
CSE 374
Programming Concepts & Tools

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Spring 2010

Lecture 22 – Shared-Memory Concurrency

Concurrency

- Computation where “multiple things happen at the same time” is inherently more complicated than sequential computation
- Entirely new kinds of bugs and obligations
- Two forms of concurrency:
 - time-slicing: only one computation at a time but preempt to provide responsiveness or mask I/O latency
 - true parallelism: more than one CPU (e.g., new consumer machines have two, newer machines have 4-8, your laptop has ?, ...)
- No problem unless the different computations need to communicate or use the same resources

Example: processes

- The O/S runs multiple processes “at once”.
- Why? (Convenience, efficient use of resources, performance)
- No problem: keep their address-spaces separate.
- But they do communicate/share via files (and pipes).
- Things can go wrong, e.g., a *race condition*:
 echo "hi" > someFile
 foo='cat someFile'
 # assume foo holds the string “hi”??
- The O/S provides *synchronization mechanisms* to avoid this (see CSE 410)

The old story

- We said a running Java or C program had code, a heap, global variables, a stack, and “what is executing right now” (in assembly, a *program counter*).
- C, Java support parallelism similarly (other languages can be different):
 - One pile of code, global variables, and heap.
 - Multiple “stack + program counter”s — called threads
 - Threads can be *pre-empted* whenever by a *scheduler*
 - Threads can communicate (or mess each other up) via *shared memory*.
- Various *synchronization mechanisms* control what *thread interleavings* are possible.
 - “Do not do your thing until I am done with my thing”

Threads in C and Java

C: The POSIX Threads (pthreads) library

```
#include <pthread.h>
```

- Link with `-lpthread`
- `pthread_create` takes a function pointer and an argument for it; runs it as a separate thread.
- Many types, functions, macros for threads, locks, etc.

Java: Built into the language

- Subclass `java.lang.Thread` overriding `run`
- Create a `Thread` object and call its `start` method
- Any object can “be synchronized on” (later)

Why do this?

Convenient structure of code

- Example: two threads using information computed by the other
- Example: failure-isolation – each “file request” in its own thread so if a problem just “kill that request”
- Example: Fairness – one slow computation only takes some of the CPU time without your own complicated timer code. Avoids starvation

Performance

- Run other threads while one is reading/writing to disk (or other slow thing that can happen in parallel)
- Use more than one CPU at the same time
 - The way computers will get faster over the next decade
 - So no parallelism means no faster.

Simple synchronization

- If one thread did nothing of interest to any other thread, why is it running?
- So threads have to *communicate* and *coordinate*.
 - Use each others' results; avoid messing up each other's computation.
- Simplest two ways not to mess each other up (don't underestimate!):
 1. Do not access the same memory.
 2. Do not mutate shared memory.
- Next simplest: One thread does not run until/unless another thread is done
 - Called a *join*

Using parallel threads

A common pattern for expensive computations:

- Split the work
- Join on all the helper threads
- Called fork-join parallelism

To avoid bottlenecks, each thread should have about the same amount of work (load-balancing)

- Performance depends on number of CPUs available and will typically be less than “perfect speedup”

Less structure

- Often you have a bunch of threads running at once and they might need the same mutable memory at the same time but probably not.
- Want to be correct without sacrificing parallelism.
- Example: A bunch of threads processing bank transactions:
 - withdraw, deposit, transfer, currentBalance, ...
 - chance of two threads accessing the same account at the same time very low, but not zero.
 - want mutual exclusion (a way to keep each other out of the way when there is contention)

The issue

```
struct Acct { int balance; /* ... other fields ... */ };

int withdraw(struct Acct * a, int amt) {
    if(a->balance < amt) return 1; // 1==failure
    a->balance -= amt;
    return 0;                       // 0==success
}
```

- This code is correct in a sequential program.
- It may have a race condition in a concurrent program, allowing a negative balance.
- Discovering this bug is very hard with testing since the interleaving has to be “just wrong”.

atomic

Program must indicate what must appear to happen all-at-once.

```
int withdraw(struct Acct * a, int amt) {
    atomic {
        if(a->balance < amt) return 1;    // 1==failure
        a->balance -= amt;
    }
    return 0;    // 0==success
}
```

Reasons not to do “too much” in an atomic:

- Correctness: If another thread needs an intermediate result to compute something you need, must “expose” it.
- Performance: Parallel threads must access disjoint memory
 - Actually read/read conflicts can happen in parallel

Getting it “just right”

- This code is probably wrong because critical sections too small:

```
atomic { if(a->balance < amt) return 1; }  
atomic { a->balance -= amt; }
```

- This code (skeleton) is probably wrong because the critical section is too big:
 - Assume other guy does not compute until data is set

```
atomic {  
    data_for_other_guy = 42; // set some global  
    ans = wait_for_other_guy_to_compute();  
    return ans;  
}
```

So far

- Shared-memory concurrency where multiple threads might access the same mutable data at the same time is tricky
 - Must get size of critical sections just right
- It's worse because
 - atomic does not yet exist in languages like C and Java
- Instead programmers must use locks (a.k.a. mutexes) or other mechanisms, usually to get the behavior of critical sections
 - But misuse of locks will violate the “all-at-once” property
 - Or lead to other bugs we haven't seen yet

Lock basics

A lock is *acquired* and *released* by a thread.

