CSE 451: Operating Systems

Spring 2020

Module 6

Synchronization

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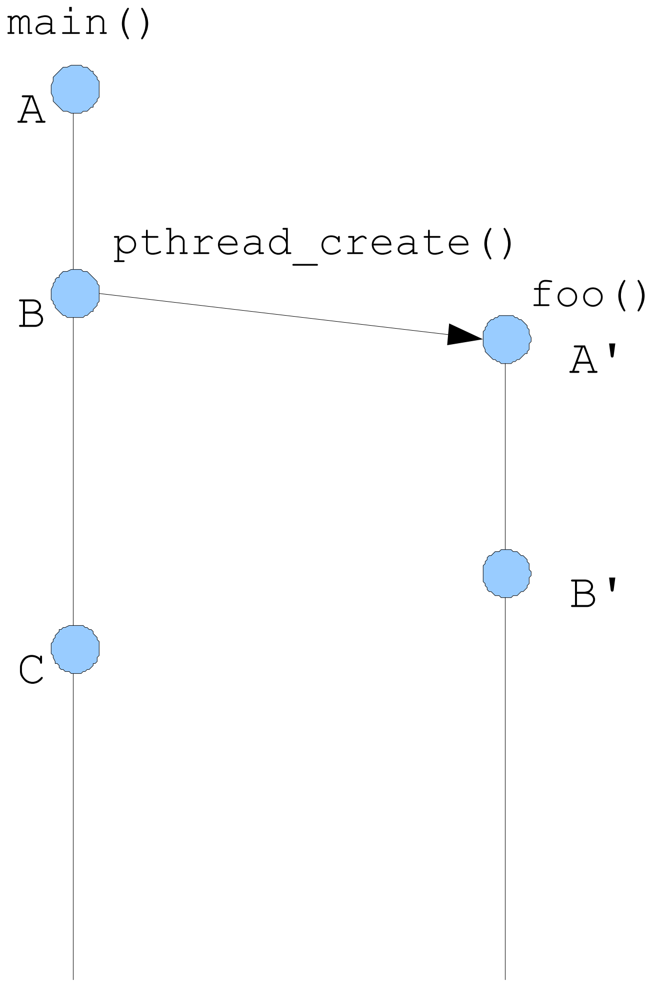
Announcements

- Midterm this Friday
- Where?
  - Canvas quiz
- When?
  - You’ll have 50 minutes between 11:20 am and 12:30 pm on Friday

Temporal relations

- Machine instructions executed by a single thread are totally ordered
  - A < B < C < …
  - *(Okay, we know they're not, because that's too slow. But however they're executed it has the same effect as totally ordered execution, usually.)*
- Absent synchronization, instructions executed by distinct threads must be considered unordered
  - Not X < X', and not X' < X
- Not X < X' and not X' < X is simultaneous
  - unordered
  - at the same time

Example



Y-axis is "time"

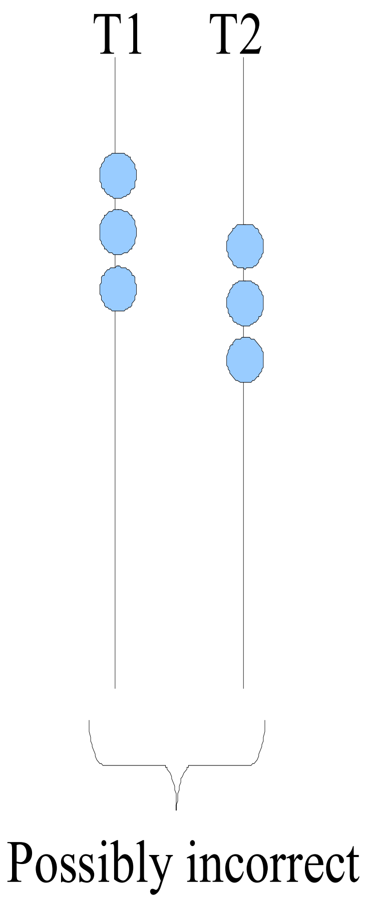
Could be one core, could be multiple cores.

