CSE 451: Operating Systems
Winter 2022

Module 7
Synchronization

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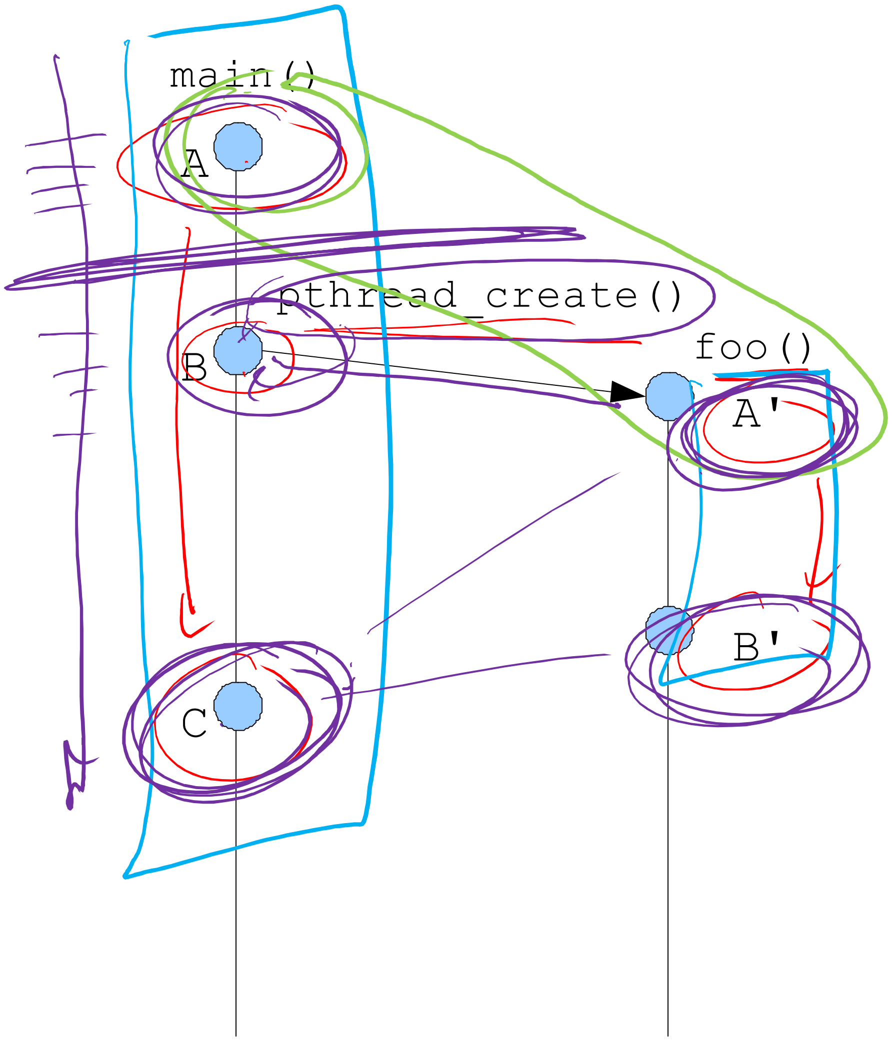
Temporal relations

- Instructions executed by a single thread are totally ordered
  - A < B < C < …
- Absent synchronization, instructions executed by distinct threads must be considered unordered / simultaneous
  - Not X < X’, and not X’ < X

Example

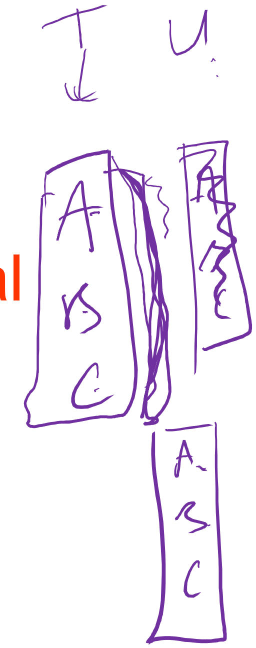


Y-axis is "time."

