Lecture Overview

- Overview of cooperating processes and synchronization
  - Terms and concepts
  - Mutual exclusion with busy waiting and spin locks
  - Mutual exclusion and deadlock with semaphores
  - Mutual exclusion with monitors
  - Linux Kernel Synchronization

Cooperating Processes

- Once we have multiple processes or threads, it is likely that two or more of them will want to communicate with each other
- Process cooperation (i.e., interprocess communication) deals with three main issues
  - Passing information between processes/threads
  - Making sure that processes/threads do not interfere with each other
  - Ensuring proper sequencing of dependent operations
- These issues apply to both processes and theads
  - Initially we concentrate on shared memory mechanisms

Cooperating Processes

- An *independent* process cannot affect or be affected by the execution of another process.
- A *cooperating* process can affect or be affected by the execution of another process
- Advantages of process cooperation
  - Information sharing
  - Computation speed-up
  - Modularity
  - Convenience

Issues for Cooperating Processes

- Race conditions
  - A *race condition* is a situation where the semantics of an operation on shared memory are affected by the arbitrary timing sequence of collaborating processes
- Critical regions
  - A *critical region* is a portion of a process that accesses shared memory
- Mutual exclusion
  - *Mutual exclusion* is a mechanism to enforce that only one process at a time is allowed into a critical region

Cooperating Processes Approach

- Any approach to process cooperation requires that
  - No two processes may be simultaneously inside their critical regions
  - No assumptions may be made about speeds or the number of CPUs
  - No process running outside of its critical region may block other processes
  - No process should have to wait forever to enter its critical region

Cooperating Processes

Consider a shared, bounded-buffer

```
public class Buffer {
   private volatile int count = 0;
   private volatile int in = 0, out = 0;
   private Object[] buffer = new Object[10];

   public void enter(Object item) {
      // producer calls this method
   }

   public Object remove() {
       // consumer calls this method
   }
}
```

Cooperating Processes

The `remove()` operation on the bounded-buffer

```
// consumer calls this method
public Object remove() {
   Object item;
   while (count == 0)
      ; // do nothing
   // remove an item from the buffer
   --count;
   item = buffer[out];
   out = (out + 1) % buffer.length;
   return item;
}
```

Cooperating Processes

The `enter()` operation on the bounded-buffer

```
// producer calls this method
public void enter(Object item) {
   while (count == buffer.length)
      ; // do nothing
   // add an item to the buffer
   ++count;
   buffer[in] = item;
   in = (in + 1) % buffer.length;
}
```

Mutual Exclusion with Busy Waiting

Mutual exclusion via *busy waiting* / *spin locks*

```
while (TRUE) {
    while (turn != 0)        /* loop */ ;
    critical_region( );
    turn = 1;
    noncritical_region( );
}
```

```
while (TRUE) {
    while (turn != 1)        /* loop */ ;
    critical_region( );
    turn = 0;
    noncritical_region( );
}
```

- Constantly uses CPU, so it is inefficient
- The above algorithm enforces strict alternation of process execution
- A process may end up being blocked by another process that is not in a critical region

Mutual Exclusion with Busy Waiting

Peterson's solution for mutual exclusion via busy waiting

```
#define FALSE  0
#define TRUE   1
#define N      2                      /* number of processes */

int turn;                             /* whose turn is it? */
int interested[N];                    /* all values initially 0 (FALSE) */

void enter_region(int process);       /* process is 0 or 1 */
{
     int other;                       /* number of the other process */

     other = 1 - process;             /* the opposite of process */
     interested[process] = TRUE;      /* show that you are interested */
     turn = process;                  /* set flag */
     while (turn == process && interested[other] == TRUE) /* null statement */ ;
}

void leave_region(int process)        /* process: who is leaving */
{
     interested[process] = FALSE;     /* indicate departure from critical region */
}
```

Mutual Exclusion with Busy Waiting

Mutual exclusion and busy waiting with hardware support

```
enter_region:
      TSL REGISTER,LOCK              | copy lock to register and set lock to 1
      CMP REGISTER,#0                | was lock zero?
      JNE enter_region               | if it was non zero, lock was set, so loop
      RET | return to caller; critical region entered


leave_region:
      MOVE LOCK,#0                   | store a 0 in lock
      RET | return to caller
```

- Many processors offer a “test and set” atomic instruction
  - An *atomic* instruction cannot be interrupted