- At most one thread “holds it” at any moment
- Acquiring it “blocks” until the holder releases it and the blocked thread acquires it
 - Many threads might be waiting; one will “win”.
 - The lock-implementer avoids race conditions on the lock-acquire
- So to keep two things from happening at the same time, surround them with the same lock-acquire/lock-release

Locks in C/Java

- C: Need to initialize and destroy mutexes (a synonym for locks).
 - The joys of C
- An initialized (pointer to a) mutex can be locked or unlocked via library function calls.
- Java: A synchronized statement is an acquire/release.
 - Any object can serve as a lock.
 - Lock is released on any control-transfer out of the block (return, break, exception, ...)
 - “Synchronized methods” just save keystrokes

Choosing how to lock

- Now we know what locks are (how to make them, what acquiring/releasing means), but programming with them correctly and efficiently is difficult...
 - As before, if critical sections are too small we have races; if too big we may not communicate enough to get our work done efficiently.
 - But now, if two “synchronized blocks” grab different locks, they can be interleaved even if they access the same memory
 - A “data race”
 - Also, a lock-acquire blocks until a lock is available and only the current-holder can release it.
 - Can have “deadlock” ...

Deadlock

Object a;
Object b;

```
void m1() {  
    synchronized a {  
        synchronized b {  
            ... ..  
        }  
    }  
}  
  
void m2() {  
    synchronized b {  
        synchronized a {  
            ... ..  
        }  
    }  
}
```

- A cycle of threads waiting on locks means none will ever run again!
- Avoidance: All code acquires locks in the same order (very hard to do). Ad hoc: Don't hold onto locks too long or while calling into unknown code.
- Recovery: detect deadlocks, kill off and rerun one of the processes (databases)

Rules of thumb

- Any one of the following are sufficient for avoiding races:
 - Keep data thread-local (an object is reachable, or at least only accessed by, one thread).
 - Keep data read-only (do not assign to object fields after an object's constructor)
 - Use locks consistently (all accesses to an object are made while holding a particular lock)
 - Use a partial-order to avoid deadlock (over-simple example: do not hold multiple locks at once?)
- These are tough invariants to get right, but that's the price of multithreaded programming today.
- But... one way to do all the above is to have “one lock for all shared data” and that is inefficient...

False sharing

- “False sharing” refers to not allowing separate things to happen in parallel. Example:

```
synchronized x {      synchronized x {  
    ++y;                ++z;  
}
```

- More realistic example: one lock for all bank accounts rather than one for each account
- On the other hand, acquiring/releasing locks is not so cheap, so “locking more with the same lock” can improve performance.
- This is the “locking granularity” question
 - Coarser vs. finer granularity

What about this?

- If each bank account has its own lock, how do you write a “transfer” method such that no other thread can see the “wrong total balance”?

```
// race (not data race)           // potential deadlock
void xfer(int a, Acct other){      void xfer(int a, Acct other){
    synchronized(this) {          synchronized(this) {
        balance += a;              synchronized(other) {
        other.balance -= a;        balance += a;
    }                               other.balance -= a;
}                                   }
}                                   }}}
```

- The problem is there is no relative order among accounts, so “inverse transfers” could deadlock

A final gotcha

- You would naturally assume that all memory accesses happen in “some consistent order” that is “determined by the code”.
- Unfortunately, compilers and chips are often allowed to cheat (reorder)! The assertion in the right thread may fail!

initially flag==false

```
data = 42;           while(!flag) { }  
flag = true;        assert(data==42);
```

- To disallow reordering the programmer must:
 - Use lock acquires (no reordering across them), or
 - Declare flag to be volatile (for experts, not us)

Conclusion

- Threads make a lot of otherwise-correct approaches incorrect.
 - Writing “thread-safe” libraries can be excruciating.
 - Use an expert implementation, e.g., Java’s `ConcurrentHashMap`?
- But they are increasingly important for efficient use of computing resources (“the multicore revolution”).
- Locks and shared-memory are (just) one common approach