Last Class: Synchronization

- Wrap-up on CPU scheduling
  - –MLFQ and Lottery scheduling
- Synchronization
  - – Mutual exclusion
  - – Critical sections
- Example: Too Much Milk
- Locks
- Synchronization primitives are required to ensure that only one thread executes in a critical section at a time.

Today: Synchronization: Locks and Semaphores

- More on hardware support for synchronization
- Implementing locks using disabling interrupts, test&set and busy waiting
- What are semaphores?
  - – Semaphores are basically generalized locks.
  - – Like locks, semaphores are a special type of variable that supports two atomic operations and offers elegant solutions to synchronization problems.
  - – They were invented by Dijkstra in 1965.

Hardware Support for Synchronization

- Implementing high level primitives requires low-level hardware support
- What we have and what we want

	Concurrent programs
Low-level atomic operations (hardware)	load/store interrupt disable test&set
High-level atomic operations (software)	lock semaphore monitors send & receive

Implementing Locks By Disabling Interrupts

- There are two ways the CPU scheduler gets control:
  - **Internal Events:** the thread does something to relinquish control (e.g., I/O).
  - **External Events:** interrupts (e.g., time slice) cause the scheduler to take control away from the running thread.
- On uniprocessors, we can prevent the scheduler from getting control as follows:
  - **Internal Events:** prevent these by not requesting any I/O operations during a critical section.
  - **External Events:** prevent these by disabling interrupts (i.e., tell the hardware to delay handling any external events until after the thread is finished with the critical section)
- Why not have the OS support Lock.Acquire() and Lock.Release as system calls?

Implementing Locks by Disabling Interrupts

- For uniprocessors, we can disable interrupts for high-level primitives like locks, whose implementations are private to the kernel.
- The kernel ensures that interrupts are not disabled forever, just like it already does during interrupt handling.

```
class Lock {
  public:
    void Acquire();
    void Release();
  private:
    int value;
    Queue Q;
}
 Lock() {
  // lock is free
  value = 0;
  // queue is empty
  Q = 0;
 }
```

```
Acquire(T Thread){
  disable interrupts;
  if (value == BUSY) {
     add T to Q
     T.Sleep();
  } else {
     value = BUSY;
  }
  enable interrupts; }
```

```
Release() {
  disable interrupts;
  if queue not empty {
     take thread T off Q
     put T on ready queue
  } else {
     value = FREE
  }
  enable interrupts; }
```


Wait Queues

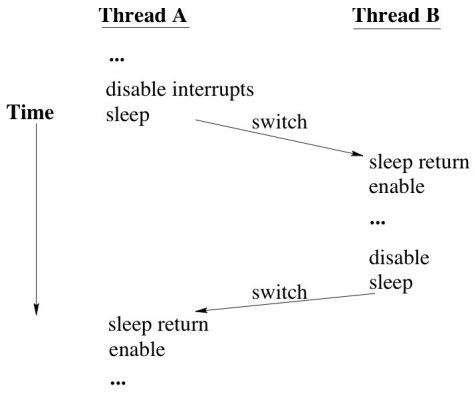
When should Acquire re-enable interrupts when going to sleep?

- **Before putting the thread on the wait queue?**
  - No, Release could check the queue, and not wake up the thread.
- **After putting the thread on the wait queue, but before going to sleep?**
  - No, Release could put the thread on the ready queue, but it could already be on the ready queue. When the thread wakes up, it will go to sleep, missing the wakeup from Release.

=>We still have a problem with multiprocessors.

Example

- When the sleeping thread wakes up, it returns from Sleep back to Acquire.
- Interrupts are still disabled, so its ok to check the lock value, and if it is free, grab the lock and turn on interrupts.



Atomic read-modify-write Instructions

- Atomic read-modify-write instructions *atomically* read a value from memory into a register and write a new value.
  - Straightforward to implement simply by adding a new instruction on a uniprocessor.
  - On a multiprocessor, the processor issuing the instruction must also be able to *invalidate* any copies of the value the other processes may have in their cache, i.e., the multiprocessor must support some type of *cache coherence.*

- **Examples:**
  - **Test&Set:** (most architectures) read a value, write '1' back to memory.
  - **Exchange:** (x86) swaps value between register and memory.
  - **Compare&Swap:** (68000) read value, if value matches register value r1, exchange register r2 and value.

Implementing Locks with Test&Set

- **Test&Set:** reads a value, writes '1' to memory, and returns the old value.

```
class Lock {            Acquire() {
  public:               // if busy do nothing
    void Acquire();       while (test&set(value) == 1);
    void Release();     }
  private:            Release() {
    int value;          value = 0;
}                   }
Lock() {
  value = 0;
}
```

- If lock is free (value = 0), test&set reads 0, sets value to 1, and returns 0. The Lock is now busy: the test in the while fails, and Acquire is complete.
- If lock is busy (value = 1), test&set reads 1, sets value to 1, and returns 1. The while continues to loop until a Release executes.

Busy Waiting

```
Acquire(){
  //if Busy, do nothing
  while (test&set(value) == 1);
}
```

- What's wrong with the above implementation?
  - What is the CPU doing?
  - What could happen to threads with different priorities?
- How can we get the waiting thread to give up the processor, so the releasing thread can execute?

