CSE 451: Operating Systems

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Module 6

Synchronization

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Temporal relations

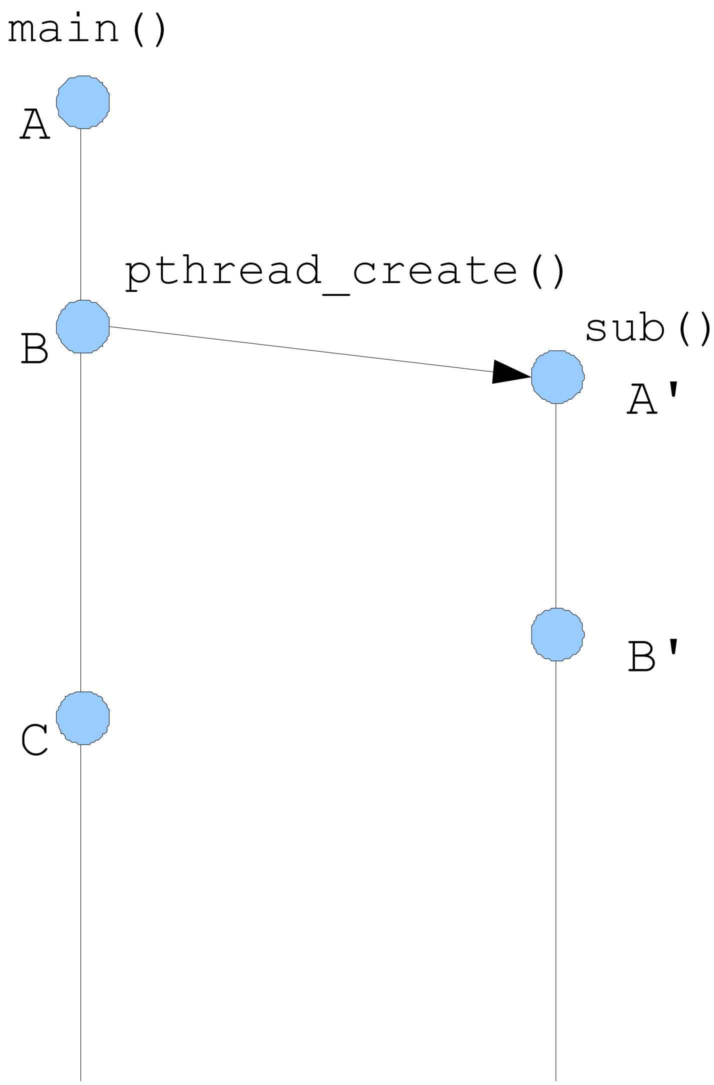
- Machine instructions executed by a single thread are totally ordered
  - A < B < C < …
  - This is called "program order"
  - *(Interesting aside: actually, that isn't necessarily true, physically. To go fast, each core tries to execute many instructions at once, possibly out of order. However, it does so in a way that it has the same effect as totally ordered execution. Usually.)*

- Unless there is explicit 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

- If X and X' access the same memory location, and at least one of them is a write, it is a "data race"

Example



Y-axis is "time"

Could be one core, could be multiple cores.

