CS 422/522 Design & Implementation of Operating Systems

Lectures 8-9: Implementing Synchronization

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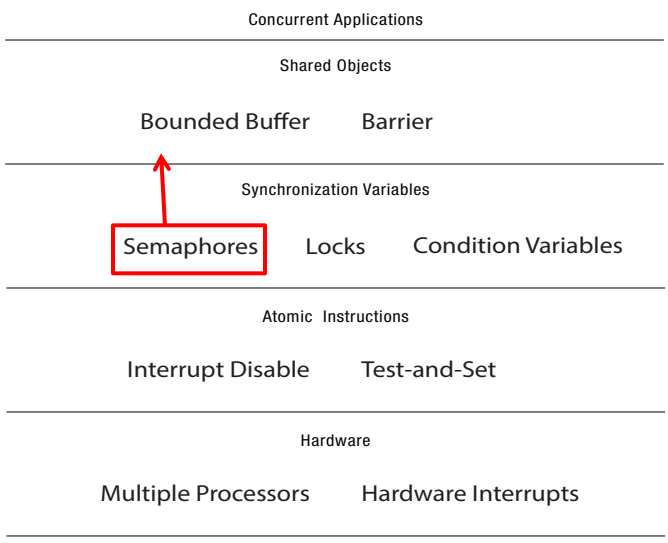
The big picture



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Semaphores (Dijkstra 1965)

- Semaphores are a kind of generalized lock.
  - * They are the main synchronization primitives used in the earlier Unix.
- Semaphores have a non-negative integer value, and support two operations:
  - **semaphore->P():** an atomic operation that waits for semaphore to become positive, then decrements it by 1
  - **semaphore->V():** an atomic operation that increments semaphore by 1, waking up a waiting P, if any.
- Semaphores are like integers except:

  (1) none-negative values; (2) only allow P&V --- can't read/write value except to set it initially; (3) operations must be atomic: two P's that occur together can't decrement the value below zero. Similarly, thread going to sleep in P won't miss wakeup from V, even if they both happen at about the same time.

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Implementing semaphores

P means "test" (proberen in Dutch)
V means "increment" (verhogen in Dutch)

```
class Semaphore { int value = initialValue; }

Semaphore::P()  {
   Disable interrupts;
   while (value == 0) {
      Put on queue of threads waiting
      for this semaphore;
      Go to sleep;
   }
   value = value - 1;
   Enable interrupts
}
```

```
Semaphore::V()  {
   Disable interrupts;
   if  anyone on wait queue {
      Take a waiting thread off wait
      queue and put it on the ready
      queue;
   }
   value = value + 1;
   Enable interrupts
}
```

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Binary semaphores

Like a lock; also known as "mutex"; can only have value 0 or 1 (unlike the previous "counting semaphore" which can be any non-negative integers)

```
class Semaphore { int value = 0 or 1; }

Semaphore::P()  {
   Disable interrupts;
   while (value == 0) {
      Put on queue of threads waiting
      for this semaphore;
      Go to sleep;
   }
   value = 0;
   Enable interrupts
}
```

```
Semaphore::V()  {
   Disable interrupts;
   if  anyone on wait queue {
      Take a waiting thread off wait
      queue and put it on the ready
      queue;
   }
   value = 1;
   Enable interrupts
}
```

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How to use semaphores

- Binary semaphores can be used for mutual exclusion:

  initial value of 1; P() is called before the critical section; and V() is called after the critical section.

```
semaphore->P();
// critical section goes here
semaphore->V();
```

- Scheduling constraints
  - having one thread to wait for something to happen
    - Example: Thread::Join, which must wait for a thread to terminate. By setting the initial value to 0 instead of 1, we can implement waiting on a semaphore
- Controlling access to a finite resource

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Scheduling constaints

- Something must happen after one another

```
Initial value of semaphore = 0;
Fork a child thread
Thread::Join calls P     // will wait until something
                         // makes the semaphore positive
-------------------------------------------------------------------

Thread finish calls V    // makes the semaphore positive
                          // and wakes up the thread
                          // waiting in Join
```

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Scheduling with semaphores

- In general, scheduling dependencies between threads T_1, T_2, …, T_n can be enforced with n-1 semaphores, S_1, S_2, …, S_{n-1} used as follows:
  - T_1 runs and signals V(S_1) when done.
  - T_m waits on S_{m-1} (using P) and signals V(S_m) when done.
- (contrived) example: schedule print(f(x,y))

```
float  x, y, z;
sem   Sx = 0, Sy = 0, Sz = 0;
```

