CS 318 Principles of Operating Systems

Fall 2019

Lecture 6: Synchronization

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Before we start…: Too Much Milk

	Alice	Bob
12:30	Look in fridge. Out of milk.	
12:35	Leave for store.	
12:40	Arrive at store.	Look in fridge. Out of milk.
12:45	Buy milk.	Leave for store.
12:50	Arrive home, put milk away.	Arrive at store.
12:55		Buy milk.
1:00		Arrive home, put milk away. Oh no!

Before we start…: exercise #1

`x` is a global variable initialized to 0

Thread 1

```
void foo()
{
    x++;
}
```

Thread 2

```
void bar()
{
    x--;
}
```

- **After thread 1 and thread 2 finishes, what is the value of x?**
  - could be 0, 1, -1
  - Why?

Before we start…: exercise #2

```
int p = 0, ready = 0;
```

Processor #1

```
p = 1000;
ready = 1;
```

Processor #2

```
while (!ready);
use(p);
```

- **What value of `p` is passed to `use`?**
  - could be 0, 1000
  - Why?
- **What if `p` holds an address?**

Synchronization Motivation

- **Threads cooperate in multithreaded programs**
  - To share resources, access shared data structures
  - To coordinate their execution
- **For correctness, we need to control this cooperation**
  - Thread schedule is non-deterministic
    - Scheduling is not under program control
    - Threads interleave executions arbitrarily and at different rates
    - Behavior changes when re-run program
  - Multi-word operations are not atomic
  - Compiler/hardware instruction reordering

Shared Resources

We 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, etc.
  - Patterns for coordinating accesses to shared resources
    - Bounded buffer, producer-consumer, etc.

Classic Example: Bank Account Balance

- **TODO: 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;
}
```

- **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 server:**

```
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:**

Execution sequence seen by CPU

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

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

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

Context switch

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

How Interleaved Can It Get?

How contorted can the interleavings be?

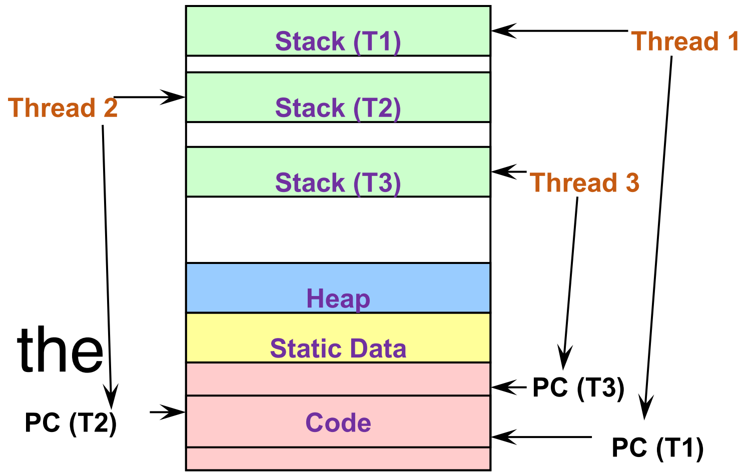
- **We'll assume that the only atomic operations are instructions**
  - e.g., reads and writes of words
  - the hardware may not even give you that!
- **We'll assume that a context switch can occur at any time**
- **We'll assume that you can delay a thread as long as you like as long as it's not delayed forever**

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

Shared Resources

- **Problem: concurrent threads accessed a shared resource without any synchronization**
  - Known as a race condition
- **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 apply 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 the stack for thread T1 to another thread T2
- **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**
  - This allows us to have larger atomic blocks
- **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
  - Example: sharing your bathroom with housemates
- **What requirements would you place on a critical section?**

Critical Section Requirements

1) **Mutual exclusion (mutex)**
   - 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
   - A thread in the critical section will eventually leave it
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

About Requirements

There are three kinds of requirements that we'll use

- **Safety property: nothing bad happens**
  - Mutex
- **Liveness property: something good happens**
  - Progress, Bounded Waiting
- **Performance requirement**
  - Performance
- **Properties hold for each run, while performance depends on all the runs**
  - Rule of thumb: When designing a concurrent algorithm, worry about safety first (but don't forget liveness!)

Too Much Milk, Try #1

- **Try #1: leave a note**

```
if (milk == 0) {           // if no milk
   if (note == 0) {        // if no note
      note = 1;            // leave note
      milk++;              // buy milk
      note = 0;            // remove note
   }
}
```

What can go wrong?

Too Much Milk, Try #2

- **Try #1: leave a note**

Alice

```
if (milk == 0) {



    if (note == 0) {
        note = 1;
        milk++;
        note = 0;
    }
}
```

Bob

```
if (milk == 0) {
    if (note == 0) {
        note = 1;
        milk++;
        note = 0;
    }
}
```

Too Much Milk, Try #2

- **Try #2: leave two notes**

Alice

```
noteA = 1;
if (noteB == 0) {
   if (milk == 0) {
      milk++;
   }
}
noteA = 0;
```

Bob

```
noteB = 1;
if (noteA == 0) {
   if (milk == 0) {
      milk++;
   }
}
noteB = 0;
```

Is this safe?

