Atomic Variables
&
Nonblocking Synchronization

CMSC 433
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(with some slides due to Rance Cleaveland)
public final class Counter {
    private long value = 0;
    public synchronized long getValue() {
        return value;
    }

    public synchronized long increment() {
        return ++value;
    }
}
• Many java.util.concurrent classes perform better than synchronized alternatives. Why?
  – Atomic variables & nonblocking synchronization
• We’ve already talked about atomic variables
• Nonblocking algorithms are concurrent algorithms that derive their thread safety from low-level atomic hardware primitives (not locks)
Disadvantages of Locking

• When a thread fails to acquire lock it can be suspended
  – Context switching & resumption can be expensive
• When waiting for a lock, thread can’t do anything
• If thread holding lock is delayed, no thread that needs that lock can progress
  – Can result in priority inversion: low priority thread has lock needed by a high priority thread
• Caveat: contention, rather than locking, is the real issue. YMMV
• Locking is pessimistic
  – If contention is infrequent, most locking was unneeded

• In earlier lecture we discussed optimistic trying
  – Proceed with the update
  – Check for collision
  – If update fails, retry

• Processor can use atomic operations to support optimistic trying
Compare and Swap (CAS)

- CAS has 3 operands
  - Memory location V, expected value A, new value B
- Atomically updates V to value B, but only if current value is A
- If multiple threads try to update V only one succeeds
  - But the losers don’t get punished with suspension
  - They can just try again
public class SimulatedCAS { // not implemented this way!
    private int value;

    public synchronized int get() {return currValue;}

    public synchronized int compareAndSwap(int expectedValue, int newValue) {
        int oldValue = value;
        if (oldValue == expectedValue)
            value = newValue;
        return oldValue;
    }

    public synchronized boolean compareAndSet(int expectedValue, int newValue) {
        return (expectedValue == compareAndSwap(expectedValue, newValue));
    }
}
A Nonblocking Counter

// demonstrates the use of CAS
public class NonblockingCounter {
    private AtomicInteger value;
    
    public int getValue() {
        return value.get();
    }
    
    public int increment() {
        int v;
        do {
            v = value.get();
        }while (!value.compareAndSet(v, v + 1));
        return v + 1;
    }
}

Atomic Variables

- Generalization of volatile variables
- Allows atomic read-modify-write operations without intrinsic locking
- Scope of contention limited to a single variable
- Faster than locking -- no scheduling impact
- Like volatiles, can’t synchronize two atomic vars
- In general, doesn’t support atomic check-then-act sequences
Atomic Variable Classes

- AtomicInteger
- AtomicLong
- AtomicBoolean
- AtomicReference<T>
  - set(), get() operations
  - getAndSet() atomically sets to new value, returns old value
  - Boolean compareAndSet(int expect, int new)
  - Arithmetic (increment, decrement) as appropriate
    - getAndAdd – return old value
    - addAndGet – return new value
    - getAndIncrement
    - incrementAndGet

- Also AtomicIntegerArray, AtomicLongArray, AtomicReferenceArray
  - Each element in array supports atomic operations
Updating Complex Objects

- Example: Want to manage two related variables
  - Can’t do this with volatiles
- Idiom: turn compound update into single update
// INVARIANT: lower <= upper
// How do you make this thread-safe?
private static class IntPair {
    final int lower, upper;
    public IntPair(int lower, int upper) {....}
    public void setLower(int i) {....}
    public void setUpper(int i) {....}
}
public class CasNumberRange {
    // IntPair is a pair of Integers
    private final AtomicReference<IntPair> values =
        new AtomicReference<IntPair>(new IntPair(0, 0));

    public void setLower(int i) {
        while (true) {
            IntPair oldv = values.get(); // gets the current value atomically
            if (i > oldv.upper) throw new IllegalArgumentException();
            IntPair newv = new IntPair(i, oldv.upper);
            if (values.compareAndSet(oldv, newv)) return;
        }
    }