T1:	**T2:**	**T3:**
x = …;	P(Sx);	P(Sz);
V(Sx);	P(Sy);	print(z);
y = …;	z = f(x,y);	…
V(Sy);	V(Sz);	
…	…	

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Producer-consumer with semaphores (1)

- Correctness constraints
  - * consumer must wait for producer to fill buffers, if all empty (scheduling constraints)
  - * producer must wait for consumer to empty buffers, if all full (scheduling constaints)
  - * Only one thread can manipulate buffer queue at a time (mutual exclusion)
- General rule of thumb: use a separate semaphore for each constraint

```
Semaphore fullBuffers;        // consumer's constraint
                              // if 0, no coke in machine
Semaphore emptyBuffers;       // producer's constraint
                              // if 0, nowhere to put more coke
Semaphore mutex;              // mutual exclusion
```

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Producer-consumer with semaphores (2)

```
Semaphore fullBuffers = 0;      // initially no coke
Semaphore emptyBuffers = numBuffers;
          // initially, # of empty slots semaphore used to
          // count how many resources there are
Semaphore mutex = 1;        // no one using the machine

Producer() {
  emptyBuffers.P();      // check if there is space
                         //  for more coke
  mutex.P();             // make sure no one else
                         // is using machine

   put 1 Coke in machine;

   mutex.V();            // ok for others to use machine
   fullBuffers.V();      // tell consumers there is now
                         // a Coke in the machine
}
```

```
Consumer() {
  fullBuffers.P();       // check if there is
                         // a coke in the machine
  mutex.P();             // make sure no one
                         // else is using machine

  take 1 Coke out;

   mutex.V();            // next person's turn
   emptyBuffers.V();     // tell producer
                         // we need more
}
```

What if we have 2 producers and 2 consumers?

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Order of P&Vs --- what can go wrong

```
Semaphore fullBuffers = 0;      // initially no coke
Semaphore emptyBuffers = numBuffers;
          // initially, # of empty slots semaphore used to
          // count how many resources there are
Semaphore mutex = 1;        // no one using the machine

Producer() {
  mutex.P();              // make sure no one else
                          // is using machine
  emptyBuffers.P();       // check if there is space
                          //  for more coke

  put 1 Coke in machine;

  fullBuffers.V();        // tell consumers there is now
                          // a Coke in the machine
  mutex.V();              // ok for others to use machine
}
```

```
Consumer() {
  mutex.P();              // make sure no one
                          // else is using machine
  fullBuffers.P();        // check if there is
                          // a coke in the machine

  take 1 Coke out;

  emptyBuffers.V();       // tell producer
                          // we need more
  mutex.V();              // next person's turn
}
```

Deadlock---two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes.

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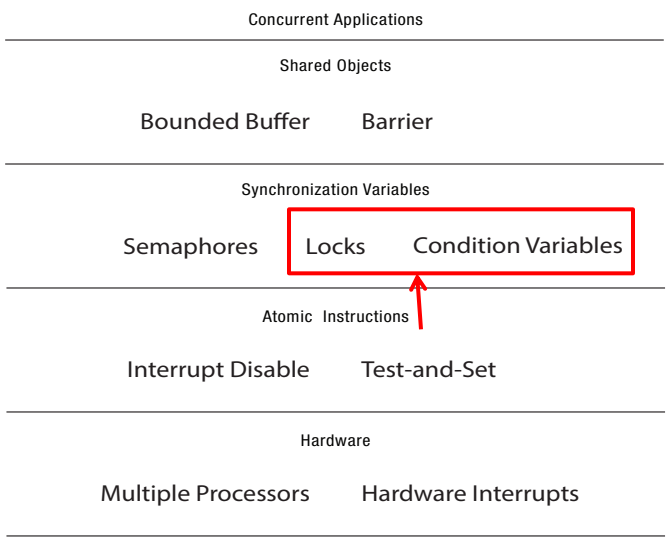
Implementing synchronization



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Implementing synchronization

Take 1: using memory load/store
- See too much milk solution/Peterson's algorithm

Take 2:

Lock::acquire()
{ disable interrupts }
Lock::release()
{ enable interrupts }

Take 3: queueing locks

No point on running the threads waiting for locks

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Lock implementation, uniprocessor

```
Lock::acquire() {

   disableInterrupts();

   if (value == BUSY) {
      waiting.add(myTCB);
      myTCB->state = WAITING;
      next = readyList.remove();
      switch(myTCB, next);
      myTCB->state = RUNNING;
   } else {
      value = BUSY;
   }

   enableInterrupts();
}
```

```
class Lock {
    private int value = FREE;
    private Queue waiting;
  public void acquire();
  public void release();
}
```

```
Lock::release() {
  disableInterrupts();
  if (!waiting.Empty()) {
       next = waiting.remove();
       next->state = READY;
       readyList.add(next);
  } else {
        value = FREE;
  }
  enableInterrupts();
}
```

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Multiprocessor

- Read-modify-write instructions
  - Atomically read a value from memory, operate on it, and then write it back to memory
  - Intervening instructions prevented in hardware
- Examples
  - Test and set
  - Intel: xchgb, lock prefix
  - Compare and swap
- Any of these can be used for implementing locks and condition variables!

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Spinlocks

A spinlock is a lock where the processor waits in a loop for the lock to become free

- Assumes lock will be held for a short time
- Used to protect the CPU scheduler and to implement locks

```
Spinlock::acquire() {
  while (testAndSet(&lockValue) == BUSY)
    ;
}

Spinlock::release() {
  lockValue = FREE;
  memorybarrier();
}
```

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How many spinlocks?

- Various data structures
  - Queue of waiting threads on lock X
  - Queue of waiting threads on lock Y
  - List of threads ready to run
- One spinlock per kernel?
  - Bottleneck!
- Instead:
  - One spinlock per lock
  - One spinlock for the scheduler ready list
    - Per-core ready list: one spinlock per core

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What thread is currently running?

- Thread scheduler needs to find the TCB of the currently running thread
  - To suspend and switch to a new thread
  - To check if the current thread holds a lock before acquiring or releasing it
- On a uniprocessor, easy: just use a global
- On a multiprocessor, various methods:
  - Compiler dedicates a register (e.g., r31 points to TCB running on this CPU; each CPU has its own r31)
  - If hardware has a special per-processor register, use it
  - Fixed-size stacks: put a pointer to the TCB at the bottom of its stack
    - Find it by masking the current stack pointer

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Lock implementation, multiprocessor

```
class Lock {
  private int value = FREE;
  private SpinLock spinLock;
  private Queue waiting; …}
Lock::acquire() {
   disableInterrupts();
   spinLock.acquire();
   if (value == BUSY) {
      waiting.add(myTCB);
      scheduler->suspend(&spinlock);
   } else {
      value = BUSY;
      spinLock.release();
   }
   enableInterrupts();
}
```

```
Lock::release() {

   disableInterrupts();
   spinLock.acquire();

   if (!waiting.Empty()) {
      next = waiting.remove();
      scheduler->makeReady(next);
   } else {
      value = FREE;
   }

   spinLock.release();
   enableInterrupts();
}
```

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Lock implementation, multiprocessor (cont'd)

```
class Scheduler {
 private:
   Queue readyList;
   SpinLock  schedulerSpinLock;
 public:
   void suspend(SpinLock *lock);
   void makeReady(Thread *thread);
}

void
Scheduler::makeReady(TCB *thread) {
   disableInterrupts();
   schedulerSpinLock.acquire();

   readyList.add(thread);
   thread->state = READY;

   schedulerSpinLock.release();
   enableInterrupts();
}
```

```
void
Scheduler::suspend(SpinLock *lock) {
   TCB *chosenTCB;

   disableInterrupts();
   schedulerSpinLock.acquire();

   lock->release();

   runningThread->state = WAITING;
   chosenTCB = readyList.getNextThread();
   thread_switch(runningThread, chosenTCB);
   runningThread->state = RUNNING;

   schedulerSpinLock.release();
   enableInterrupts();
}
```

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Condition variable implementation, multiprocessor

```
class CV {
  private Queue waiting;
  public void wait(Lock *lock);
  public void signal();
  public void broadcast();
}

// Monitor lock held by current thread.
void CV::wait(Lock *lock) {
    assert(lock.isHeld());
    waiting.add(myTCB);
    // Switch to new thread & release lock.
    scheduler.suspend(&lock);
    lock->acquire();
}
```

```
// Monitor lock held by current thread.
void CV::signal() {
    if (waiting.notEmpty()) {
        thread = waiting.remove();
        scheduler.makeReady(thread);
    }
}

void CV::broadcast() {
    while (waiting.notEmpty()) {
        thread = waiting.remove();
        scheduler.makeReady(thread);
    }
}
```