- A < B < C
- A' < B'
- A < A'
- C == A'
- C == B'

Critical Sections / Mutual Exclusion / Locks

- Sequences of instructions that may get incorrect results if executed simultaneously are called critical sections
- (We also use the term race condition to refer to a situation in which the results depend on timing)
- Mutual exclusion means "not simultaneous"
  - Either A < B or B < A
  - We don't care which
- Forcing mutual exclusion between two critical section executions is sufficient to ensure correct execution – guarantees ordering
- One way to guarantee mutually exclusive execution is using locks

Critical sections



When do critical sections arise?

- One common pattern:
  - read-modify-write of
    - a shared value (variable)
      - in code that can be executed concurrently

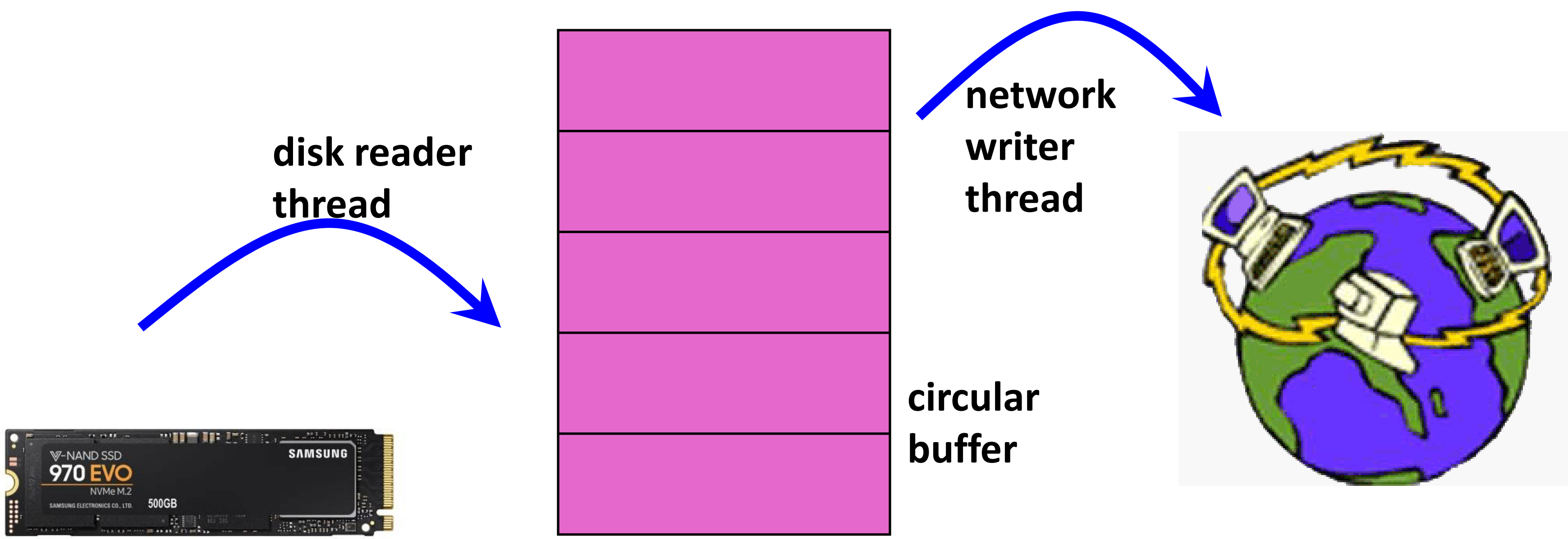
  (Note: There may be only one copy of the code (e.g., a procedure), but it can be executed by more than one thread at a time)

- Shared variables
  - Globals and heap-allocated variables
  - to keep your sanity, NOT local variables (which are on the stack)

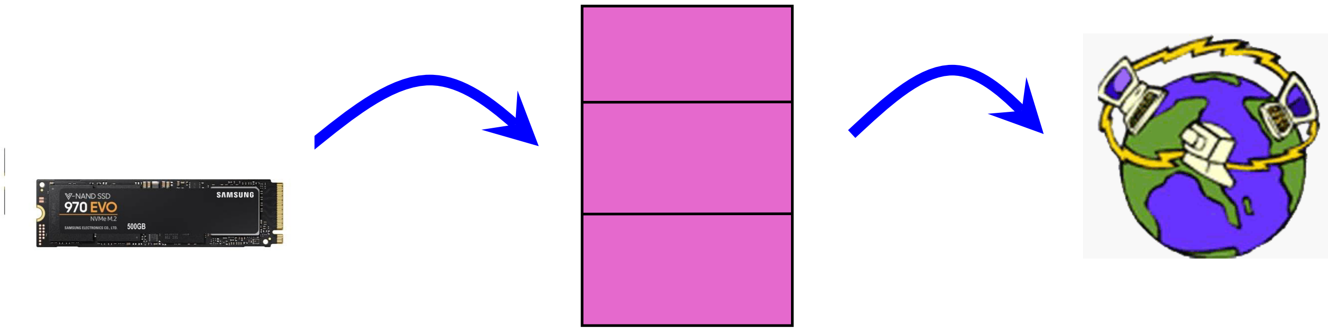
  (Never give a reference to a stack-allocated (local) variable to another thread, unless you're superhumanly careful …)

