Lecture 27: Concurrency 3

CS 62
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Some slides based on those from Dan Grossman, U. of Washington

Thread-Local

- Whenever possible, don't share resources
  - Easier to have each thread have its own thread-local copy of a resource than to have one with shared updates
  - This is correct only if threads don't need to communicate through the resource
    - That is, multiple copies are a correct approach
    - Example: Random objects
  - Note: Since each call-stack is thread-local, never need to synchronize on local variables
- *In typical concurrent programs, the vast majority of objects should be thread-local: shared-memory should be rare – minimize it*

Immutable

- Whenever possible, don't update objects
  - Make new objects instead
- One of key tenets of functional programming
  - Hopefully you study this in 52
  - Generally helpful to avoid side-effects
  - Much more helpful in a concurrent setting
- If a location is only read, never written, no synchronization is necessary!
  - Simultaneous reads are not races and not a problem
- *Programmers over-use mutation – minimize it*

Dealing with the Rest

- Guideline: No data races
  - Never allow two threads to read/write or write/write the same location at the same time
  - Use synchronized!!
- Necessary: In Java or C, a program with a data race is almost always wrong

Worse Than You Think!

```
class C {
  private int x = 0;
  private int y = 0;

  void f() {
    x = 1;
    y = 1;
  }
  void g() {
    int a = y;
    int b = x;
    assert(b >= a);
  }
}
```

- Assertion always true w/ single threaded.
- Looks always true for multithreaded.
  - OK if f not called at all
  - OK after f completes
  - Looks OK if in middle of f
- But have race condition

Memory Reordering

- For performance reasons, compiler and hardware reorder memory operations.
- But, but, ...
  - Compiler/hardware will never perform a memory reordering that affects the result of a single-threaded program
  - The compiler/hardware will never perform a memory reordering that affects the result of a data-race-free multi-threaded program
- So: If no interleaving of your program has a data race, then need not worry: result will be equivalent to some interleaving

A Second Fix

- If label field *volatile,* accesses don't count as data races
- Implementation forces memory consistency
  - though slower!
- Should have used this in CS 51 w/shared variables.
- Really for experts -- better to use locks.

Lock Granularity

- Coarse-grained: Fewer locks, i.e., more objects per lock
  - Example: One lock for entire data structure (e.g., array)
  - Example: One lock for all bank accounts
- Fine-grained: More locks, i.e., fewer objects per lock
  - Example: One lock per data element (e.g., array index)
  - Example: One lock per bank account
- "Coarse-grained vs. fine-grained" is really a continuum.

Trade-Offs

- Coarse-grained advantages
  - Simpler to implement
  - Faster/easier to implement operations that access multiple locations (because all guarded by the same lock)
  - Much easier: ops that modify data-structure shape
- Fine-grained advantages
  - More simultaneous access (performance when coarse-grained would lead to unnecessary blocking)
- Guideline:
  - Start with coarse-grained (simpler) and move to fine-grained (performance) only if contention on the coarser locks becomes an issue. Alas, often leads to bugs.

Critical-section granularity

- A second, orthogonal granularity issue is critical-section size
  - How much work to do while holding lock(s)
- If critical sections run for too long:
  - Performance loss because other threads are blocked
- If critical sections are too short:
  - Bugs because you broke up something where other threads should not be able to see intermediate state
- Guideline: Don't do expensive computations or I/O in critical sections, but also don't introduce race conditions

Example: ArrayList

- Granularity:
  - One lock for entire list *or*
  - One lock per slot
- Critical Section size
  - Suppose get access to element, do something expensive to see if needs an update and then update
    - If too large, then all other accesses blocked
    - If too small, then element in slot may change while check.

Don't Roll Your Own!

- Most data structures provided in standard libraries
  - Point of lectures is to understand the key trade-offs and abstractions
- Especially true for concurrent data structures
  - Far too difficult to provide fine-grained synchronization without race conditions
  - Standard thread-safe libraries like ConcurrentHashMap written by world experts
- Guideline: Use built-in libraries whenever they meet your needs *Vector vs ArrayList*

Deadlock

Deadlock

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt, BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

- What locks are held at a.deposit(amt)?
- Is this a problem?

Deadlock

- Suppose have separate threads, each transferring to each others' account

Thread 1: `x.transferTo(1,y)`

Thread 2: `y.transferTo(1,x)`

```
Time ↓

Thread 1:                    Thread 2:
acquire lock for x
do withdraw from x
                             acquire lock for y
                             do withdraw from y
                             block on lock for x
block on lock for y
```

Deadlock

- A deadlock occurs when there are threads $T_1, \ldots, T_n$ such that:
  - For i=1,..,n-1, T_i is waiting for a resource held by T_{i+1}
  - T_n is waiting for a resource held by T_1
- In other words, there is a cycle of waiting
  - Formalize as a graph of dependencies with cycles bad
- Deadlock avoidance in programming amounts to techniques to ensure a cycle can never arise

A Last Example

- Bounded buffer is a queue with a fixed size.
  - Like event queue
  - Implemented in an array that wraps around.
- Producer threads do work and enqueue result
- Consumer threads dequeue results and perform work on them.
- Must synchronize access to the queue.

Attempt 1

```
class Buffer<E> {
 E[] array = (E[])new Object[SIZE];
 ... // front, back fields, isEmpty, isFull methods
 synchronized void enqueue(E elt) {
  if(isFull())
    ???
  else
    ... add to array and adjust back ...
 }
 synchronized E dequeue() {
  if(isEmpty()) {
    ???
  else
    ... take from array and adjust front ...
 }
}
```

Waiting

- enqueue to full buffer should not raise exception
  - Wait until there is room
- dequeue from empty buffer should not raise exception
  - Wait until there is data
- Bad approach is “spin lock”

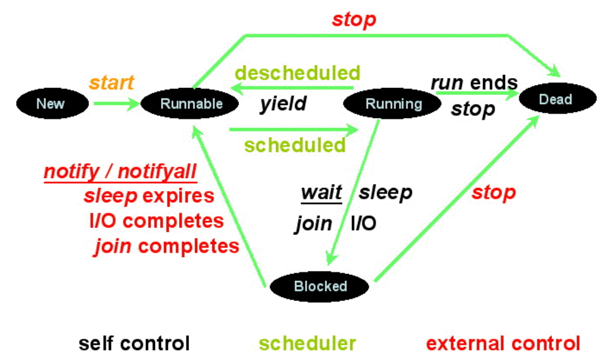
What we want ...

- Thread should wait until has needed resources
  - Release lock and wait to be notified
- Needs operating systems support
- “Condition variable” that informs waiters when conditions have changed.
- See BoundedBuffer.java
  - uses “this” as condition variable

Once Again: Use Existing Classes!

- Java libraries contain thread-safe data structures.
  - See java.util.concurrent.BlockingQueue<E> interface
    - ArrayBlockingQueue
    - LinkedBlockingQueue
  - ConcurrentHashMap
  - Vector

Java Thread Execution Model



Concurrency Summary

- Access to shared resources introduces new kinds of bugs
  - Data races
  - Deadlocks
- Requires synchronization
  - Locks for mutual exclusion
  - Condition variables for signaling others
- Guidelines for use help avoid common pitfalls
- Getting shared-memory correct is hard!
  - But other models (e.g., message passing) not a panacea