CSE 451: Operating Systems
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Module 3
Synchronization

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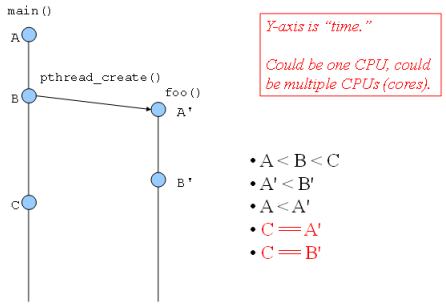
Temporal Relations: Key Concept Review

- Instructions executed by a single thread are totally ordered
  - A < B< C < …
- Absent synchronization, instructions executed by distinct threads are *simultaneous*
  - (not A < A') and (not A' < A)
- A sequence of instructions is atomic if the effects of all of them appear to occur at once as viewed by any other (correctly operating) thread
- (Nearly all) single machine instructions are atomic
  - Write x
  - Read y

Example: In the beginning…



Y-axis is "time."

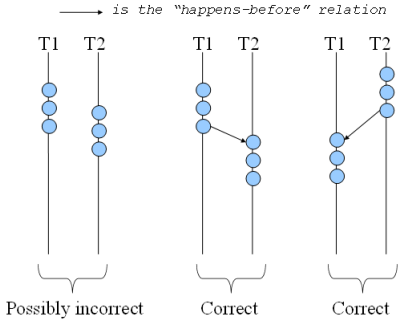
Could be one CPU, could be multiple CPUs (cores).

- 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
- 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
  - It's not always necessary (concurrent executions may sometimes get correct results by luck), but it's impractical to try to exploit that
- One way to guarantee mutually exclusive execution is using locks

Critical sections



When Do Critical Sections Arise?

- Well… the simple answer is "whenever simultaneous execution could result in incorrect answers," but that isn't very helpful
- One common pattern:
  - read-modify-write of…
  - a shared value (variable) while…
  - 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
  - NOT local variables
  - *Note: never give a reference to a stack allocated (local) variable to another thread (unless you're superhumanly careful…)*

The classic 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
  balance -= amount;                     // modify
  put_balance(account, balance);         // write
  return balance;
}
```

- Now suppose that you and your S.O. 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?

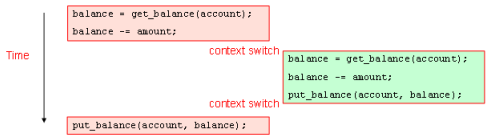
- Assume the bank's application is multi-threaded
- A random thread is assigned a transaction when it is submitted

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

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


Interleaved schedules

- The problem is that the execution of the two threads can be interleaved:



- What's the account balance after this sequence?
- How often is this sequence likely to occur?

Aside: 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);
  return balance;
}
```

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


How About Now?

```
int xfer(from, to, amt) {
  int bal = withdraw(from, amt);
  withdraw( to, -amt );
  return bal;
}
```

```
int xfer(from, to, amt) {
  int bal = withdraw(from, amt);
  withdraw( to, -amt );
  return bal;
}
```

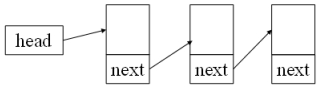
- Morals:
  - Interleavings are hard to reason about
    - We make a lot of mistakes
    - Control-flow analysis is hard for tools to get right
  - Identifying critical sections and ensuring mutually exclusive execution is… "easier"

Another Classic Example

```
i++;
```

```
i++;
```

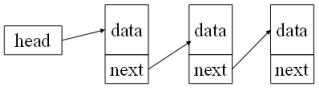
Final Classic Example




```
for (p=head; p; p = p->next ) {
  <examine *p>
}
```

```
while (head) {
  oldHead = head;
  head = head->next;
  free(oldHead);
}
```


Other Final Classic Example




```
for (p=head; p; p = p->next ) {
  <examine *p>
}
```

```
for (p=head; p; p = p->next ){
  p->data = p->data + 1;
}
```


"Critical section solution" requirements

- 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
    - vs. fairness?
  - 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

- Locks (today)
  - very primitive, minimal semantics; used to build others
- Semaphores (tomorrow)
  - basic, easy to get the hang of, hard to program with
- Condition Variables (tomorrow)
  - general (i.e., primitive) "wait until" mechanism with mutual exclusion
- Monitors (tomorrow)
  - high level, requires language support, implicit operations
  - easy to program with; Java "`synchronized()`" as an example
- Messages (day after tomorrow)
  - simple model of communication and synchronization based on (atomic) transfer of data across a channel
  - direct application to distributed systems

Locks, But First...