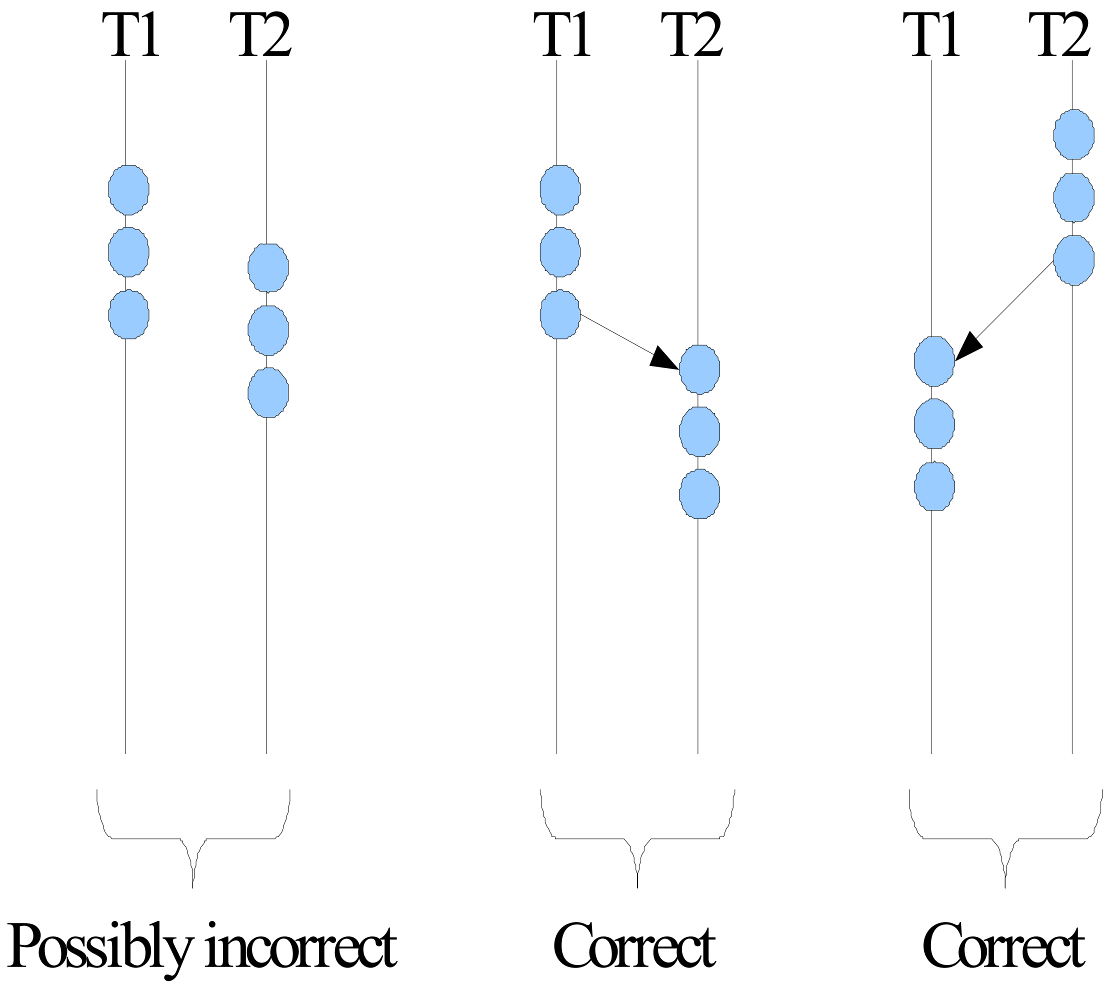
- A < B < C
- A' < B'
- A < A'
- C == A'
- C == B'

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

How many cores are in use here?



When do critical sections arise?

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

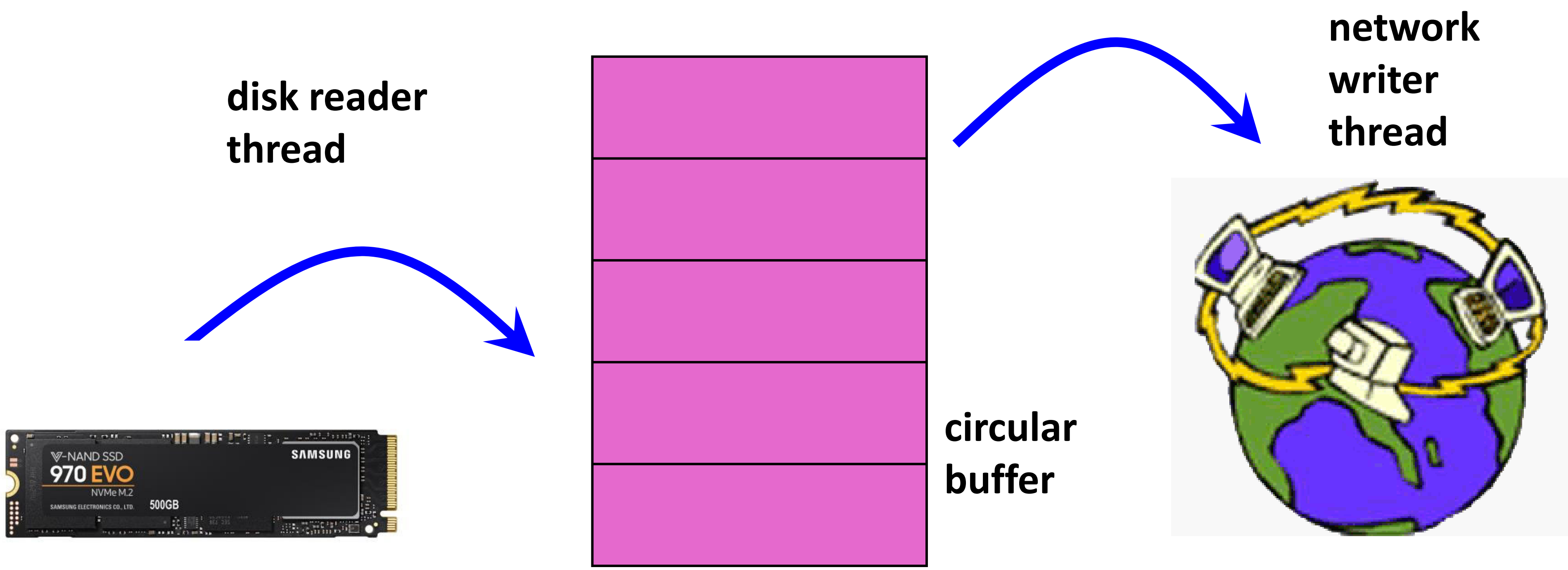
  (Note: There may be only one copy of the code (e.g., a procedure), but it can be executed by more than one thread at a time)