Could be one CPU, could be multiple CPUs (cores).

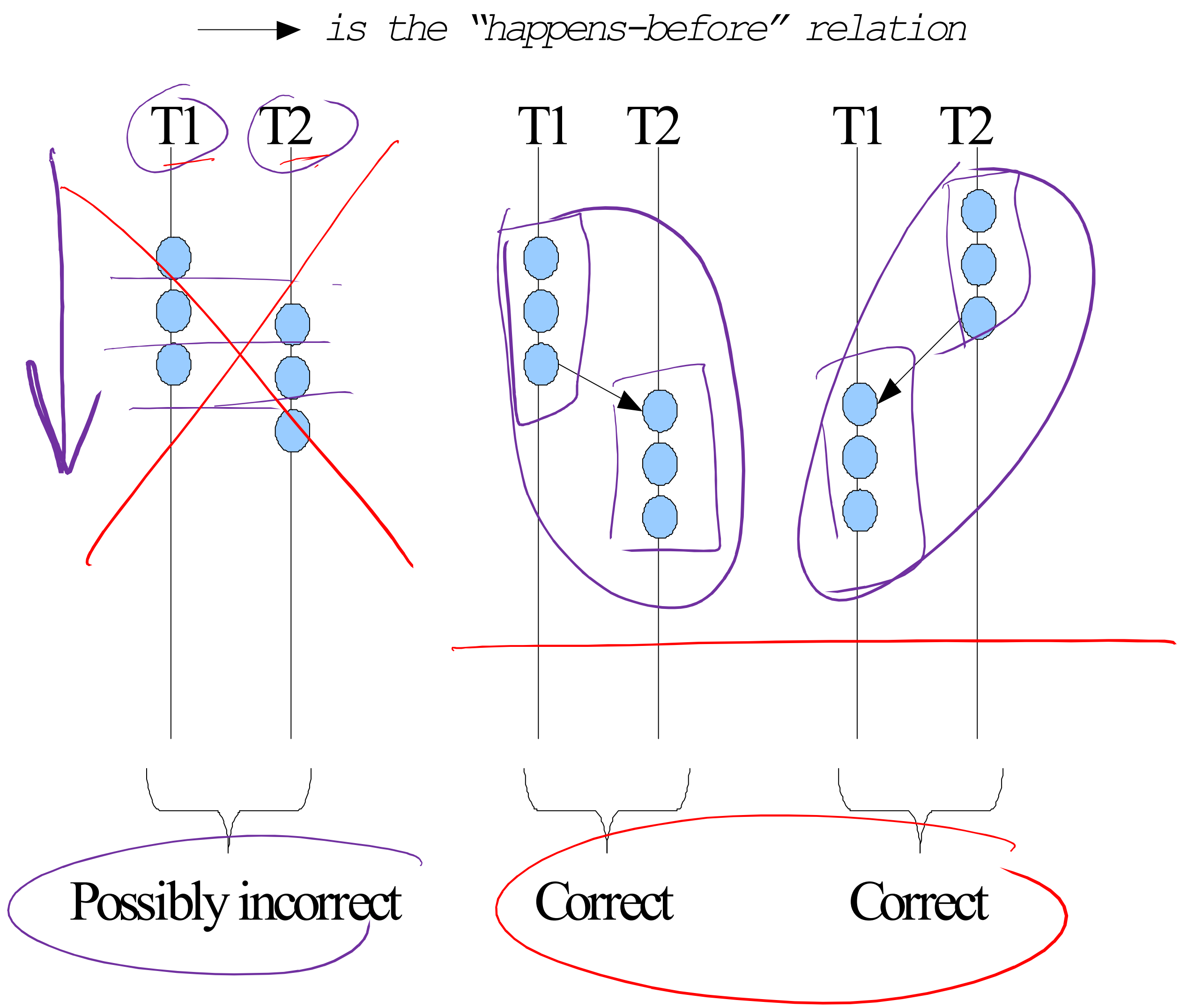
- A < B < C
- A' < B'
- A < A'
- C == A'
- C == B'

Critical Sections / Mutual Exclusion



- 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"
  - 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?

