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:
  ```c
  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:

```java
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:

```java
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

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)

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;
}

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

Implementing Locks (1)

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

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

- 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.

```c
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!

```c
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:

```c
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

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)
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

Next time...

- Same as last -- Read Section 2.3
TODO

- 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)

Administrivia

- 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 27th
  - 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!
Semaphores

- 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

Blocking in Semaphores

- 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
Using Semaphores

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

```c
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
It is undefined which thread runs after a signal
```

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