- A possible critical section solution is to arrange for all executions to occur on a single thread
  - E.g., use thread `n` where `n == account % #threads`
  - This turns a sharable variable into an un-shared variable
- Pros:
  - Simple
  - Fast
- Cons:
  - Load balancing among threads
  - What to do if the CS involves two accounts (e.g., xfer())?
  - Assigning tasks to threads probably involves a critical section (!)
- This idea is useful on multi-cores, and perhaps even more common in distributed systems

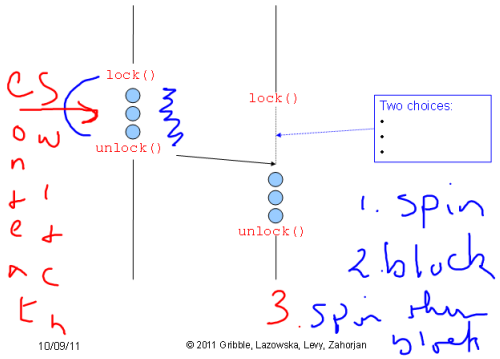
```
int withdraw(account, amount) {
  int balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  return balance;
}
```

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


Locks

- Locks are memory objects with two operations
  - `lock()`: obtain the right to enter the critical section
  - `unlock()`: give up the right to be in the critical section
- `lock()` prevents progress of the thread until the lock can be acquired

Locks: Example execution



Using locks

```
int withdraw(account, amount) {
  lock(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  unlock(lock);
  return balance;
}
```

critical section

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

```
lock(lock)
put_balance(account, balance);
unlock(lock);
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
unlock(lock);
```

- What happens when green tries to acquire the lock?
- Why is the "return" outside the critical section?
  - is this ok?

Implementing Spinlocks

- How do we implement locks? Here's one attempt:

```
struct lock_t {
  int held = 0;
} lock;
void lock(lock) {
   while (lock->held);
   lock->held = 1;
}
void unlock(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 locks (cont.)

- Problem is that implementation of locks has critical sections, too!
  - the lock/unlock 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 instruction implemented in hardware, not C code

Implementing Locks Using Test-and-Set

- So, to fix our broken spinlocks, do:

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

mutual exclusion?
progress?
bounded waiting?
performance?

Reminder of use …

```
int withdraw(account, amount) {
  lock(lock);
  balance = get_balance(account);
  balance -= amount;
  put_balance(account, balance);
  unlock(lock);
  return balance;
}
```

critical section

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