Does it ensure liveness?

Too Much Milk, Try #3

- **Try #3: monitoring note**

Alice

```
noteA = 1;
while (noteB == 1);
if (milk == 0) {
   milk++;
}
noteA = 0;
```

Bob

```
noteB = 1;
if (noteA == 0) {
   if (milk == 0) {
      milk++;
   }
}
noteB = 0;
```

Is this safe?

Does it ensure liveness?

Mechanisms For Building Critical Sections

- **Atomic read/write**
  - Can it be done?
- **Locks**
  - 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)

Mutex with Atomic R/W: Try #1

```
int turn = 1;
```

T₁ → T_1

```
while (true) {
    while (turn != 1);
    critical section
    turn = 2;
    outside of critical section
}
```

T_2

```
while (true) {
    while (turn != 2);
    critical section
    turn = 1;
    outside of critical section
}
```

This is called alternation

- **Does it satisfy the safety requirement?**
  - Yes
- **Does it satisfy the liveness requirement?**
  - No, T1 can go into infinite loop outside of the critical section preventing T2 from entering

Mutex with Atomic R/W: Peterson's Algorithm

```
int turn = 1;
bool try1 = false, try2 = false;
```

```
while (true) {
    try1 = true;
    turn = 2;
    while (try2 && turn != 1) ;
    critical section
    try1 = false;
    outside of critical section
}
```

```
while (true) {
    try2 = true;
    turn = 1;
    while (try1 && turn != 2) ;
    critical section
    try2 = false;
    outside of critical section
}
```

- **Does it satisfy the safety requirement?**
- **Does it satisfy the liveness requirement?**

Mutex with Atomic R/W: Peterson's Algorithm

```
int turn = 1;
bool try1 = false, try2 = false;
```

```
while (true) {
{¬ try1 ∧ (turn == 1 ∨ turn == 2) }
1     try1 = true;
{ try1 ∧ (turn == 1 ∨ turn == 2) }
2     turn = 2;
{ try1 ∧ (turn == 1 ∨ turn == 2) }
3     while (try2 && turn != 1);
{  try1 ∧ (turn == 1 ∨ ¬ try2 ∨
      (try2 ∧ (yellow at 6 or at 7))) }
      critical section
4     try1 = false;
{¬ try1 ∧ (turn == 1 ∨ turn == 2) }
      outside of critical section
}
```

```
while (true) {
{¬ try2 ∧ (turn == 1 ∨ turn == 2) }
5     try2 = true;
{ try2 ∧ (turn == 1 ∨ turn == 2) }
6     turn = 1;
{ try2 ∧ (turn == 1 ∨ turn == 2) }
7     while (try1 && turn != 2);
{  try2 ∧ (turn == 2 ∨ ¬ try1 ∨
      (try1 ∧ (green at 2 or at 3))) }
      critical section
8     try2 = false;
{¬ try2 ∧ (turn == 1 ∨ turn == 2) }
      outside of critical section
}
```

(green at 4) ∧ (yellow at 8) ⇒ try1 ∧ (turn == 1 ∨ ¬ try2 ∨ (try2 ∧ (yellow at 6 or at 7)))
∧ try2 ∧ (turn == 2 ∨ ¬ try1 ∨ (try1 ∧ (green at 2 or at 3)))
... ⇒ (turn == 1 ∧ turn == 2)

Locks

- **A lock is an object in memory providing two operations**
  - acquire(): wait until lock is free, then take it to enter a C.S
  - release(): release lock to leave a C.S, waking up anyone waiting for it
- **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)**
  - Can break apart Peterson's to implement a spinlock

Too Much Milk, Try #4

- **Try #4: lock**

Alice

```
lock.acquire();
if (milk == 0) {
  milk++;
}
lock.release();
```

Bob

```
lock.acquire();
if (milk == 0) {
  milk++;
}
lock.release();
```

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 green 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

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

- **Hardware executes it atomically!**
- **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?

- **Other similar flavor atomic instructions: xchg, CAS**

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 is the value of held?**
- **What about multiprocessors?**
- **Implement it with xchg, Compare-And-Swap**

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 (on a uniprocessor)
- **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 Pintos uses as its primitive
- **In a "real" system, this is only available to the kernel**
  - Why?
- **Disabling interrupts is insufficient on a multiprocessor**
  - Interrupts are only disabled on a per-core basis
  - 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 (CS) 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**

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)        } Interrupts Disabled
…
Critical section     } Interrupts Enabled
…
release(lock)        } Interrupts Disabled
```

See Pintos threads/synch.c: sema_down/up

Summary

- **Why we need synchronizations**
- **Critical sections**
- **Simple algorithms to implement critical sections**
- **Locks**
- **Lock implementations**

Next Time…

- **Read Chapters 30, 31**