

# **CSE 451: Operating Systems**

## **Winter 2003**

### **Lecture 7**

### **Synchronization**

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# Synchronization

- Threads cooperate in multithreaded programs
  - to **share** resources, access shared data structures
    - e.g., threads accessing a memory cache in a web server
  - also, to **coordinate** their execution
    - e.g., a disk reader thread hands off a block to a network writer
- For correctness, we have to control this cooperation
  - must assume threads **interleave executions arbitrarily** and at **different rates**
    - scheduling is not under application writers' control
  - we control cooperation using **synchronization**
    - enables us to restrict the interleaving of executions
- Note: this also applies to processes, not just threads
  - and it also applies across machines in a distributed system

# Shared Resources

- We'll focus on coordinating access to shared resources
  - basic problem:
    - two concurrent threads are accessing a shared variable
    - if the variable is read/modified/written by both threads, then access to the variable must be controlled
    - otherwise, unexpected results may occur
- Over the next two lectures, we'll look at:
  - mechanisms to control access to shared resources
    - low level mechanisms like locks
    - higher level mechanisms like mutexes, semaphores, monitors, and condition variables
  - patterns for coordinating access to shared resources
    - bounded buffer, producer-consumer, ...

# The classic example

- Suppose we have to implement a function to withdraw money from a bank account:

```
int withdraw(account, amount) {  
    balance = get_balance(account);  
    balance -= amount;  
    put_balance(account, balance);  
    return balance;  
}
```

- Now suppose that you and your S.O. share a bank account with a balance of \$100.00
  - what happens if you both go to separate ATM machines, and simultaneously withdraw \$10.00 from the account?

# Example continued

- Represent the situation by creating a separate thread for each person to do the withdrawals
  - have both threads run on the same bank mainframe:

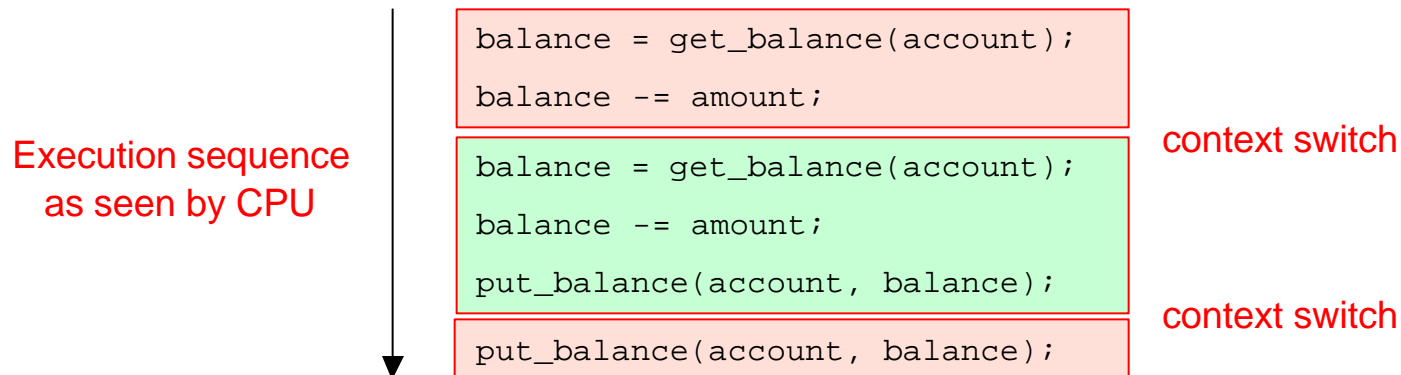
```
int withdraw(account, amount) {  
    balance = get_balance(account);  
    balance -= amount;  
    put_balance(account, balance);  
    return balance;  
}
```

```
int withdraw(account, amount) {  
    balance = get_balance(account);  
    balance -= amount;  
    put_balance(account, balance);  
    return balance;  
}
```

- What's the problem with this?
  - what are the possible balance values after this runs?

# Interleaved Schedules

- The problem is that the execution of the two threads can be interleaved, assuming preemptive scheduling:



- What's the account balance after this sequence?
  - who's happy, the bank or you? ;)

# The crux of the matter

- The problem is that two concurrent threads (or processes) access a **shared resource** (account) without any **synchronization**
  - creates a **race condition**
    - output is non-deterministic, depends on timing
- We need mechanisms for controlling access to shared resources in the face of concurrency
  - so we can reason about the operation of programs
    - essentially, re-introducing determinism
- Synchronization is necessary for any shared data structure
  - buffers, queues, lists, hash tables, ...