Locks using Test&Set with minimal busy-waiting

- Can we implement locks with test&set without any busy-waiting or disabling interrupts?
- No, but we can minimize busy-waiting time by atomically checking the lock value and giving up the CPU if the lock is busy

```
class Lock {
  // same declarations as earlier
   private int guard;
}
Acquire(T:Thread) {
  while (test&set(guard) == 1)  ;
  if (value != FREE) {
     put T on Q;
     T->Sleep() & set guard = 0;
  } else {
     value = BUSY;
     guard = 0;
  } }
```

```
Release() {
  // busy wait
  while (test&set(guard) == 1) ;
  if Q is not empty {
     take T off Q;
     put T on ready queue;
  } else {
     value = FREE;
  }
  guard = 0;
}
```


Semaphores

- **Semaphore:** an integer variable that can be updated only using two special atomic instructions.
- **Binary (or Mutex) Semaphore:** (same as a lock)
  - Guarantees mutually exclusive access to a resource (only one process is in the critical section at a time).
  - Can vary from 0 to 1
  - It is initialized to free (value = 1)
- **Counting Semaphore:**
  - Useful when multiple units of a resource are available
  - The initial count to which the semaphore is initialized is usually the number of resources.
  - A process can acquire access so long as at least one unit of the resource is available

Semaphores: Key Concepts

- Like locks, a semaphore supports two atomic operations, Semaphore.Wait() and Semaphore.Signal().

```
S.Wait()          // wait until semaphore S
                  // is available
<critical section>

S.Signal()        // signal to other processes
                  // that semaphore S is free
```

- Each semaphore supports a queue of processes that are waiting to access the critical section (e.g., to buy milk).
- If a process executes **S.Wait()** and semaphore S is free (non-zero), it continues executing. If semaphore S is not free, the OS puts the process on the wait queue for semaphore S.
- A **S.Signal()** unblocks one process on semaphore S's wait queue.

Binary Semaphores: Example

- Too Much Milk using locks:

Thread A

```
Lock.Acquire();
if (noMilk){
  buy milk;
}
Lock.Release();
```

Thread B

```
Lock.Acquire();
if (noMilk){
  buy milk;
}
Lock.Release();
```

- Too Much Milk using semaphores:

Thread A

```
Semaphore.Wait();
if (noMilk){
  buy milk;
}
Semaphore.Signal();
```

Thread B

```
Semaphore.Wait();
if (noMilk){
  buy milk;
}
Semaphore.Signal();
```

Implementing Signal and Wait

```
class Semaphore {
  public:
    void Wait(Process P);
    void Signal();
  private:
   int value;
   Queue Q;    // queue of processes;
}
Semaphore(int val) {
   value = val;
   Q = empty;
}
```

```
Wait(Process P) {
   value = value - 1;
   if (value < 0) {
      add P to Q;
      P->block();
} }
Signal() {
   value = value + 1;
   if (value <= 0){
      remove P from Q;
      wakeup(P);
} }
```

=> Signal and Wait of course must be atomic!

Signal and Wait: Example

P1: S.Wait();
S.Wait();
S.Signal();
S.Signal();

P2: S.Wait();
S.Signal();

		value	Queue	process state: execute or block P1	P2
		2	empty	execute	execute
P1:	S->Wait();				
P2:	S->Wait();				
P1:	S->Wait();				
P2:	S->Signal();				
P1:	S->Signal();				
P1:	S->Signal();				

Signal and Wait: Example

```
P1:   S->Wait();
P2:   S->Wait();
P1:   S->Wait();
P1:   S->Signal();
P2:   S->Signal();
P1:   S->Signal();
```

value	Queue	P1	P2
2	empty	execute	execute

Using Semaphores

- **Mutual Exclusion:** used to guard critical sections
  - the semaphore has an initial value of 1
  - S->Wait() is called before the critical section, and S->Signal() is called after the critical section.
- **Scheduling Constraints:** used to express general scheduling constraints where threads must wait for some circumstance.
  - The initial value of the semaphore is usually 0 in this case.
  - **Example:** You can implement thread *join* (or the Unix system call waitpid (PID)) with semaphores:

```
Semaphore S;

S.value = 0; // semaphore initialization

Thread.Join        Thread.Finish
   S.Wait();          S.Signal();
```

Multiple Consumers and Producers

```
class BoundedBuffer {
   public:
     void Producer();
     void Consumer();
   private:
     Items buffer;
 // control access to buffers
     Semaphore mutex;
    // count of free slots
     Semaphore empty;
    // count of used slots
     Semaphore full;
}
BoundedBuffer::BoundedBuffer
(int N){
     mutex.value = 1;
     empty.value = N;
     full.value  = 0;
     new buffer[N];
}
```

```
BoundedBuffer::Producer(){
   <produce item>
   empty.Wait(); // one fewer slot, or
wait
   mutex.Wait(); // get access to
buffers
   <add item to buffer>
   mutex.Signal(); // release buffers
   full.Signal(); // one more used slot
}
BoundedBuffer::Consumer(){
   full.Wait(); //wait until there's an
item
   mutex.Wait(); // get access to
buffers
   <remove item from buffer>
   mutex.Signal(); // release buffers
   empty.Signal(); // one more free
slot
   <use item> }
```


Multiple Consumers and Producers Problem

	empty	full
initially	● ● ● ●	○ ○ ○ ○
Producer 1		
empty->wait();	● ● ● ○	
...		
full->signal();		● ○ ○ ○
Producer 2		
empty->wait();	● ● ○ ○	
...		
full->signal();		● ● ○ ○
Consumer		
full->wait();		● ○ ○ ○
...		
empty->signal();	● ● ● ○	

Summary

- Locks can be implemented by disabling interrupts or busy waiting
- Semaphores are a generalization of locks
- Semaphores can be used for three purposes:
  - To ensure mutually exclusive execution of a critical section (as locks do).
  - To control access to a shared pool of resources (using a counting semaphore).
  - To cause one thread to wait for a specific action to be signaled from another thread.