Temporal relations

User view of parallel threads

• Instructions executed by a single thread are totally ordered
  – $A < B < C < \ldots$

• In absence of synchronization,
  – instructions executed by distinct threads must be considered unordered / simultaneous
  – Not $X < X'$, and not $X' < X$

Hardware largely supports this
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
• Race condition 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
Critical sections

→ is the “happens-before” relation

Possibly incorrect  Correct  Correct
When do critical sections arise?

• One common pattern:
  – read-modify-write of
  – a shared value (variable)
  – in code that can be executed by concurrent threads

• Shared variable:
  – Globals and heap-allocated variables
  – NOT local variables (which are on the stack)
Race conditions

• A program has a **race condition** (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
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 CashPoint 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;
}
```

```c
int withdraw(account, amount) {
    int balance = get_balance(account);
    balance -= amount;
    put_balance(account, balance);
    spit out cash;
}
```
The problem is that the execution of the two threads can be interleaved:

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;
}
```
• **Moral:**
  - 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 can make things easier
Another example

```java
int i = 0;

i++;  // Increment i

i++;  // Increment i again
```
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
Implementing Mutual Exclusion

How do we do it?

- via hardware: special machine instructions
- via OS support: OS provides primitives via system call
- via software: entirely by user code

Of course, OS support needs internal hardware or software implementation.

How do we do it in software?

We assume that mutual exclusion exists in hardware, so that memory access is atomic: only one read or write to a given memory location at a time. (True in almost all architectures.) (Exercise: is such an assumption necessary?)

We will now try to develop a solution for mutual exclusion of two processes, $P_0$ and $P_1$. (Let $\hat{i}$ mean $1 - i$.)

In practise this is unrealistic
Mutex – first attempt

Suppose we have a global variable \( \text{turn} \). We could say that when \( P_i \) wishes to enter critical section, it loops checking \( \text{turn} \), and can proceed iff \( \text{turn} = i \). When done, flips \( \text{turn} \). In pseudocode:

```plaintext
while ( turn != i ) {}
/* critical section */
turn = \hat{i};
```

This has obvious problems:

- processes busy-wait
- the processes must take strict turns

although it does enforce mutex.
Need to keep state of each process, not just id of next process.
So have an array of two boolean flags, $\text{flag}[i]$, indicating whether $P_i$ is in critical. Then $P_i$ does:

```c
while ( flag[\hat{i}] ) { }
flag[i] = true;
/* critical section */
flag[i] = false;
```

This doesn’t even enforce mutex: $P_0$ and $P_1$ might check each other’s flag, then both set own flags to true and enter critical section.
Mutex – Third attempt

Maybe set one’s own flag before checking the other’s?

```c
flag[i] = true;
while ( flag[\^i] ) {} /* critical section */
flag[i] = false;
```

This does enforce mutex. (Exercise: prove it.)

But now both processes can set flag to true, then loop for ever waiting for the other! This is *deadlock*. 
Mutex – Fourth attempt

Deadlock arose because processes insisted on entering critical section and busy-waited. So if other process’s flag is set, let’s clear our flag for a bit to allow it to proceed:

```c
flag[\bi\] = true;
while ( flag[\bi\] ) {
    flag[\bi\] = false;
    /* sleep for a bit */
    flag[\bi\] = true;
}
/* critical section */
flag[\bi\] = false;
```

OK, but now it is possible for the processes to run in exact synchrony and keep deferring to each other – *livelock*. 
Peterson's Algorithm

flag[i] = true;
turn = i;
while ( flag[i] && turn == i ) {}
/* critical section */
flag[i] = false;

Works but we want something easier for programmers
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
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()

Two choices:

• Spin
• Block
• (Spin-then-block)

unlock()
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?
- What is the right granularity of locking?
Using locks

```c
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?
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

• Race condition in acquire
• Could use Peterson – but assumes atomic read and writes and no compiler optimization
Peterson’s Algorithm

flag[i] = true;
turn = \( \hat{i} \);
while ( flag[\( \hat{i} \) ] && turn == \( \hat{i} \) ) {} /* critical section */
flag[i] = false;

Assumes write to turn atomic
Assumes flag[1-i] is not hoisted, (its loop invariant)
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”
  – Compiler can hoist code that is invariant

• Need help from the hardware
  – atomic instructions
    • test-and-set, compare-and-swap, …
Spinlocks: 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 …
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
  - Ok as ensure acquiring only happens for a short time

- We’ll see later how to build blocking locks
  - But there is overhead – can be cheaper to spin
Summary

• Synchronization introduces temporal ordering
• Synchronization can eliminate races
• Peterson’s Algorithm
• 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)