

# **CSE 120**

## **Principles of Operating Systems**

**Fall 2001**

Lecture 5: Synchronization

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## **Synchronization**

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- Threads cooperate in multithreaded programs
  - ♦ To share resources, access shared data structures
    - » Threads accessing a memory cache in a Web server
  - ♦ To coordinate their execution
    - » One thread executes relative to another (recall ping-pong)
- For correctness, we need to control this cooperation
  - ♦ Threads interleave executions arbitrarily and at different rates
  - ♦ Scheduling is not under program control
- We control cooperation using synchronization
  - ♦ Synchronization enables us to restrict the possible interleavings of thread executions
- Discuss in terms of threads, also applies to processes

# Shared Resources

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- We will initially focus on coordinating access to shared resources
- Basic problem
  - ♦ If two concurrent threads (processes) are accessing a shared variable, and that variable is read/modified/written by those threads, then access to the variable must be controlled to avoid erroneous behavior
- Over the next couple of lectures, we will look at
  - ♦ Mechanisms to control access to shared resources
    - » Locks, mutexes, semaphores, monitors, condition variables, ...
  - ♦ Patterns for coordinating accesses to shared resources
    - » Bounded buffer, producer-consumer, etc.

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# Classic Example

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- Suppose we have to implement a function to handle withdrawals from a bank account:

```
withdraw (account, amount) {  
    balance = get_balance(account);  
    balance = balance – amount;  
    put_balance(account, balance);  
    return balance;  
}
```
- Now suppose that you and your significant other share a bank account with a balance of \$1000.
- Then you each go to separate ATM machines and simultaneously withdraw \$100 from the account.

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## Example Continued

- We'll represent the situation by creating a separate thread for each person to do the withdrawals
- These threads run on the same bank machine:

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

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

- What's the problem with this implementation?
  - Think about potential schedules of these two threads

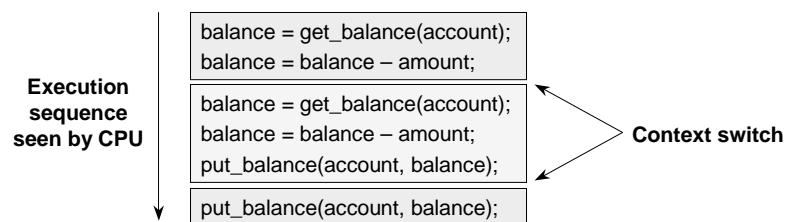
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## Interleaved Schedules

- The problem is that the execution of the two threads can be interleaved:



- What is the balance of the account now?
- Is the bank happy with our implementation?

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## Shared Resources

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- The problem is that two concurrent threads (or processes) accessed a shared resource (account) without any synchronization
  - Known as a race condition (memorize this buzzword)
- We need mechanisms to control access to these shared resources in the face of concurrency
  - So we can reason about how the program will operate
- Our example was updating a shared bank account
- Also necessary for synchronizing access to any shared data structure
  - Buffers, queues, lists, hash tables, etc.

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## When Are Resources Shared?

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- Local variables are not shared (private)
  - 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 and static objects are shared
  - Stored in the static data segment, accessible by any thread
- Dynamic objects and other heap objects are shared
  - Allocated from heap with malloc/free or new/delete

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# Mutual Exclusion

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- 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

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Critical sections have the following requirements:

- 1) Mutual exclusion
  - If one thread is in the critical section, then no other is
- 2) Progress
  - If some thread T is not in the critical section, then T cannot prevent some other thread S from entering the critical section
- 3) Bounded waiting (no starvation)
  - If some thread T is waiting on the critical section, then T will eventually enter the critical section
- 4) Performance
  - The overhead of entering and exiting the critical section is small with respect to the work being done within it

# Mechanisms For Building Critical Sections

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- Locks
  - ◊ Very primitive, minimal semantics, used to build others
- Semaphores
  - ◊ Basic, easy to get the hang of, but hard to program with
- Monitors
  - ◊ High-level, requires language support, operations implicit
- Messages
  - ◊ Simple model of communication and synchronization based on atomic transfer of data across a channel
  - ◊ Direct application to distributed systems
  - ◊ Messages for synchronization are straightforward (once we see how the others work)

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# Locks

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- While one thread executes “withdraw”, we want some way to prevent other threads from executing in it
- Locks are one way to do this
- A lock is an object in memory providing two operations
  - ◊ acquire(): before entering the critical section
  - ◊ release(): after leaving a critical section
- Threads pair calls to acquire() and release()
  - ◊ Between acquire()/release(), the thread holds the lock
  - ◊ acquire() does not return until any previous holder releases
  - ◊ What can happen if the calls are not paired?
- Locks can spin (a spinlock) or block (a mutex)

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# Using Locks

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

Critical  
Section

```
acquire(lock);  
balance = get_balance(account);  
balance = balance - amount;
```

```
acquire(lock);  
  
put_balance(account, balance);  
release(lock);
```

```
balance = get_balance(account);  
balance = balance - amount;  
put_balance(account, balance);  
release(lock);
```

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

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# Implementing Locks (1)

- How do we implement locks? Here is one attempt:

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

busy-wait (spin-wait)  
for lock to be released

- This is called a spinlock because a thread spins waiting for the lock to be released
- Does this work?

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## Implementing Locks (2)

- No. Two independent threads may both notice that a lock has been released and thereby acquire it.