- Shared variables
  - Globals and heap-allocated variables
  - to keep your sanity, follow the convention of NOT sharing local variables (which are on the stack) across threads

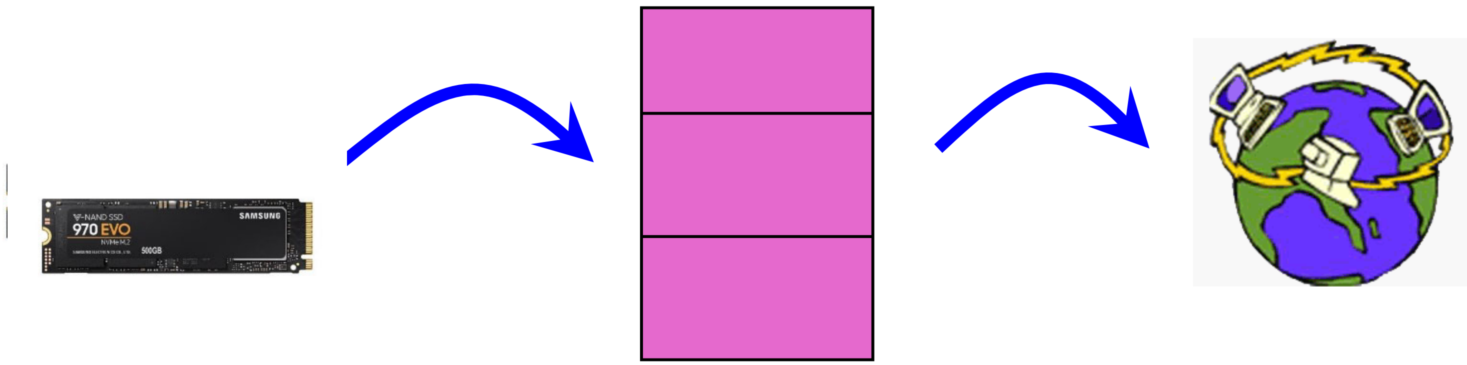
    (Never give a reference to a stack-allocated (local) variable to another thread, unless you're superhumanly careful …)
  - *Can you pass a local as an argument to a function?*

Example: buffer management

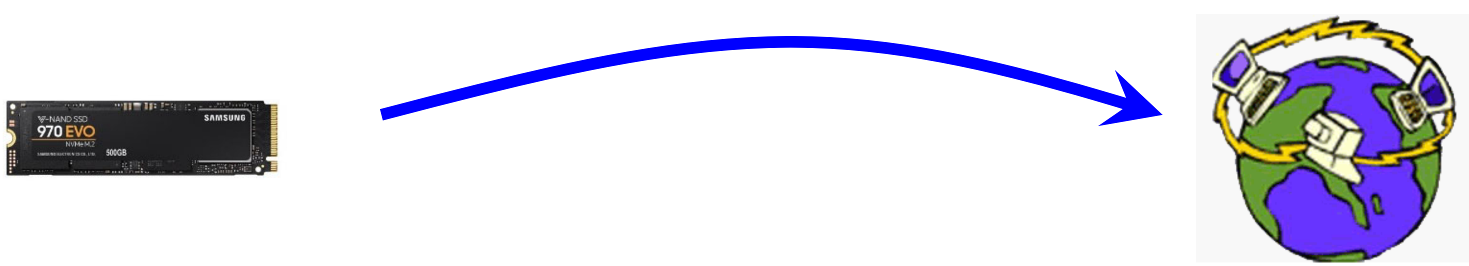
- In this example, one thread puts data into a buffer that another thread reads from
- Shared resource: buffer data structure
- Read-modify-write: each slot is either empty or free; operations get() and put() both read and modify a slot status



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 $500.
- What happens if you both go to separate ATM machines, and simultaneously withdraw $50 from the account?

