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 blocks to a network writer thread through a circular buffer

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/modifed/written by both threads, then access to the variable must be controlled
    • otherwise, unexpected results may occur
  • Over the next several 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:

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

• 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?
Interleaved schedules

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

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

- What’s the account balance after this sequence?谁’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

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 critical 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 an 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 an 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

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

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

Spinlocks

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

```c
struct lock {
    int held = 0;
}
void acquire(lock) {
    while (lock->held);
    lock->held = 1;
}
void release(lock) {
    lock->held = 0;
}
```
- Why doesn’t this work?
  - where is the race condition?

Implementing locks (cont.)

- 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/enable interrupts
  - to prevent context switches

Spinlocks redux: Test-and-Set

- CPU provides the following as one atomic instruction:

```c
bool test_and_set(bool *flag) {
    bool old = *flag;
    *flag = True;
    return old;
}
```
- So, to fix our broken spinlocks, do:

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

Reminder of use …

- How does a thread blocked on an “acquire” (that is, stuck in a test-and-set loop) yield the CPU?
  - calls yield(), or there’s an involuntary context switch
Problems with spinlocks

- Spinlocks work, but are horribly wasteful!
  - If a thread is spinning on a lock, the thread holding the lock cannot make progress
  - And neither can anyone else!
- Only want spinlocks as primitives to build higher-level synchronization constructs
  - “Do not try this at home!”

Another approach: Disabling interrupts

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

Problems with disabling interrupts

- Only available to the kernel
  - Can’t allow user-level to disable interrupts!
- Insufficient on a multiprocessor
  - Each processor has its own interrupt mechanism
- “Long” periods with interrupts disabled can wreak havoc with devices
- Just as with spinlocks, you only want to use disabling of interrupts to build higher-level synchronization constructs

Summary

- Synchronization can be provided by locks, semaphores, monitors, messages ...
- Locks are the lowest-level mechanism
  - Very primitive in terms of semantics – error-prone
  - Implemented by spin-waiting (crude) or by disabling interrupts (also crude, and can only be done in the kernel)
- In our next exciting episode ...
  - Semaphores are a slightly higher level abstraction
    - Less crude implementation too
  - Monitors are significantly higher level
    - Utilize programming language support to reduce errors