reading: Chapter 5
  - Next week 5 & 7

Recap

- Mutual exclusion/synchronization
  - Disabling interrupts in critical section
  - Locks: Acquire(lock) and Release(lock)
    - Disable interrupts within Acquire() so test-and-set is atomic
    - spinlock implementation
    - Test-and-Set implementation

Synchronization

Bounded Buffer




```
while(1) {!
    while(counter==MAX);!
    buffer[in] = nextdata;!
    in = (in+1) % MAX;!
    counter++;!
}!
```

```
while(1) {!
    while(counter==0);!
    getdata = buffer[out];!
    out = (out+1) % MAX;!
    counter--;!
}!
```

Producer writes new data into buffer and increments counter

counter updates can conflict!

Consumer reads new data from buffer and decrements counter

Synchronization

counter++; can compile into several machine language instructions, e.g.

```
reg1 = counter;
reg1 = reg1 + 1;
counter = reg1;
```

counter--; can compile into several machine language instructions, e.g.

```
reg2 = counter;
reg2 = reg2 - 1;
counter = reg2;
```

If these low-level instructions are *interleaved*, e.g. due to context-switching, then the results of counter's value can be unpredictable

A Race Condition Example

- Let brackets [value] denote local value of counter in either the producer or consumer's process. counter=5 initially.

```
// counter++                          // counter--;
(1)  reg1 = counter;      [5]    (2)  reg2 = counter;      [5]
(3)  reg1 = reg1 + 1;     [6]    (4)  reg2 = reg2 - 1;     [4]
(5)  counter = reg1;      [6]    (6)  counter = reg2;      [4]
```

- Counter should be 5 with 1 producer and 1 consumer, but counter = 4! Reversing steps (5) and (6) sets counter=6
- Undesirable and unpredictable *race condition*
- Basic Problem: unprotected access to a shared variable (counter)

Critical Section

- Some kernel data structures could be subject to race conditions, e.g. access to list of open files
- Kernel developer must ensure that no such race conditions occur
- User or kernel developer identifies *critical sections* in code where each process accesses shared variables
  - access to critical sections is controlled by special *entry* and *exit* code

```
while(1) {

    entry section

        critical section (manipulate common var's)

    exit section

        remainder section code

}
```

Critical Section

- Critical section access should satisfy multiple properties

Mutual Exclusion

- if process P_i is executing in its critical section, then no other processes can be executing in their critical sections

Progress

- if no process is executing in its critical section and some processes wish to enter their critical sections, then only those processes that are not executing in their remainder sections can participate in the decision on which will enter its critical section next
- this selection cannot be postponed indefinitely (OS must make a decision eventually, hence "progress")

Bounded Waiting

- there exists a bound, or limit, on the number of times other processes can enter their critical sections after a process X has made a request to enter its critical section and before that request is granted (no starvation)

Disabling Interrupts

```
shared int counter;
```

Code for p_1

```
disableInterrupts();
counter++;
enableInterrupts();
```

Code for p_2

```
disableInterrupts();
counter--;
enableInterrupts();
```

Drawbacks?

- Interrupts could be disabled a **long time**
  - Interrupts can be disabled too long, e.g. if the critical section has many lines of code
  - Can prevent useful I/O from being processed
  - Can prevent useful progress on other processes

A Lock Example

```
shared int counter;
shared Lock lock;
```

Code for p_1

```
Acquire(lock);
...
counter++;
...
Release(lock);
```

Code for p_2

```
Acquire(lock);
...
counter--;
...
Release(lock);
```

- Lock-based solutions only work if all processes participate and surround critical sections with entry and exit code to synchronize access to shared data
- Acquire and Release implemented as system calls

A Flawed Lock Implementation

```
shared boolean lock = FALSE;
shared int counter;
```

Code for p_1

```
/* Acquire the lock */
  while(lock){ no_op;}
  lock = TRUE;

/* Execute critical
      section */
  counter++;

/* Release lock */
  lock = FALSE;
```

Code for p_2

```
/* Acquire the lock */
  while(lock){ no_op;}
  lock = TRUE;

/* Execute critical
      section */
  counter--;

/* Release lock */
  lock = FALSE;
```

Testing of the lock using a while() is subject to a race condition

example from Pearson slides

A Correct Lock Implementation

```
Acquire(lock) {
  disableInterrupts();

/* Wait for lock */
  while(lock) {
     enableInterrupts();
     disableInterrupts();
  }
  lock = TRUE;
  enableInterrupts();
}
```

```
Release(lock) {
  disableInterrupts();
  lock = FALSE;
  enableInterrupts();
}
```