```
lock(lock)
put_balance(account, balance);
unlock(lock);
```

```
balance = get_balance(account);
balance -= amount;
put_balance(account, balance);
unlock(lock);
```

- How does a thread spinning on a lock (that is, stuck in a test-and-set loop) yield the CPU?
  - calls yield( ) *(spin-then-block)*
  - there's an involuntary context switch

Problems With Locks #1

- You can forget to unlock…
  - Typically due to overlooking some exceptional control flow
- What happens?
- Why doesn't the compiler warn you that your code might not unlock a lock it locked?

control flow is undecidable

Problems With Locks #2

- Locks can result in "deadlock"
  - Thread 0 is waiting for thread 1 which is waiting for thread 2 which is waiting for thread 0
- Deadlocks are not restricted just to locks
- More on this in a later module…

Problems with Locks #3: Granularity

- Acquiring a lock is overhead (compared to the code required by a single-threaded implementation), so…
- At the extreme, having only a single lock that gives you the rights to all critical section code minimizes lock acquisition overhead
  - "coarse grained locking"
  - also restricts potential concurrency
- At the other extreme, you might have try to maximize potential concurrency
  - "fine grained locking"
  - often means using using many different locks

Problems with Locks #4: Spin? Wait?

- Spinlocks work, but can be horribly wasteful!
  - if the thread holding the lock is not running, you'll spin for a scheduling quantum
  - plus, spinning can actually slow down the thread that holds the lock…
  - `(pthread_spin_t)`
- Blocking locks work, but can be horribly wasteful!
  - If the lock is busy, there's a two context switch overhead cost to be paid to acquire it, minimum
    - The lock might be busy for only a few cycles, so it could have been cheaper to spin
  - `(pthread_mutex_t)`
- Spin-then-block locks
  - Spin for a little while (10's or 100's of cycles), then block
  - Why?
    - If you know the typical lock holding time is small, and it's been 100's of cycles, odds are the lock holder isn't currently running
      - This is an example of residual life that increases (steeply) after some short amount of time has elapsed

Spinning and Granularity

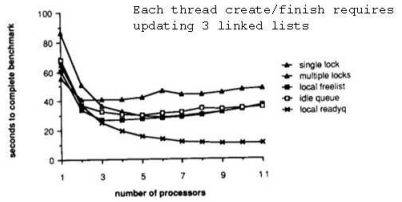
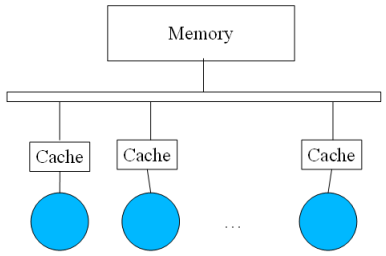


Fig. 1. Principal results for thread management—elapsed time to create, start, and finish 1 000 000 null threads (measured).

The performance implications of thread management alternatives for shared-memory multiprocessors
www.cs.washington.edu/homes/tom/pubs/thread89.pdf

How Spinning Slows the Lock Holder



Detecting Race Conditions

- Informally, we say a program has a race condition (aka "data race") if the result of an execution 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

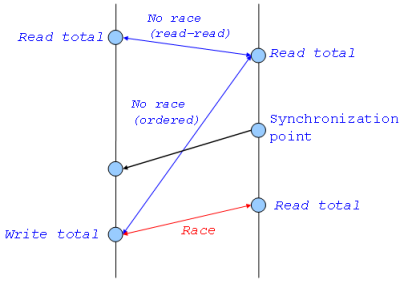
Race Detectors

- There are tools that try to detect race conditions
  - We'll use one called `helgrind`
- They need a formal definition of what a race is
  - The definition varies, but the key is two accesses to a shared variable that are "simultaneous" (not ordered), at least one of which is a write
- Note: the formal definition can result in many false positives (detections of non-problems)
  - Example: two threads write 0 to shared variable `total`

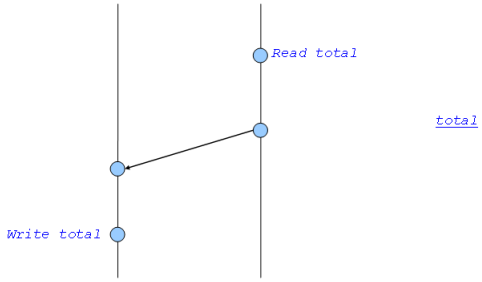
How Race Detectors Work

- First of all, they're still a bit exotic / experimental / primitive
- Basically, they monitor thread executions to construct a "happens before" thread graph relating them
  - Happens-before arcs are introduced by things like locks, which they recognize as a call to pthread_mutex_lock()
- They then detect unsynchronized accesses by annotating each word/byte of memory with tags indicating where in the thread synchronization graph the operations arose
- They manage that by simulating the hardware instructions…
- They can be "a wee slow"

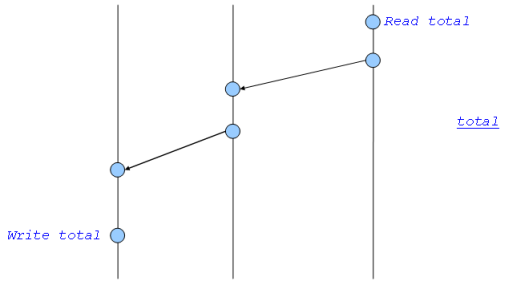
Race Detection Example



Race Detection Example



Race Detection Example



What's Next?

- Synchronization introduces temporal ordering
  - E.g., adds a "not simultaneous" edge
    - Critical sections
  - Or adds a "happens before" edge to the thread graph
    - Other kinds of synchronization
- Adding synchronization can eliminate races
  - That's handy!
- There are other synchronization primitives
  - For mutual exclusion
  - For "happens before"
- We'll have a look at some…