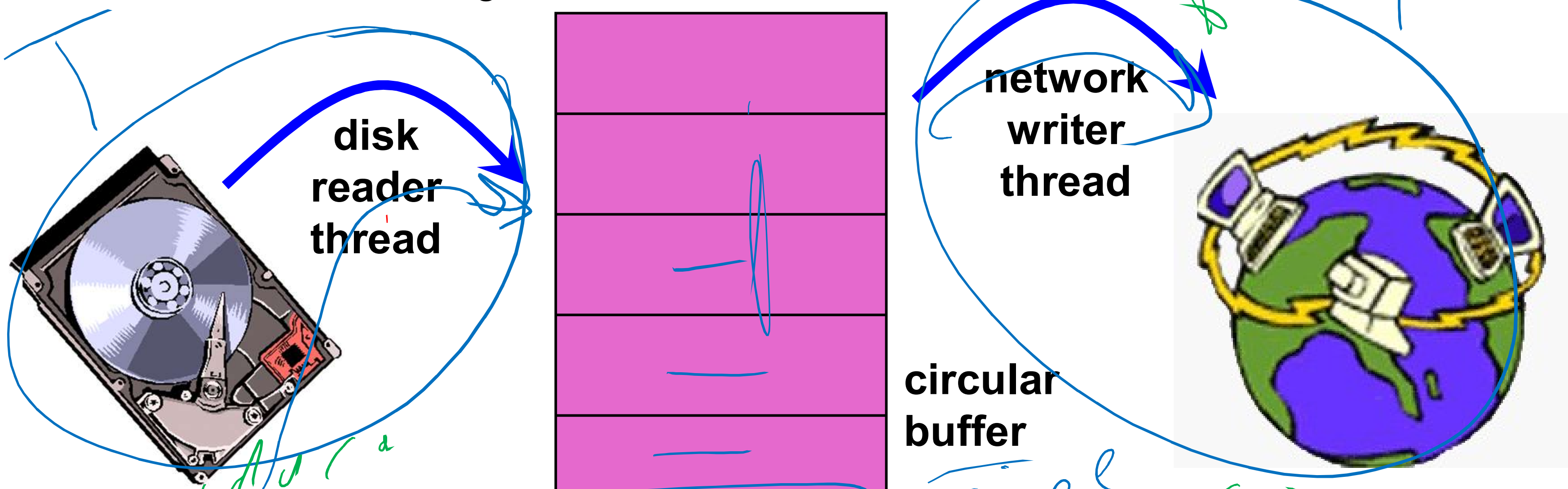
- One common pattern:
  - read-modify-write of
  - a shared value (variable)
  - in code that can be executed concurrently

    (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 variable:
  - Globals and heap-allocated variables
  - NOT local variables (which are on the stack)

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

Example: buffer management

- 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



Example: shared bank account

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

```
int withdraw(account, amount) {
  int balance = get_balance(account);      // read
  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 $100.00
  - what happens if you both go to separate ATM machines, and simultaneously withdraw $10.00 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);
  balance -= amount;
  put_balance(account, balance);
  spit out cash;
}
```