- Assume the bank's application is multi-threaded, and…
- 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?
- Can this happen if there is only one physical core?

How many cores are in use in this example?

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;
  }
}
```

Correct critical section requirements

- Correct critical sections have the following requirements

1. mutual exclusion
   - at most one thread is in the critical section
   - Ridiculous solution so far: Don't let any code execute critical section, ever
2. progress
   - if thread T is outside the critical section, then T cannot prevent thread S from entering the critical section
   - Ridiculous solution so far: Let there be one "chosen thread" that is allowed to execute critical sections, but no others
     - *That actually isn't always a bad idea...*
3. 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
4. performance
   - the overhead of entering and exiting the critical section is small with respect to the work being done within it (related to granularity)
   - *High overhead solution: all threads wanting to enter critical section contact a server and the server replies when it's your turn to enter*

Synchronization mechanisms for building critical sections

- Locks (spinlocks)
  - 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; 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

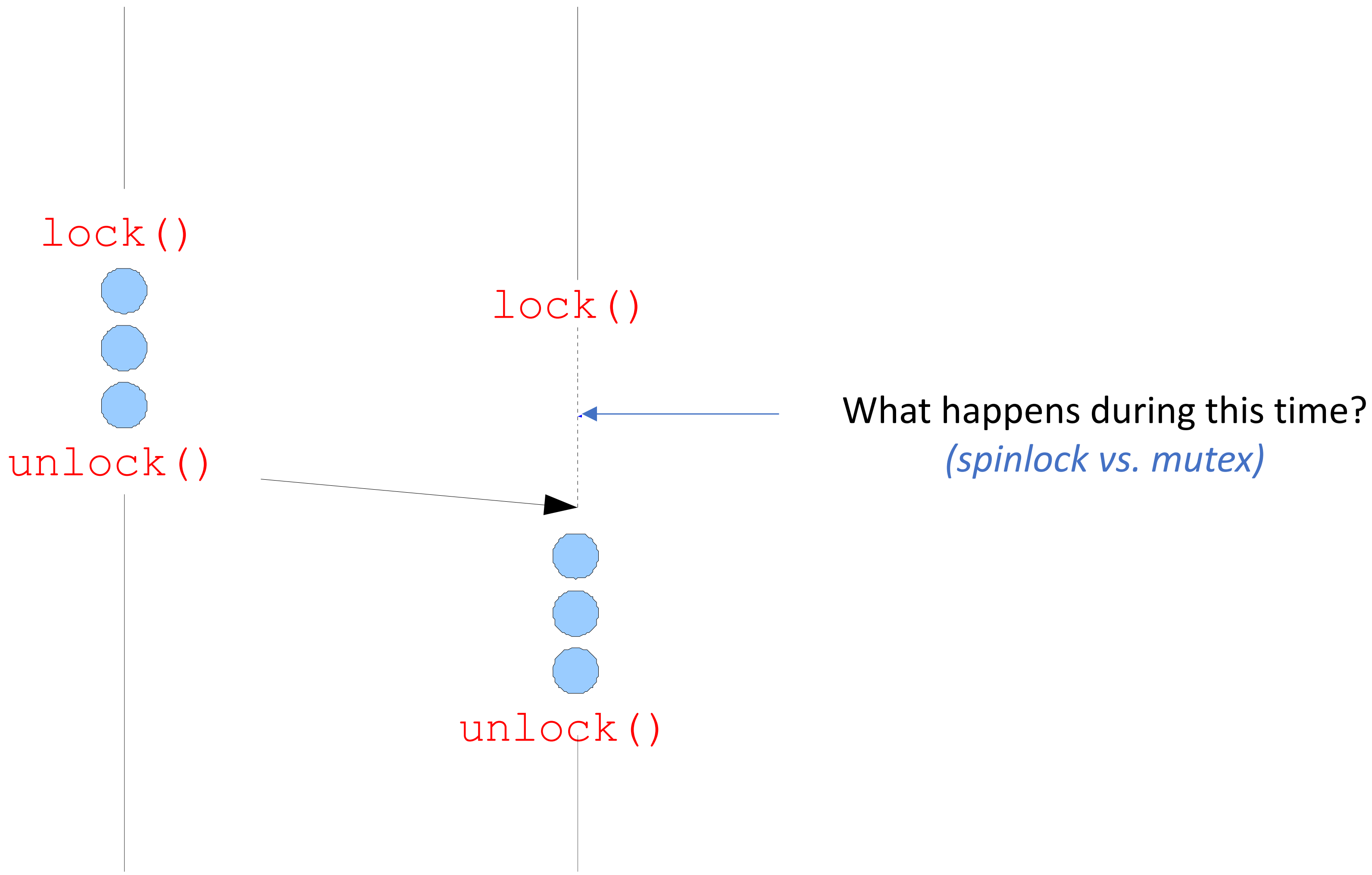
Locking (Locks)

- Locking has two operations:
  - `acquire()`: obtain the right to enter the critical section
  - `release()`: give up the right to be in the critical section
  - *(Note: terminology can vary: acquire/release, lock/unlock)*

- acquire()/release() provide the four conditions required to be a critical section solution

- A lock is (usually) a memory object and code that supports those operations in a particular way (that we'll see shortly)

Locks: Example



Acquire/Release

- Each threads pairs calls to `acquire()` and `release()`
  - between `acquire()` and `release()`, the thread holds the lock
- The `acquire()` call is the request.
  The return is the response indication that the caller now "owns" (holds) the lock
  - at most one thread can hold a lock at a time

- What happens if the calls aren't paired (fail to call 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 => lots 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?
  - Could it be put inside the critical section?

