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

\begin{itemize}
  \item A < B < C
  \item A' < B'
  \item A < A'
  \item C == A'
  \item C == B'
\end{itemize}

Y-axis is "time."

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

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Critical sections

→ is the "happens-before" relation

Possibly incorrect

Correct

Correct

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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:

```c
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

```c
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:

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

balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
spit out cash;

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?

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

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

• 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

lock()
unlock()
lock()
unlock()

Two choices:
• Spin
• Block
• (Spin-then-block)
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)
Using locks

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

```c
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?

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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:

```c
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:

```c
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 ...))
• 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)
Another approach: Disabling interrupts

```c
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