# When are Resources Shared?

- Local variables are not shared
  - refer to data on the stack, each thread has its own stack
  - never pass/share/store a pointer to a local variable on another thread's stack
- Global variables are shared
  - stored in the static data segment, accessible by any thread
- Dynamic objects are shared
  - stored in the heap, shared if you can name it
    - in C, can conjure up the pointer
      - e.g. `void *x = (void *) 0xDEADBEEF`
    - in Java, strong typing prevents this
      - must pass references explicitly



# Mutual Exclusion

- We want to use **mutual exclusion** to synchronize access to shared resources
- Code that uses mutual exclusion to synchronize its execution is called a **critical section**
  - only one thread at a time can execute in the critical section
  - all other threads are forced to wait on entry
  - when a thread leaves a critical section, another can enter

# Critical Section Requirements

- Critical sections have the following requirements
  - mutual exclusion
    - at most one thread is in the critical section
  - progress
    - if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
  - bounded waiting (no starvation)
    - if thread T is waiting on the critical section, then T will eventually enter the critical section
      - assumes threads eventually leave critical sections
  - performance
    - the overhead of entering and exiting the critical section is small with respect to the work being done within it

# Mechanisms for Building Crit. Sections

- Locks
  - very primitive, minimal semantics; used to build others
- Semaphores
  - basic, easy to get the hang of, hard to program with
- Monitors
  - high level, requires language support, implicit operations
  - easy to program with; Java “`synchronized()`” as example
- Messages
  - simple model of communication and synchronization based on (atomic) transfer of data across a channel
  - direct application to distributed systems

# Locks

- A lock is a object (in memory) that provides the following two operations:
  - **acquire( )**: a thread calls this before entering a critical section
  - **release( )**: a thread calls this after leaving a critical section
- Threads pair up calls to **acquire( )** and **release( )**
  - between **acquire( )** and **release( )**, the thread **holds** the lock
  - **acquire( )** does not return until the caller holds the lock
    - at most one thread can hold a lock at a time (usually)
  - so: what can happen if the calls aren't paired?
- Two basic flavors of locks
  - spinlock
  - blocking (a.k.a. “mutex”)

# Using Locks

```
int withdraw(account, amount) {  
    acquire(lock);  
    balance = get_balance(account);  
    balance -= amount;  
    put_balance(account, balance);  
    release(lock);  
    return balance;  
}
```

} critical section

acquire(lock)  
balance = get\_balance(account);  
balance -= amount;

acquire(lock)

put\_balance(account, balance);  
release(lock);

balance = get\_balance(account);  
balance -= amount;  
put\_balance(account, balance);  
release(lock);


- What happens when green tries to acquire the lock?
- Why is the “return” outside the critical section?
  - is this ok?

# Spinlocks

- How do we implement locks? Here's one attempt:

```
struct lock {  
    int held = 0;  
}  
void acquire(lock) {  
    while (lock->held);  
    lock->held = 1;  
}  
void release(lock) {  
    lock->held = 0;  
}
```

the caller "busy-waits",  
or spins for lock to be  
released, hence spinlock



- Why doesn't this work?
  - where is the race condition?

# Implementing locks (continued)

- Problem is that implementation of locks has critical sections, too!
  - the acquire/release must be atomic
    - atomic == executes as though it could not be interrupted
    - code that executes “all or nothing”
- Need help from the hardware
  - atomic instructions
    - test-and-set, compare-and-swap, ...
  - disable/reenable interrupts
    - to prevent context switches

# Spinlocks redux: Test-and-Set

- CPU provides the following as **one atomic instruction**:

```
bool test_and_set(bool *flag) {  
    bool old = *flag;  
    *flag = True;  
    return old;  
}
```

- So, to fix our broken spinlocks, do:

```
struct lock {  
    int held = 0;  
}  
void acquire(lock) {  
    while(test_and_set(&lock->held));  
}  
void release(lock) {  
    lock->held = 0;  
}
```



# Problems with spinlocks

- Horribly wasteful!
  - if a thread is spinning on a lock, the thread holding the lock cannot make process
- How did lock holder yield the CPU in the first place?
  - calls `yield( )` or `sleep( )`
  - involuntary context switch
- Only want spinlocks as primitives to build higher-level synchronization constructs

# Disabling Interrupts

- An alternative:

```
struct lock {  
}  
void acquire(lock) {  
    cli();    // disable interrupts  
}  
void release(lock) {  
    sti();    // reenale interrupts  
}
```

- Can two threads disable interrupts simultaneously?
- What's wrong with interrupts?
  - only available to kernel (why? how can user-level use?)
  - insufficient on a multiprocessor
    - back to atomic instructions
- Like spinlocks, only use to implement higher-level synchronization primitives