    // setUpper() similar to setLower()
}
Performance Comparison

• Will show two implementations of a pseudo-random number generator (PRNG)
  – One uses locks: ReentrantLockPseudoRandom.java
  – One is nonblocking: AtomicPseudoRandom.java

• PRNG issues
  – Next value based on last value, so you need to remember last value

• How do lock-based and non-lock-based implementations compare?
public class ReentrantLockPseudoRandom extends PseudoRandom {
    private final Lock lock = new ReentrantLock(false);
    private int seed;
    ReentrantLockPseudoRandom(int seed) {this.seed = seed;}

    public int nextInt(int n) {
        lock.lock();
        try {
            int s = seed;  seed = calculateNext(s);  int remainder = s % n;
            return remainder > 0 ? remainder : remainder + n;
        } finally {
            lock.unlock();
        }
    }
}
public class AtomicPseudoRandom extends PseudoRandom {
    private AtomicInteger seed;

    AtomicPseudoRandom(int seed) {
        this.seed = new AtomicInteger(seed);
    }

    public int nextInt(int n) {
        while (true) {
            int s = seed.get();
            int nextSeed = calculateNext(s);
            if (seed.compareAndSet(s, nextSeed)) {
                int remainder = s % n;
                return remainder > 0 ? remainder : remainder + n;
            }
        }
    }
}
Nonblocking Algorithm Flavors

• **Wait-Free**
  – All threads complete in finite count of steps
  – Low priority threads cannot block high priority threads

• **Lock-Free**
  – Every successful step makes global progress
  – Individual threads may starve; priority inversion possible
  – No live-lock

• **Obstruction-Free**
  – A single thread in isolation completes in finite count of steps
  – Threads may block each other; live-lock possible
  – Example: optimistic retry
Comparing Performance

MacPro, OS X Snow Leopard, 8 cores, 8 GB of RAM
Nonblocking Algorithms

- No locks
- Stopping one thread will not prevent global progress
  - Immune to deadlock
  - Starvation is possible
- Writing correct nonblocking algorithms is very hard!
public class ConcurrentStack <E> {
    private static class Node <E> {
        public final E item;   public Node<E> next;
        public Node(E item) {
            this.item = item;
        }
    }
    AtomicReference<Node<E>> top = new AtomicReference<Node<E>>(());
    public void push(E item) {
        Node<E> newHead = new Node<E>(item);
        Node<E> oldHead;
        do {
            oldHead = top.get();
            newHead.next = oldHead;
        } while (!top.compareAndSet(oldHead, newHead));
    }
}
public E pop() {
    Node<E> oldHead;  Node<E> newHead;
    do {
        oldHead = top.get();
        if (oldHead == null)
            return null;
        newHead = oldHead.next;
    } while (!top.compareAndSet(oldHead, newHead));
    return oldHead.item;
}
Nonblocking Stack

- See: ConcurrentStack.java & SynchStack.java
A Nonblocking Queue

• Rule of thumb— limit change to one variable
• Harder for a Queue because we need to update both head and tail
• See: SynchQueue.java & ConcurrentQueue.java
Overview of Michael & Scott Approach

• Make sure queue is always in consistent state
• Threads should know whether another operation is already in progress
  – Thread B can wait for thread A to finish before starting
• Prevents corruption, but late thread can fail if early thread fails
Overview of Michael & Scott Approach

• If thread B arrives while operation in progress for thread A, let B finish update for A
  – Then B can progress without waiting for A
  – If A finds some of its work done, it doesn’t repeat. It just skips doing it itself
Michael & Scott Nonblocking Queue

- Queue with two elements in quiescent state
Michael & Scott Nonblocking Queue

• Queue in intermediate state during insertion
  - After the new element is added but before the tail pointer is updated
Michael & Scott Nonblocking Queue

• Queue in quiescent state again after the tail pointer is updated
Michael & Scott Nonblocking Queue