Mutual Exclusions with Semaphores

- Mutual exclusion using semaphores
  - A *semaphore* is a non-negative integer value
  - Two atomic operations are supported on a semaphore
    - *down* = decrements the value, since the value cannot be negative, the process blocks if the value is zero
    - *up* = increments the value; if there are any processes waiting to perform a down, then they are unblocked
  - Initializing a semaphore to 1 creates a mutual exclusion (*mutex*) semaphore
  - Initializing a semaphore to 0 creates a signaling semaphore
  - Initializing a semaphore to other values can be used for resource allocation and synchronization

Mutual Exclusions with Semaphores

- Mutual exclusion using semaphores
  - Busy waiting versus blocking
    - Semaphores can use busy waiting, but generally they are implemented using blocking
    - With blocking, a process/thread that fails to acquire the semaphore does not loop continuously, instead it is blocked and another thread is scheduled
    - This is more efficient since it does not waste CPU cycles and allows other processes/threads to make progress

Mutual Exclusions with Semaphores

Mutex semaphore implementation

```
mutex_lock:
      TSL REGISTER,MUTEX          | copy mutex to register and set mutex to 1
      CMP REGISTER,#0             | was mutex zero?
      JZE ok                      | if it was zero, mutex was unlocked, so return
      CALL thread_yield           | mutex is busy; schedule another thread
      JMP mutex_lock              | try again later
ok:   RET | return to caller; critical region entered

mutex_unlock:
      MOVE MUTEX,#0               | store a 0 in mutex
      RET | return to caller
```

Deadlock with Semaphores

- *Deadlock* is when two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Let S and Q be two semaphores initialized to 1

P_0	P_1
$P(S)$;	$P(Q)$;
P(Q);	P(S);
⋮	⋮
V(S);	V(Q);
V(Q)	V(S);

- Starvation is indefinite blocking when a process is never removed from the semaphore queue in which it was suspended

Mutual Exclusion with Monitors

- Mutual exclusion using monitors
  - Semaphores are very low-level and error prone
    - The require the programmer to use them properly
  - A *monitor* is a high-lever programming language construct that packages data and the procedures to modify the data
    - The data can only be modified using the supplied procedures
    - Only one process is allowed inside the monitor at a time
  - Monitors also have *condition variables* that have two operations, *wait* and *signal*
    - Calling *wait* blocks the calling process
    - Calling *signal* unblocks waiting processes
    - Since condition variables are inside of a monitor there is no race condition when accessing them

Mutual Exclusion with Monitors

```
monitor example
        integer i;
        condition c;

        procedure producer( );
        .
        .
        .
        end;

        procedure consumer( );
        .
        .
        .
        end;
end monitor;
```

Example of a monitor

Process Cooperation with Messages

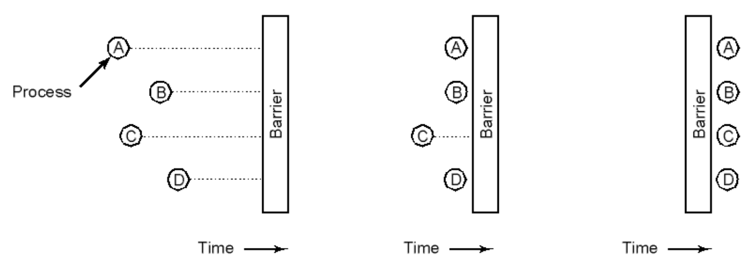
- IPC using message passing
  - The previous IPC approaches required some sort of shared memory for communication
    - This does not work well for some sorts of IPC, such as in distributed systems
  - Message passing has different complications, like lost messages

Process Cooperation with Messages

- IPC using message passing

```
#define N 100                               /* number of slots in the buffer */

void producer(void)
{
     int item;
     message m;                             /* message buffer */

     while (TRUE) {
          item = produce_item( );           /* generate something to put in buffer */
          receive(consumer, &m);            /* wait for an empty to arrive */
          build_message(&m, item);          /* construct a message to send */
          send(consumer, &m);               /* send item to consumer */
     }
}

void consumer(void)
{
     int item, i;
     message m;

     for (i = 0; i < N; i++) send(producer, &m);  /* send N empties */
     while (TRUE) {
          receive(producer, &m);            /* get message containing item */
          item = extract_item(&m);          /* extract item from message */
          send(producer, &m);               /* send back empty reply */
          consume_item(item);               /* do something with the item */
     }
}
```

Process Cooperation with Barriers



- Barrier
  - Processes perform computation and approach a barrier
  - Processes block when they reach the barrier after finishing their computation
  - Once all processes arrives, then all are unblocked

Cooperation Process Problems

- Classic synchronization problems
  - Bounded-buffer
  - Readers-writers
  - Dining philosophers
  - Sleeping barber