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

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

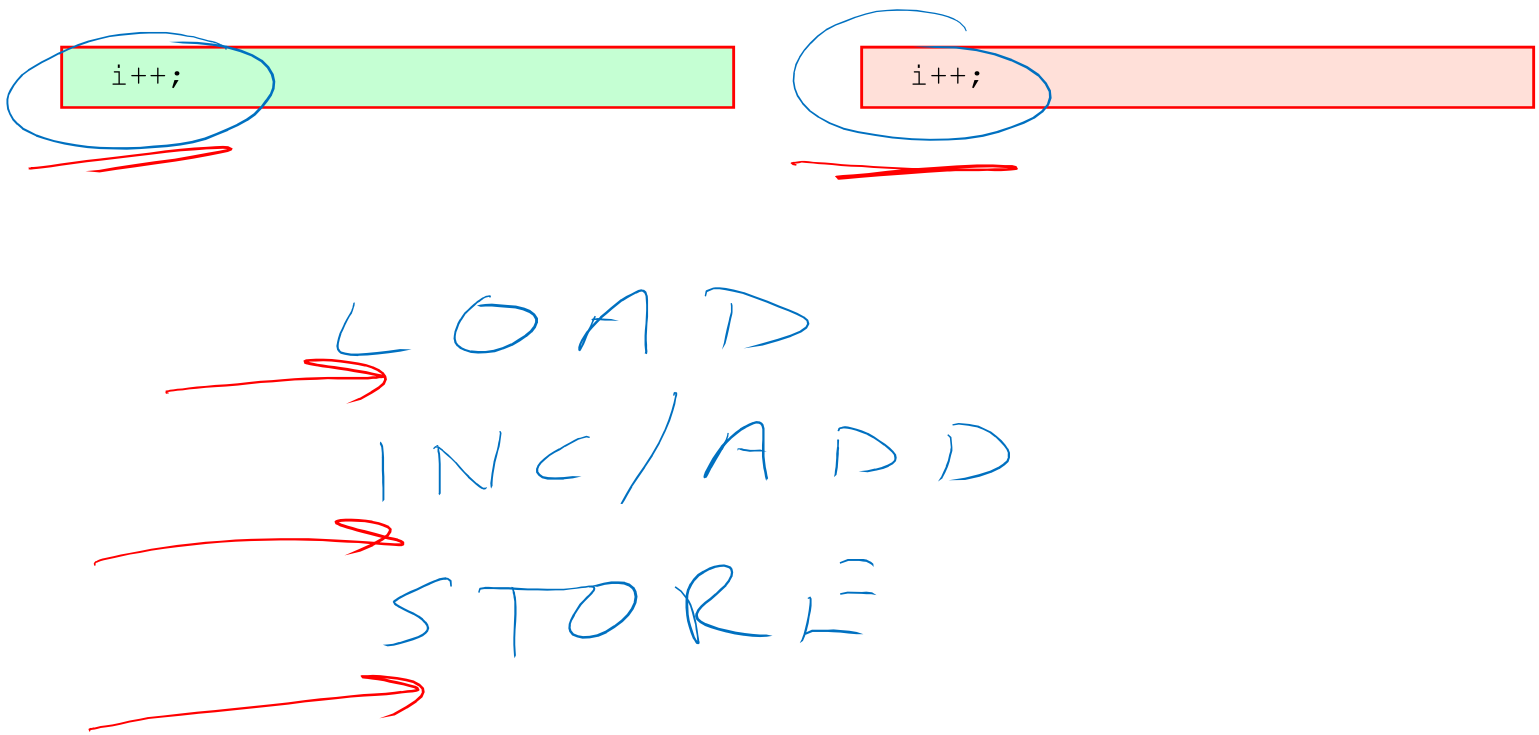
How About Now?

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

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

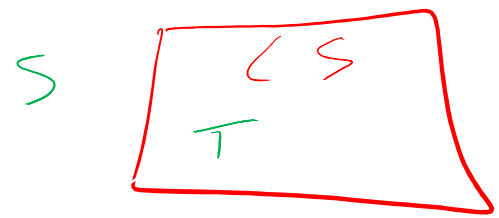
- Morals:
  - Interleavings are hard to reason about
    - We make lots of mistakes
    - Control-flow analysis is hard for tools to get right
  - Identifying critical sections and ensuring mutually exclusive access is … “easier”

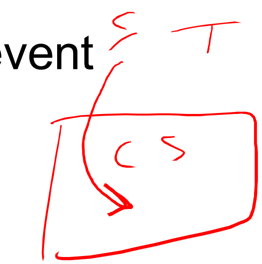
Another example



Correct critical section requirements

- Correct 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
  - 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

- Spinlocks
  - primitive, minimal semantics; used to build others
- Semaphores (and non-spinning locks)
  - 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

Back to in-person instruction (subject to change)