- Observation: if tail.next is non-null, then an operation is in progress
- If a thread finds an operation in progress, it will try to advance tail to return queue to stable state
  - Then it will reload tail and repeat process
public class ConcurrentQueue <E> {
    private static class Node <E> {
        final E item;
        final AtomicReference<Node<E>> next;
        public Node(E item, Node<E> next) {
            this.item = item;
            this.next = new AtomicReference<Node<E>>(next);
        }
    }
    private final Node<E> dummy = new Node<E>(null, null);
    private final AtomicReference<Node<E>> head = new AtomicReference<Node<E>>(dummy);
    private final AtomicReference<Node<E>> tail = new AtomicReference<Node<E>>(dummy);
public boolean put(E item) {
    Node<E> newNode = new Node<E>(item, null);
    while (true) {
        Node<E> curTail = tail.get();
        Node<E> tailNext = curTail.next.get();
        if (curTail == tail.get()) { // did tail change?
            if (tailNext != null) { // Queue in intermediate state, advance tail
                tail.compareAndSet(curTail, tailNext);
            } else { // In quiescent state, try inserting new node
                if (curTail.next.compareAndSet(null, newNode)) {
                    // Insertion succeeded, try advancing tail
                    tail.compareAndSet(curTail, newNode); // will fail if tail already moved
                    return true;
                }
            }
        }
    }
}
public E take() {
    for (;;) {
        Node<E> oldHead = head.get();  // get current head
        Node<E> oldTail = tail.get();   // get current tail
        Node<E> oldHeadNext = oldHead.next.get();  // get current head.next
        if (oldHead == head.get()) {     // Are head, tail, and next consistent?
            if (oldHead == oldTail) {     // Queue empty or tail being updated?
                if (oldHeadNext == null) {  // Is queue empty?
                    return null; // Queue is empty, can't take
                    tail.compareAndSet(oldTail, oldHeadNext);  // tail updated. try to advance it
                } else {
                    if (head.compareAndSet(oldHead, oldHeadNext))
                        return oldHeadNext.item;
                }
            } else {  // No need to deal with tail
                if (head.compareAndSet(oldHead, oldHeadNext))
                    return oldHeadNext.item;
            }
        }
    }
}
public boolean put(E item) {
    Node<E> newNode = new Node<E>(item, null);
    while (true) {
        Node<E> curTail = tail.get();
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        if (curTail == tail.get()) {// did tail change?
            if (tailNext != null) { // Queue in int. state, advance tail
                tail.compareAndSet(curTail, tailNext);
            } else { // In quiescent state, try inserting new node
                if (curTail.next.compareAndSet(null, newNode)) {
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                }
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                    return true;
                }
            }
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                    // Insertion succeeded, try advancing tail
                    tail.compareAndSet(curTail, newNode);
                    // will fail if tail already moved
                    return true;
                }
            }
        }
    }
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        Node<E> curTail = tail.get();
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                }
            }
        }
        return true;
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                }
            }
        }
        return true;
    }
}
public boolean put(E item) {
    Node<E> newNode = new Node<E>(item, null);
    while (true) {
        Node<E> curTail = tail.get();
        Node<E> tailNext = curTail.next.get();
        if (curTail.equals(tail.get())) {// did tail change?
            if (tailNext != null) { // Queue in int. state, advance tail
                tail.compareAndSet(curTail, tailNext);
                head
            } else { // In quiescent state, try inserting new node
                if (curTail.next.compareAndSet(null, newNode)) {
                    // Insertion succeeded, try advancing tail
                    tail.compareAndSet(curTail, newNode);
                    // will fail if tail already moved
                }
            }
            return true;
        }
    }
}
Trace 1: T1 wins

```java
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                }
            }
        }
    }
    return true;
}
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            }
        }
        return true;
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                    return true;
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            }
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                    if (curTail.next.compareAndSet(newNode)) {
                        // Insertion succeeded, try advancing tail
                        tail.compareAndSet(curTail, newNode);
                    } else {
                        return true;
                    }
                } else {
                    return true;
                }
            }
        }
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