Example: buffer management

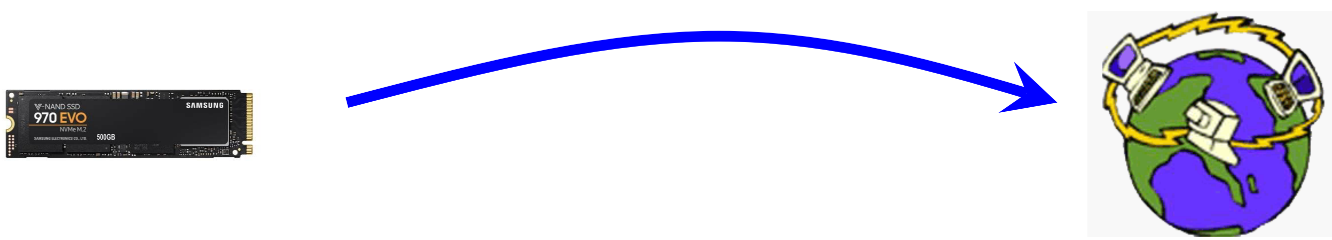
- In this example, one thread puts data into a buffer that another thread reads from
- Shared resource: buffer
- Read-modify-write: each slot is either empty or free, and operations get() and put() both read the status and modify it



Why use threads in that example?



vs.



The classic shared bank account example

- Suppose we have to implement a function to withdraw money from a bank account:

```
int withdraw(account, amount) {
  int balance = get_balance(account);      // read
  if (balance >= amount) {
        balance -= amount;                 // modify
        put_balance(account, balance);     // write
        spit out cash;
  }
}
```

- Now suppose that you and your partner share a bank account with a balance of $100.
- What happens if you both go to separate ATM machines, and simultaneously withdraw $15 from the account?

- Assume the bank's application is multi-threaded
- A random thread is assigned a transaction when that transaction is submitted

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  if (balance >= amount) {
     balance -= amount;
     put_balance(account, balance);
     spit out cash;
  }
}
```

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  if ( balance >= amount ) {
     balance -= amount;
     put_balance(account, balance);
     spit out cash;
  }
}
```

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);
spit out cash;
```

context switch

```
put_balance(account, balance);
spit out cash;
```

- What’s the account balance after this sequence?
  - Who’s happy, the bank or you?
  - Suppose the two of you make simultaneous deposits?
- How often is this sequence likely to occur?

Other Execution Orders

- Which interleavings are ok? Which are not?

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  if ( balance >= amount ) {
    balance -= amount;
     put_balance(account, balance);
     spit out cash;
  }
}
```

```
int withdraw(account, amount) {
  int balance = get_balance(account);
  if ( balance >= amount ) {
    balance -= amount;
    put_balance(account, balance);
    spit out cash;
  }
}
```

How About Now?

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

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

- Morals:
  - Interleavings are hard to reason about
    - We make lots of mistakes
    - Control-flow analysis is hard for tools to get right
  - Identifying critical sections and ensuring mutually exclusive access is … "easier"
  - We'd like it to be easier still!

Another example

```
i++;
```

```
i++;
```

Moral?