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

A context switch can occur here, causing a race condition

## Implementing Locks (3)

- The problem is that the implementation of locks has critical sections, too
- How do we stop the recursion?
- The implementation of acquire/release must be atomic
  - ♦ An atomic operation is one which executes as though it could not be interrupted
  - ♦ Code that executes “all or nothing”
- How do we make them atomic?
- Need help from hardware
  - ♦ Atomic instructions (e.g., test-and-set)
  - ♦ Disable/enable interrupts (prevents context switches)

## Atomic Instructions: Test-And-Set

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- The semantics of test-and-set are:
  - Record the old value
  - Set the value to indicate available
  - Return the old value
- Hardware executes it atomically!

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

- When executing test-and-set on “flag”
  - What is value of flag afterwards if it was initially False? True?
  - What is the return result if flag was initially False? True?

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## Using Test-And-Set

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- Here is our lock implementation with test-and-set:

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

- When will the while return?
- What about multiprocessors?

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## Problems with Spinlocks

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- The problem with spinlocks is that they are wasteful
  - If a thread is spinning on a lock, then the thread holding the lock cannot make progress
- How did the lock holder give up the CPU in the first place?
  - Lock holder calls yield or sleep
  - Involuntary context switch
- Only want to use spinlocks as primitives to build higher-level synchronization constructs

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## Disabling Interrupts

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- Another implementation of acquire/release is to disable interrupts:

```
struct lock {  
}  
void acquire (lock) {  
    disable interrupts;  
}  
void release (lock) {  
    enable interrupts;  
}
```

- Note that there is no state associated with the lock
- Can two threads disable interrupts simultaneously?

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## On Disabling Interrupts

- Disabling interrupts blocks notification of external events that could trigger a context switch (e.g., timer)
  - This is what Nachos uses as its primitive
- In a “real” system, this is only available to the kernel
  - Why? (From your homework)
  - What could user-level programs use instead?
- Disabling interrupts is insufficient on a multiprocessor
  - Back to atomic instructions
- Like spinlocks, only want to disable interrupts to implement higher-level synchronization primitives
  - Don't want interrupts disabled between acquire and release

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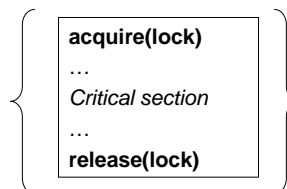
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## Summarize Where We Are

- Goal: Use mutual exclusion to protect critical sections of code that access shared resources
- Method: Use locks (spinlocks or disable interrupts)
- Problem: Critical sections can be long

### Spinlocks:

- Threads waiting to acquire lock spin in test-and-set loop
- Wastes CPU cycles
- Longer the CS, the longer the spin
- Greater the chance for lock holder to be interrupted



### Disabling Interrupts:

- Should not disable interrupts for long periods of time
- Can miss or delay important events (e.g., timer, I/O)

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# Higher-Level Synchronization

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- Spinlocks and disabling interrupts are useful only for very short and simple critical sections
  - Wasteful otherwise
  - These primitives are “primitive” – don’t do anything besides mutual exclusion
- Need higher-level synchronization primitives that:
  - Block waiters
  - Leave interrupts enabled within the critical section
- All synchronization requires atomicity
- So we’ll use our “atomic” locks as primitives to implement them

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# Next time...

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- Same as last -- Read Section 2.3

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## TODO

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- More annotations on pictures
- Change example?
- Difference between sync for logical vs. physical parallelism (uni vs. multiprocessor)
- What happens when three threads try to acquire lock?
  - Scheduling
- Picture showing use of spinlocks and interrupts just for acquire and release
- See yield after calling test-and-set (Nutt:p206)

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## Administrivia

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- Homework #2
  - Due 10/19
  - The answers to almost all problems are short
  - But still require some thinking...
- Speaking of race conditions...
  - Chancellor's 5K Run on the 27<sup>th</sup>
  - Finish before me and
    - » You get 1 point added to your lecture grade
    - » Or a gold star on your homework (your choice)
  - Shouldn't be hard...I don't run that fast
- Programming Contest Tomorrow!

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# Semaphores

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- Semaphores are data structures that also provide mutual exclusion to critical sections
  - ♦ Block waiters, interrupts enabled within CS
  - ♦ Described by Dijkstra in THE system in 1968
- Semaphores count the number of threads using a critical section (more later)
- Semaphores support two operations:
  - ♦ wait(semaphore): decrement, block until semaphore is open
    - » Also P() after the Dutch word for test
  - ♦ signal(semaphore): increment, allow another thread to enter
    - » Also V() after the Dutch word for increment

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# Blocking in Semaphores

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- Associated with each semaphore is a queue of waiting processes
- When wait() is called by a thread:
  - ♦ If semaphore is open, thread continues
  - ♦ If semaphore is closed, thread blocks on queue
- signal() opens the semaphore:
  - ♦ If a thread is waiting on the queue, the thread is unblocked
  - ♦ If no threads are waiting on the queue, the signal is remembered for the next thread
    - » In other words, signal() has “history”
    - » This history uses a counter

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# Using Semaphores

- Use is similar to the locks, but semantics are different

```
struct account {  
    double balance;  
    semaphore S;  
}  
withdraw (account, amount) {  
    wait(account->S);  
    tmp = account->balance;  
    tmp = tmp - amount;  
    account->balance = tmp;  
    signal(account->S);  
    return tmp;  
}
```

Threads  
block

```
wait(account->S);  
tmp = account->balance;  
tmp = tmp - amount;  
  
wait(account->S);  
  
wait(account->S);  
  
account->balance = tmp;  
signal(account->S);  
  
...  
signal(account->S);  
  
...  
signal(account->S);
```

It is undefined which  
thread runs after a signal

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