CSE 451: Operating Systems
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Module 7
Synchronization

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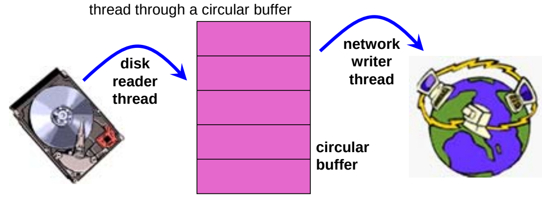
Synchronization

- 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



- 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
  - (I'll almost never say "process" again!)
- 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 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:

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

- Now suppose that you and your partner 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?

- Represent the situation by creating a separate thread for each person to do the withdrawals
  - have both threads run on the same bank mainframe:

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

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


Interleaved schedules

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

Execution sequence as seen by CPU

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

- What's the account balance after this sequence?
  - who's happy, the bank or you?
- How often is this unfortunate sequence likely to occur?

Other Execution Orders

- Which interleavings are ok? Which are not?

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

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


How About Now?

```
int xfer(from, to, amt) {
  int bal = withdraw( from, amt );
  deposit( to, amt );
  return bal;
}
```

```
int xfer(from, to, amt) {
  int bal = withdraw( from, amt );
  deposit( to, amt );
  return bal;
}
```


And This?

```
i++;
```

```
i++;
```


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, scalars, …

What resources are 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
- Mutual exclusion makes reasoning about program behavior easier
  - making reasoning easier leads to fewer bugs
- 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
    - vs. fairness?
  - 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 a 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 "owns" (holds) the lock
    - at most one thread can hold a lock at a time
  - so: what can happen if the calls aren't paired?
- Two basic flavors of locks
  - spinlock
  - blocking (a.k.a. "mutex")

Using locks

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

critical section

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

```
acquire(lock)
```

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

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

```
return balance;
```

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

Spinlocks

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

```
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 (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/reenable interrupts
    - to prevent context switches

Spinlocks redux: Test-and-Set

- CPU provides the following as one atomic instruction:

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

- Remember, this is a single uninterruptible instruction…

Spinlocks redux: Test-and-Set

- So, to fix our broken spinlocks, do:

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

- mutual exclusion?
- progress?
- bounded waiting?
- performance?

Reminder of use …

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

critical section

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

```
acquire(lock)
```

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

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

```
return balance;
```

- How does a thread blocked on an "acquire" (that is, stuck in a test-and-set loop) yield the CPU?
  - calls yield( ) *(spin-then-block)*
  - 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! (Why?)
- Only want spinlocks as primitives to build higher-level synchronization constructs
  - Why is this okay?

Another approach: Disabling interrupts

```
struct lock {
}
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