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Semaphore implementation, a comparison

```
Semaphore::P() {
    disableInterrupts();
    spinLock.acquire();

    if (value == 0) {
        waiting.add(myTCB);
        suspend(&spinlock);
    } else {
        value--;
    }

    spinLock.release();
    enableInterrupts();
}
```

```
Semaphore::V() {
    disableInterrupts();
    spinLock.acquire();

    if (!waiting.Empty()) {
        next = waiting.remove();
        scheduler->makeReady(next);
    } else {
        value++;
    }

    spinLock.release();
     enableInterrupts();
}
```

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"Semaphores considered harmful!"

- Using separate lock and condition variable classes makes code more self-documenting and easier to read
  - The code is clearer when the role of each synchronization variable is made clear through explicit typing
- A stateless condition variable bound to a lock is a better abstraction for generalized waiting than a semaphore
  - Semaphores rely on the programmer to carefully map the object's state to the semaphore's value …
- Nevertheless, semaphores are used for synchronizing communication between an I/O device and threads waiting for I/O completion.

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Implementing Condition Variables using Semaphores (Take 1)

```
wait(lock) {
   lock.release();
   semaphore.P();
   lock.acquire();
}
signal() {
   semaphore.V();
}
```

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Implementing Condition Variables using Semaphores (Take 2)

```
wait(lock) {
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    if (semaphore queue is not empty)
        semaphore.V();
}
```

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Implementing Condition Variables using Semaphores (Take 3)

```
wait(lock) {
    semaphore = new Semaphore;
    queue.Append(semaphore);   // queue of waiting threads
    lock.release();
    semaphore.P();
    lock.acquire();
}
signal() {
    if (!queue.Empty()) {
        semaphore = queue.Remove();
        semaphore.V();          // wake up waiter
    }
}
```

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Lock implementation, Linux

- Most locks are free most of the time
  - Why?
  - Linux implementation takes advantage of this fact
- Fast path
  - If lock is FREE, and no one is waiting, two instructions to acquire the lock
  - If no one is waiting, two instructions to release the lock
- Slow path
  - If lock is BUSY or someone is waiting, use multiproc impl.
- User-level locks
  - Fast path: acquire lock using test&set
  - Slow path: system call to kernel, use kernel lock

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Lock implementation, Linux

```
struct mutex {
 /* 1: unlocked ;
    0: locked;
    negative : locked,
       possible waiters */

 atomic_t  count;
 spinlock_t wait_lock;
 struct list_head wait_list;
};
```

```
// atomic decrement
// %eax is pointer to count

lock decl (%eax)
jns 1f // jump if not signed
        // (if value is now 0)
call slowpath_acquire
1:
```

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Communicating Sequential Processes (CSP/Google Go)

- A thread per shared object
  - Only thread allowed to touch object's data
  - To call a method on the object, send thread a message with method name, arguments
  - Thread waits in a loop, get msg, do operation
- No memory races!

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Example: Bounded Buffer

```
get() {
    lock.acquire();
    while (front == tail) {
        empty.wait(lock);
    }
    item = buf[front % MAX];
    front++;
    full.signal(lock);
    lock.release();
    return item;
}
```

```
put(item) {
    lock.acquire();
    while ((tail – front) == MAX) {
        full.wait(lock);
    }
    buf[tail % MAX] = item;
    tail++;
    empty.signal(lock);
    lock.release();
}
```

Initially: front = tail = 0; MAX is buffer capacity
empty/full are condition variables

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Bounded Buffer (CSP)

```
while (cmd = getNext()) {
   if (cmd == GET) {
      if (front < tail) {
          // do get
          // send reply
          // if pending put, do it
         // and send reply
       } else
          // queue get operation
   }
```

```
else { // cmd == PUT
      if ((tail – front) < MAX) {
          // do put
         // send reply
          // if pending get, do it
        // and send reply
      } else
        // queue put operation
}
```

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Locks/CVs vs. CSP

- Create a lock on shared data
  = create a single thread to operate on data
- Call a method on a shared object
  = send a message/wait for reply
- Wait for a condition
  = queue an operation that can't be completed just yet
- Signal a condition
  = perform a queued operation, now enabled

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Remember the rules

- Use consistent structure
- Always use locks and condition variables
- Always acquire lock at beginning of procedure, release at end
- Always hold lock when using a condition variable
- Always wait in while loop
- Never spin in sleep()

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