Correct critical section requirements

- Correct critical sections have the following requirements
  - mutual exclusion
    - at most one thread is in the critical section
  - progress
    - Ridiculous solution so far: Don’t let any code execute critical section, ever
    - if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
  - bounded waiting (no starvation)
    - Ridiculous solution so far: Let there be one “chosen thread” that is allowed to execute critical sections, but no others
      - *That actually isn’t such a bad idea...*
    - 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
    - High overhead solution: all threads wanting to enter critical section contact a server and the server replies when it’s your turn to enter

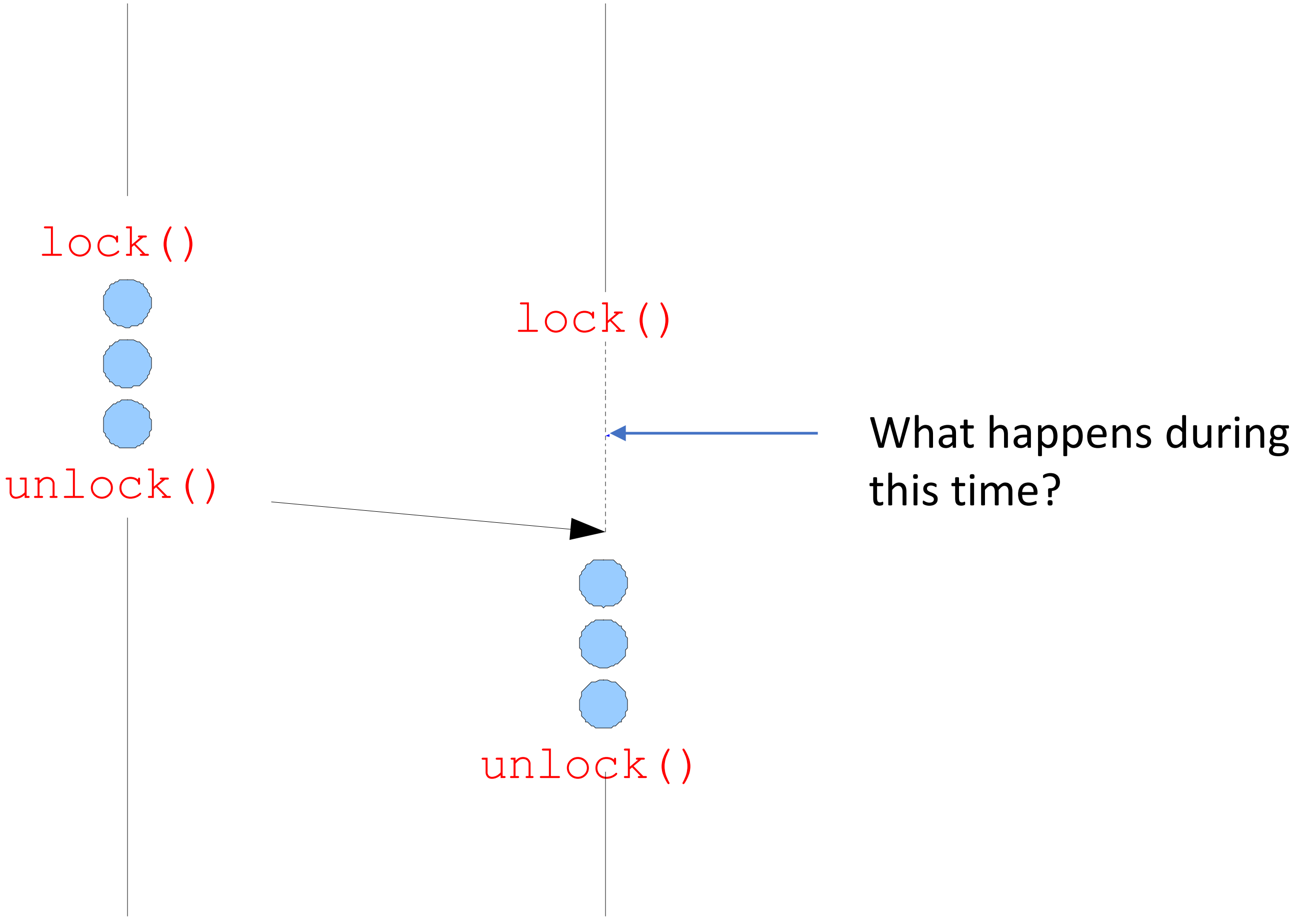
Mechanisms for building critical sections

- Spinlocks (locks)
  - primitive, minimal semantics; used to build others
- Mutexes (blocking locks)
- Semaphores
  - basic, easy to get the hang of, somewhat hard to program with
- Monitors
  - higher level, “requires” language support, implicit operations
  - easier 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 (memory) object with two operations:
  - `acquire()`: obtain the right to enter the critical section
  - `release()`: give up the right to be in the critical section
- `acquire()` prevents progress of the thread until the lock can be acquired
- (Note: terminology varies: acquire/release, lock/unlock)