- Monday January 31 we return to in-person instruction, MWF 11:30 in CSE2 G10
- The lectures will still be on Zoom and now Panopto, both live and recorded for later viewing
- Please continue to use the remote learning option if you are sick or uncomfortable attending in-person.
- If I cannot make the lectures in person, I will post a message on the class website, Ed discussion board, Canvas, and do an email blast to let you know.
- Thursday section AA will be in-person. Sections AB and AC will stay remote for now. You can choose to attend any section.
- I will need to adjust my Office hours (zoom and in-person) to handle walking between the classroom and my physical office, CSE 474

Debug Printf

- Printf is great to watch how code is being executed.
- But sometimes it gets pretty confusing about where the print is coming from, especially if there are a lot of printf's being executed.
- My trick was to preface all my debug prints with the file and line number of the printf

```
cprintf("[%s:%d] other details …\n", __FILE__, __LINE__, ...);
```

- In the xk kernel printing the PID might also be helpful.

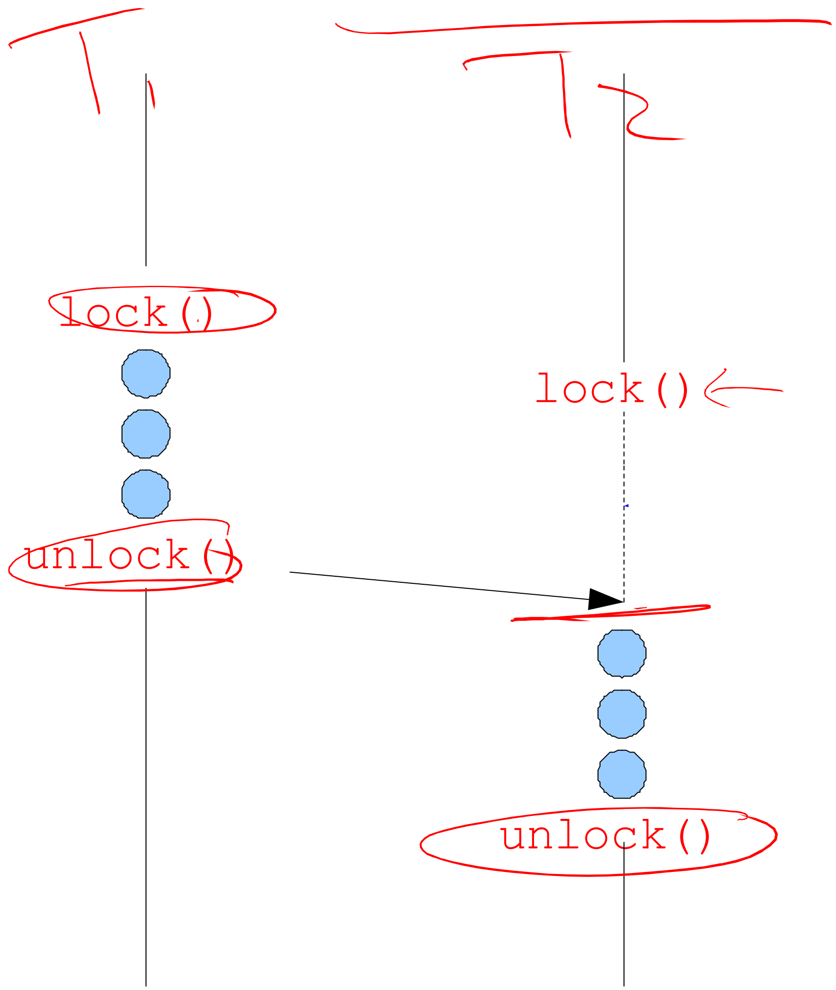
```
cprintf("[%s:%d:%d] …\n", __FILE__, __LINE__, myproc()->pid ...);
```

[proc.c:78]

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)?
    - (granularity of locking)

- Recursion
- Release a lock I don't own
- TryLock( )