- Advantage: no race condition as test-and-set is atomic
- Disadvantage:
  - busy waiting to acquire lock (A busy waiting type of lock is also called a spinlock)
  - task is stuck in Acquire() and can't do other work

example from Pearson slides

A Test-and-Set Lock Implementation

```
shared boolean lock = FALSE;
shared int counter;
```

Code for p_1

```
/* Acquire the lock */
  while(TestandSet(&lock));

/* Execute crit sect */
  counter++;

/* Release lock */
  lock = FALSE;
```

Code for p_2

```
/* Acquire the lock */
while(TestandSet(&lock));

/* Execute crit sect */
   counter--;

/* Release lock */
   lock = FALSE;
```

```
boolean TestandSet(boolean *target){
    boolean rv = *target;
    *target = TRUE;
```

This entire instruction (sequence) is atomic. The hardware enforces atomicity.

Blocking on Locks

- Simplicity of spinlocks:
  - don't require any other OS constructs, such as a queue of tasks blocked on the lock
  - If multiple tasks are blocked on the lock, they all spin
  - Can be useful if blocking time is short
- Locks can be augmented with queues to hold blocked tasks
  - OS scheduler must be involved
  - Useful when blocking time is long
  - We'll see an example of this with semaphores

Semaphores

- more general solution to mutual exclusion proposed by Dijkstra
- Semaphore S is an integer variable that, apart from initialization, is accessed only through 2 standard atomic operations
  - P(), also called wait()
    - somewhat equivalent to a test-and-set, but also *decrements* the value of S
  - V(), also called signal()
    - *increments* the value of S
  - OS provides ways to create and manipulate semaphores atomically

Semaphores

- Pseudo-code for classic semaphore
  - its value can't go below zero, i.e. classic semaphore is non-negative

"atomic"

```
P(S) {
     while(S<=0)
          {wait or no op;}
     S--;
}
```

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

atomic

P() is "atomic" in the sense that it tests S atomically, and if S<=0, then the process calling P() will *relinquish control*. Otherwise, the process continues forward and decrements S atomically.

A Semaphore Implementation

- Based only disabling and reenabling of interrupts
  - semaphores can also be implemented using TestandSet() instructions

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

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

disable interrupts because S++ might cause race condition

Also a form of spinlock
S not decremented unless it is positive

Mutual Exclusion with Semaphores

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

Process P1:

```
P(S);
   // execute crit sect
    counter++;
V(S);
```

Process P2:

```
P(S);
   // execute crit sect
    counter--;
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

Mutual Exclusion with Semaphores

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

Process P1:

```
P(S);
   // execute crit sect
    counter++;
V(S);
```

Process P2:

```
P(S);
   // execute crit sect
    counter--;
V(S);
```

- The 1st process that calls P() on semaphore S will check if S==0 (it is not), and then will atomically decrement S to 0
- The next process calling P(S) blocks on semaphore S since S=0, hence mutual exclusion is achieved
- When 1st process is done, it calls V(S), atomically incrementing S to 1

Mutual Exclusion with Semaphores

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

Process P1:

```
P(S);
   // execute crit sect
    counter++;
V(S);
```

Process P2:

```
P(S);
   // execute crit sect
    counter--;
V(S);
```

- After a V(S), all waiting processes are busy-waiting, so there is a race to see which one calls P(S) first

Binary Semaphores

- The previous example showed how to use the semaphore as a *binary* semaphore
  - its initial value was set to 1
  - a binary semaphore is also called a *mutex lock*, i.e. it can be used to provide mutual exclusion on some piece of critical code
  - Let's define a binary semaphore as a semaphore whose value can't exceed 1, even if many processes keep signal()'ing the semaphore
    - Additional logic would have to be added to the counting semaphore in its V()/signal() function to cap its maximum value to 1

Counting Semaphores

- A semaphore can also be used more generally as a *counting* semaphore
  - its initial value is n, e.g. n=10
  - the value of the semaphore could be used to keep track of the number of instances of a finite resource that are still available
    - We'll see an example later using counting semaphores to solve the general producer/consumer bounded buffer problem

Enforcing Order with Semaphores

- Enforce *order* of access between 2 processes P1 and P2
  - 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:

```
C1;             // execute C1
signal(S);      // V() semaphore
```

Process P2:

```
wait(S);        // P() semaphore
C2;             // execute C2
```

Enforcing Order with Semaphores

- if P1 executes 1st, then
  - C1 will execute 1st, then P1 V()'s semaphore, adding 1 to its value
  - Later, when P2 executes, it will call wait(S), which will decrement the semaphore to 0 – no waiting - followed by execution of C2
  - Thus C1 executes before C2

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

Process P1:

```
C1;          // execute C1
signal(S); // V() semaphore
```

Process P2:

```
wait(S);   // P() semaphore
C2;          // execute C2
```

Enforcing Order with Semaphores

- If P2 executes 1st, then
  - P2 blocks on semaphore (=0), so C2 will not be executed yet
  - Later, when P1 executes, it runs C1, then V()'s the semaphore
  - This awakens P2, which then executes C2
  - Thus C1 executes before C2

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

Process P1:

```
C1;          // execute C1
signal(S); // V() semaphore
```

Process P2:

```
wait(S);   // P() semaphore
C2;          // execute C2
```

A Revised Semaphore Definition

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

atomic

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

atomic

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

- Efficiently sleep the process until it needs to be woken up by a V()/ signal(), rather than spinlock

A Revised Semaphore Definition

- New definition allows a semaphore's value to be negative, because the decrement occurs before the test in P()
  - The absolute value of the semaphore's negative amount can be used to indicate the # 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?

Mutual Exclusion with Revised Semaphore

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

Process P1:	Process P2:	Process P3:
`P(S);`	`P(S);`	`P(S);`
`counter++;`	`counter--;`	`counter*=2;`
`V(S);`	`V(S);`	`V(S);`

- The 1st process (say P2) that calls P() on semaphore S will set S==0 and move into its critical section
- The next process (say P3) calling P(S) decrements S to -1 and blocks on semaphore, hence mutual exclusion is achieved
- The next process (say P1) calling P(S) decrements S to -2 and blocks on S – *Note how* |*S*| = *# blocked processes!*

Mutual Exclusion with Revised Semaphore

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

Process P1:	Process P2:	Process P3:
`P(S);`	`P(S);`	`P(S);`
`counter++;`	`counter--;`	`counter*=2;`
`V(S);`	`V(S);`	`V(S);`

- P2 finishes, V()'s the semaphore S, increasing its value to -1, signaling a process to unblock (P3).
- P3 finishes, V()'s the semaphore S, increasing its value to 0, causing a process to unblock (P1)
- P1 finishes, V()'s the semaphore S, increasing its value to original value of 1. No more processes to unblock.

Enforcing Order with Revised Semaphore

- If P1 hits its signal(S) first, before P2 hits wait(S), then
  - P1 will have executed C1 already, will then increment S to 1, and no process will be unblocked.
  - Later, P2 calls wait(S), decrements S from 1 to 0, and executes C2. Order is preserved: C1 executes before C2

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

Process P1:

```
C1;          // execute C1
signal(S);   // V() semaphore
```

Process P2:

```
wait(S);     // P() semaphore
C2;          // execute C2
```

Enforcing Order with Revised Semaphore

- If P2 hits wait(S) before P1 hits signal(S), then
  - P2 will decrement S to -1, and block P2 on the semaphore.
  - Next, P1 calls signal(S) having executed code C1, incrementing S from -1 to 0 and unblocking P2.
  - P2 now executes C2. Order is preserved: C1 executes before C2

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

Process P1:

```
C1;          // execute C1
signal(S);   // V() semaphore
```

Process P2:

```
wait(S);     // P() semaphore
C2;          // execute C2
```

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 Example

```
Semaphore Q= 1;      // binary semaphore as a mutex lock
Semaphore S = 1;     // binary semaphore as a mutex lock
variable R1, R2;
```

Process P1:

```
P(S);                    (step 1)
P(Q);                    (step 3)
     modify R1 and R2;
V(S);
V(Q);
```

Process P2:

```
(step 2) P(Q);
(step 4) P(S);
Deadlock!     modify R1 and R2;
          V(Q);
          V(S);
```

If steps (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

Other Deadlock 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 self-deadlock!
- A programmer forgets and omits V(mutex). Can cause deadlock.

  P1:
  P(mutex)
  critical section 1
  V(mutex)

  P2:
  P(mutex)
  critical section 2

  – P2 calls P(mutex) and executes crit sect 2. Then P1 blocks on P(mutex), then P2 blocks on P(mutex)

Other Synchronization Errors

- A programmer forgets and omits P(mutex). Can violate mutual exclusion if P(mutex) is omitted.

P1:	P2:
P(mutex)	
critical section 1	critical section 2
V(mutex)	V(mutex)

- A programmer reverses the order of P() and V(), e.g.

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