Locks: Example



Acquire/Release

- 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
- What happens if the calls aren't paired (I acquire, but neglect to release)?
- What happens if the two threads acquire different locks (I think that access to a particular shared data structure is mediated by lock A, and you think it's mediated by lock B)?
- Why is granularity of locking important
  - fine grained => not much work done between acquire() and release()
  - coarse grained => plenty of work done between acquire() and release()

Using locks

```
int withdraw(account, amount) {
  acquire(lock);
  balance = get_balance(account);
  if ( balance >= amount ) {
    balance -= amount;
    put_balance(account, balance);
  }
  release(lock);
  spit out cash;
}
```

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);
spit out cash;
```

```
spit out cash;
```

- What happens when green tries to acquire the lock?
- Why is reading the balance inside the critical section?
- Why isn't "spit out cash" inside the critical section?

Roadmap …

- Where we are eventually going:
  - The OS and/or the user-level thread package will provide some sort of efficient primitive for user programs to achieve mutual exclusion
    - for example, *locks* or *semaphores,* used with *condition variables*
  - There may be higher-level constructs provided by a programming language to help you get it right
    - for example, *monitors* – which utilize condition variables
- But somewhere, underneath it all, it turns out we require some sort of hardware support
  - Some “atomic instruction” that does at least two logically distinct things in a way that every other instruction operating on the same data executes either before or after, but not during
  - This hardware mechanism will not be utilized by user programs
  - It will be utilized in implementing somewhat higher abstractions for user programs

Spinlocks

- A spinlock is a lock where the thread attempting acquire() “spins” (tries over and over without relinquishing its core)
- How do we implement spinlocks? Here’s one attempt:

```
struct lock_t {
  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?
    - does it work if there’s only one core?

Implementing spinlocks

- Problem is that implementation of spinlocks 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 instruction
  - test-and-set, compare-and-swap, …
- atomic sequence of instructions, in some cases
  - just don’t let any other code run...
  - disable/reenable interrupts to prevent context switches
    - used in xk

Hardware Test-and-Set

- CPU hardware provides the following a single atomic instruction:

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

- Remember, this is a single atomic instruction …
  - *Remember, this is just one example of possible hardware support*

Implementing spinlocks using Test-and-Set

- So, to fix our broken spinlocks:

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

  - mutual exclusion? (at most one thread in the critical section)
  - progress? (T outside cannot prevent S from entering)
  - bounded waiting? (waiting T will eventually enter)
  - performance? (low overhead?)

Reminder of use …

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

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);
spit out cash;
```

```
spit out cash;
```

- How does a thread blocked on an “acquire” (that is, stuck in a test-and-set loop) yield the CPU?
  - voluntarily calls yield( ) *(spin-then-block)*
  - there’s an involuntary context switch (e.g., timer interrupt)

Problems with spinlocks

- Spinlocks work, but can be wasteful
  - if a thread is spinning on a lock, the thread holding the lock cannot make progress
    - You'll spin for a scheduling quantum
  - `(pthread_spin_t)`
- Generally want to use spinlocks only as primitives to build higher-level synchronization constructs
- We'll see later how to build blocking locks
  - But there is overhead – can be cheaper to spin
  - `(pthread_mutex_t)`

A second approach: Disabling interrupts

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

Problems with disabling interrupts

- Available only 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!
  - “Stuff doesn’t work”
- Just as with spinlocks, you want to use disabling of interrupts only to build higher-level synchronization constructs
  - Except maybe in xk...

Summary

- Synchronization enforces temporal ordering constraints
- Adding synchronization can eliminate races
- Synchronization can be provided by locks, semaphores, monitors, messages …
- Spinlocks are a lowest-level mechanism
  - primitive in terms of semantics – error-prone
  - implemented by spin-waiting (crude) or by disabling interrupts (even cruder)
- In our next exciting episode …
  - semaphores are a slightly higher level abstraction
    - Importantly, they are implemented by blocking, not spinning
    - Locks can also be implemented in this way
  - monitors are significantly higher level
    - utilize programming language support to reduce errors