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:

```c
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:

```c
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:

```c
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?
  – who’s happy, the bank or you? ;)

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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 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 balance;
}
```
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;
}
```

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:

```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));
}
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:

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