  - We are familiar with all of these from the concurrent programming class

Linux Kernel Synchronization

- Even on a single processor machine, not all kernel requests are handled serially because of interrupts
  - Interrupts cause kernel requests to be interleaved
  - Multiple processors makes matters worse
- Essentially, the kernel handles requests that are generated in one of two ways
  - A process in user mode causes an exception; for example, by executing the `int 0x80` assembly language instruction
  - An external device sends a signal using an IRQ line
- The sequence of instructions executed in kernel mode to handle a kernel request is called a *kernel control path*

Linux Kernel Control Paths

- In the simplest case, the CPU executes a kernel control path sequentially from the first instruction to the last
- The CPU interleaves kernel control paths when
  - A context switch occurs
  - An interrupt occurs
- Interleaving kernel control paths is necessary to implement preemptive multitasking, but it also improves throughput
- Care must be taken when modifying data structures in kernel control paths to avoid corruption

Linux Synchronization Techniques

- There are four broad synchronization techniques used in Linux
  - Nonpreemptability of processes in Kernel Mode
  - Atomic operations
  - Interrupt disabling
  - Locking

Linux Synchronization Techniques

- Nonpreemptability of processes in Kernel Mode
  - The following assertions always hold in Linux
    - No process running in kernel mode may be replaced by another process, except when it voluntarily releases the CPU
    - Interrupt or exception handlers can interrupt a process in kernel mode, but the CPU must return to the same kernel control path
    - A kernel control path performing interrupt handling can only be interrupted by another interrupt handler
  - This simplifies kernel control paths dealing with nonblocking systems calls, they are atomic
  - Data structures not modified by interrupt handlers can be safely accessed

Linux Synchronization Techniques

- Atomic operations
  - Ensure that an operation is atomic at the CPU level (i.e., executed in a single, non-interruptible instruction)
  - Atomic Intel 80x86 instructions
    - Instructions that make zero or one memory access
    - Read/modify/write instructions such as `inc` or `dec` if no other processor has taken the memory bus
    - Read/modify/write instructions prefixed with the `lock` byte (`0xf0`) because they lock the memory bus
  - In C you cannot guarantee which instructions the compile will use, so it is not possible to determine if an operation is atomic

Linux Synchronization Techniques

- Atomic operations
  - Linux provides special functions that are implemented as atomic assembly language instructions, such as
    - `atomic_read(v)`
    - `atomic_set(v, i)`
    - `atomic_add(i, v)`
    - `atomic_sub(i, v)`
    - `atomic_inc(v)`
    - `atomic_dec(v)`
    - `atomic_dec_and_test(v)`
    - `...`

Linux Synchronization Techniques

- Interrupt disabling
  - Some critical sections are too long to be defined as an atomic operation
  - Disabling interrupts is a mechanism to ensure that a kernel control path is not interrupted
    - The assembly instruction `cli` disables interrupts; `sti` resumes interrupts
    - Page faults can still interrupt the kernel control path
  - Avoid blocking calls with interrupts disabled
  - Linux provides uniprocessor interrupt disabling macros
    - `spin_lock_init()`, `spin_lock()`, `spin_unlock()`, `spin_lock_irq()`, `spin_unlock_irq()`, `write_lock_irqsave()`, `write_unlock_irqrestore()`, ...

Linux Synchronization Techniques

- Locking
  - Before entering a critical region, the kernel control path acquires a lock for that region
  - There are two locking mechanisms
    - Kernel semaphores
      - Suspends corresponding process if busy
    - Spin locks
      - Kernel control path busy waits
      - Only useful in multiprocessor systems

Linux Synchronization Techniques

- Kernel semaphore
  - Implemented by `struct semaphore`
    - `count` field is essentially the semaphore value, but when negative it denotes the number of waiting kernel control paths
    - `wait` field stores the address of a wait queue
    - `waking` field is also similar to the semaphore value and is used to ensure that only one process gets resource (or more depending on the initial value of the semaphore)
      - The waking field is protected by disabling interrupts or a spin lock and is incremented when an `up()` is performed and there are waiting processes; any waiting processes must acquire the waking lock and try to decrement the non-zero `waking` value

Linux Synchronization Techniques

- Avoid deadlock on semaphores
  - Deadlocks can only occur when a kernel control path requires multiple semaphores to enter a critical region
  - It is rare that a kernel control path needs multiple semaphores
  - In the cases that a kernel control path does need multiple semaphores, they are always acquired in the order of their addresses: lowest address is acquired first