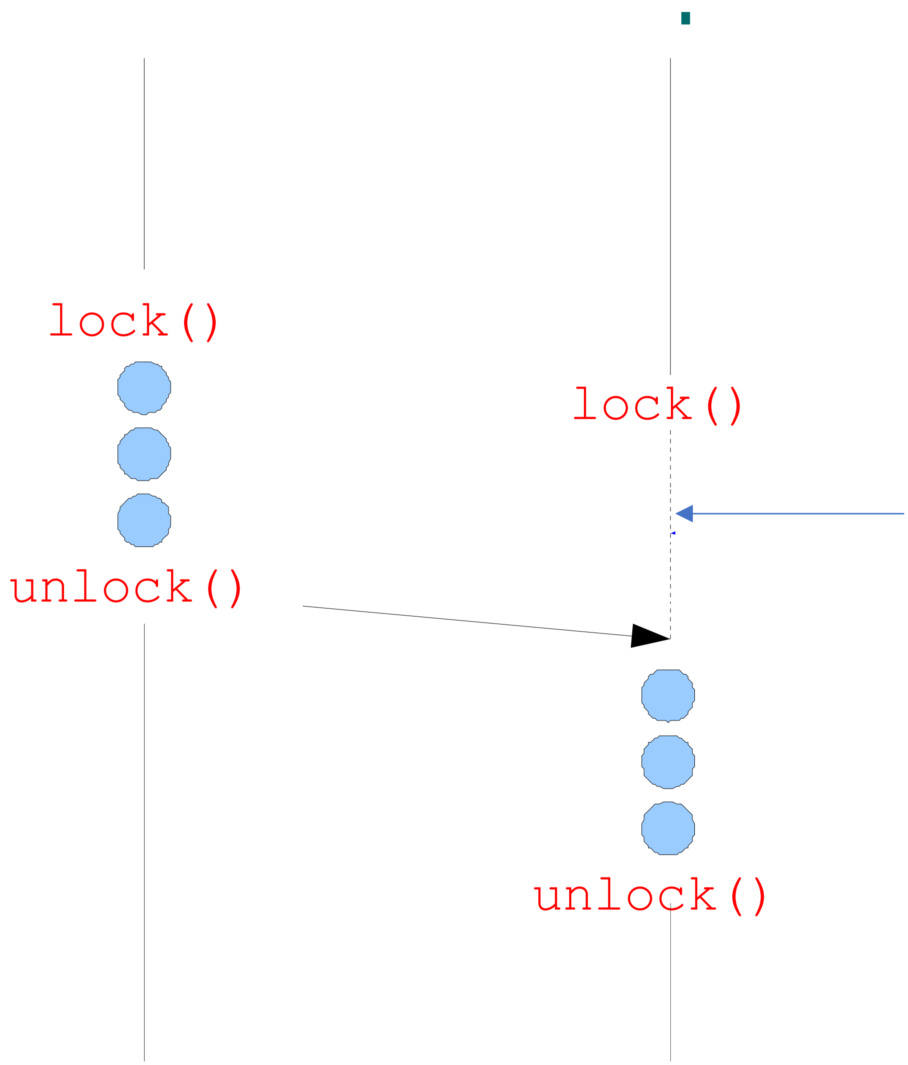
Roadmap …

- Where have we just been?
  - Critical sections are a common property of concurrent/parallel code
  - Mutual exclusion is a mechanism to ensure a kind atomic execution of critical sections

- Where are we going?
  - Synchronization constructs provide the programmer with abstractions that address synchronization problems, like critical sections
  - The most primitive/fundamental abstraction is acquire()/release(): the lock
    - It can provide a solution if used correctly
    - It's easy to mis-use it, though
  - "Higher level" synchronization abstractions provide additional semantics that can make them easier to use correctly, but usually at the cost of more overhead
  - The implementation of these higher level synchronization primitives often involves critical sections, so we layer the implementation (relying on the lock, say, for mutual exclusion)

- At the bottom of the layered implementations, it turns out we require some sort of hardware support
  - Software implementing acquire()/release "needs" to do a read-modify-write
  - Software can't use itself to achieve that, so we need lower level support
  - So we "need" some atomic instruction that does at least two logically distinct things
    - Basically, there's a read phase followed by a write phase
    - Done atomically
  - This hardware mechanism(s) are not intended to be utilized directly in user programs
    - They're used to build software that implements somewhat higher abstractions that are used in user programs

Our First Primitives: Locks and Mutexes



What happens during this time?

1. Spinlock – keep using core while waiting
2. Mutex – give up core while waiting

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 (annotation pointing to `while (lock->held);`)

- 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 is itself a critical section
  - 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

  1. atomic instruction
     - many instances of the instruction can be executed concurrently, because the hardware provides atomicity at the instruction level
     - test-and-set, compare-and-swap, …

  2. disable interrupts
     - Terrible idea…
     - Used in xk…
     - Provides for atomic sequence of arbitrary instructions, when it works

Atomic Instruction: Test-and-Set

- CPU hardware provides the following operation as a single atomic instruction:

```
bool test_and_set(bool *flag) {
  bool old = *flag;   // save value in a local (register)
  *flag = True;       // make sure value is True
  return old;         // return old value
}
```

- 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?)

Lock instruction?

- Would a single atomic instruction whose semantics were the while loop shown on the last slide be "better" than just a test-and-set instruction?
  - The instruction would execute until it found atomically that the memory location had value 0 and had set it to 1?

- Any Pro's?
- Any Con's?

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;
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release(lock);
spit out cash;
```

```
spit out cash;
```

- How could a thread spinning in acquire (that is, stuck in a test-and-set loop) yield its core?
  - voluntarily calls yield( ) *(spin-then-block lock)*
  - there’s an involuntary context switch (e.g., timer interrupt)
- When should a thread that has yielded the core be given a core again?

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)`

- Are there other "policy" choices (than spin and block)?
  - Who should make them?
  - `pthread_spin_trylock()`

A second approach: Disabling interrupts

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

What’s the key point about disabling interrupts?

Problems with disabling interrupts

- Available only to the kernel!
  - Can’t allow user-level to disable interrupts!
- Insufficient on a multicore!
  - Each core has its own interrupt mechanism
- “Long” periods with interrupts disabled can wreak havoc with devices!
  - “Stuff doesn’t work”
- Just as with spinlocks, you (would) want to use disabling of interrupts only when the duration of disabling is well understood (and short)
  - E.g., to build higher-level synchronization constructs

Summary

- Synchronization enforces temporal ordering constraints among instruction streams
  - 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 and doesn’t really work these days)
  - Make sense only when it’s “guaranteed” the lock will be released very soon
- Next…
  - Condition variables
    - Blocking as a concept/mechanism
  - Semaphores: synchronization variable
    - Importantly, they are implemented by blocking, not spinning
    - Locks can also be implemented in this way
  - Monitors: programming language support
    - are significantly higher level
    - utilize programming language support to reduce errors