Using locks

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

critical section (the lines between `acquire(lock);` and `release(lock);`)

```
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?

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 utilize in achieving 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 also utilize condition variables)
- But somewhere, underneath it all, there needs to be a way to achieve "hardware" mutual exclusion (for example, *test-and-set* used to implement *spinlocks*)
  - This mechanism will not be utilized by user programs
  - But it will be utilized in implementing what user programs see

Spinlocks

- 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?

Implementing spinlocks (cont.)

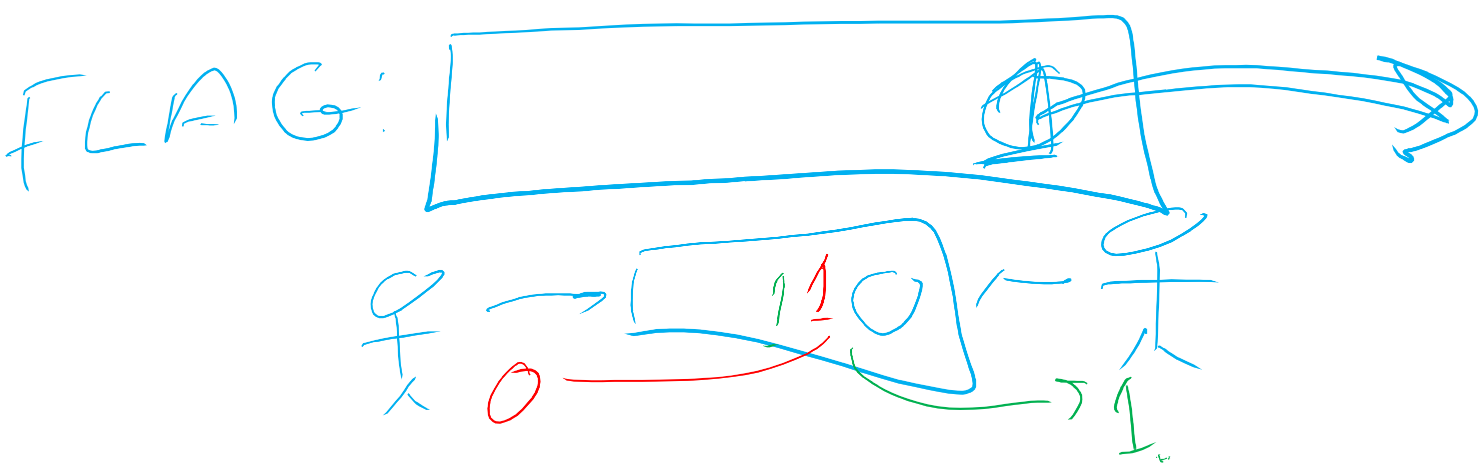
- Problem is that implementation of spinlocks has critical sections, too!
  - the acquire/release must be **atomic**
    - atomic == executes as though it could not be interrupted
    - code that executes "all or nothing"
- Need help from the hardware
  - atomic instructions
    - test-and-set, compare-and-swap, …
  - disable/reenable interrupts
    - to prevent context switches

Spinlocks redux: Hardware 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 atomic instruction …



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 (modulo the spinning part …))

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?
  - calls yield( ) *(spin-then-block)*
  - there's an involuntary context switch (e.g., timer interrupt)

Problems with spinlocks

- Spinlocks work, but are 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)
- Only want spinlocks as primitives to build higher-level synchronization constructs
  - Why is this okay?
- We'll see later how to build blocking locks
  - But there is overhead – can be cheaper to spin
  - (pthread_mutex_t)

Deckers Algorithm

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

Race conditions

- Informally, we say a program has a race condition (aka “data race”) if the result of an executing depends on timing
  - i.e., is non-deterministic

- Typical symptoms
  - I run it on the same data, and sometimes it prints 0 and sometimes it prints 4
  - I run it on the same data, and sometimes it prints 0 and sometimes it crashes

Summary

- Synchronization introduces temporal ordering
- Adding synchronization can eliminate races
- Synchronization can be provided by locks, semaphores, monitors, messages …
- Spinlocks are the lowest-level mechanism
  - 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
    - 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