CSE 120
Principles of Operating Systems

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Lecture 6: Synchronization

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Synchronization

- 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

- 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.

Classic Example

- 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.

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:

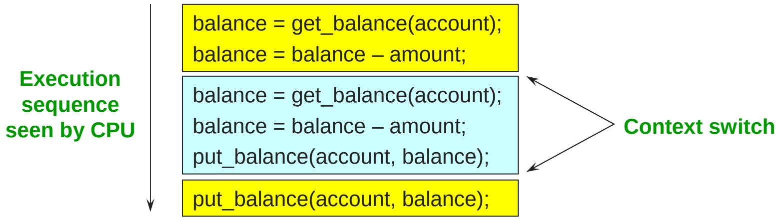
```
withdraw (account, amount) {
    balance = get_balance(account);
    balance = balance – amount;
    put_balance(account, balance);
    return balance;
}
```

```
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

Interleaved Schedules

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



```
balance = get_balance(account);
balance = balance – amount;
```

```
balance = get_balance(account);
balance = balance – amount;
put_balance(account, balance);
```

```
put_balance(account, balance);
```

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

Shared Resources

- 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.

When Are Resources Shared?

- 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

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

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Critical Section Requirements

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

- 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)

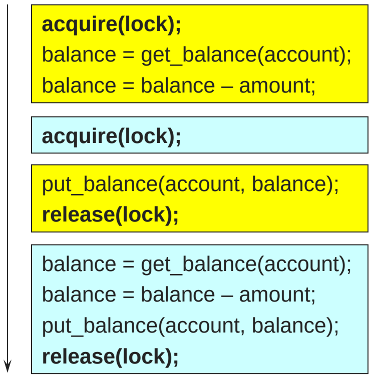
Locks

- 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)

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?
- What happens when a third thread calls acquire?

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?

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

- 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?

Using Test-And-Set

- 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?

Problems with Spinlocks

- 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

Disabling Interrupts

- 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?

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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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

acquire(lock)

…

Critical section

…

release(lock)

Disabling Interrupts:

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

Higher-Level Synchronization

- 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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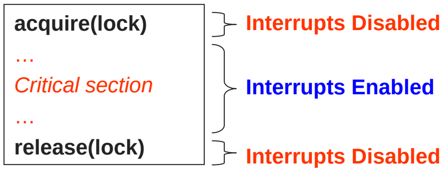
Implementing Locks (4)

- Block waiters, interrupts enabled in critical sections

```
struct lock {
    int held = 0;
    queue Q;
}
void acquire (lock) {
    Disable interrupts;
    while (lock->held) {
        put current thread on lock Q;
        block current thread;
    }
    lock->held = 1;
    Enable interrupts;
}
```

```
void release (lock) {
    Disable interrupts;
    if (Q) remove waiting thread;
    unblock waiting thread;
    lock->held = 0;
    Enable interrupts;
}
```



acquire(lock)

…

Critical section

…

release(lock)

Interrupts Disabled

Interrupts Enabled

Interrupts Disabled

Next time…

- Read Chapter 7.7 – 7.10