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Java theory and practice: Introduction to nonblocking algorithms

Look Ma, no locks!

Java™ 5.0 makes it possible for the first time to develop nonblocking algorithms in the Java language, and the `java.util.concurrent` package uses this capability extensively. Nonblocking algorithms are concurrent algorithms that derive their thread safety not from locks, but from low-level atomic hardware primitives such as *compare-and-swap*. Nonblocking algorithms can be extremely difficult to design and implement, but they can offer better throughput and greater resistance to liveness problems such as deadlock and priority inversion. In this installment of *Java theory and practice*, concurrency guru Brian Goetz illustrates how several of the simpler nonblocking algorithms work.

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When more than one thread accesses a mutable variable, all threads must use synchronization, or else some very bad things can happen. The primary means of synchronization in the Java language is the `synchronized` keyword (also known as *intrinsic locking*), which enforces mutual exclusion and ensures that the actions of one thread executing a `synchronized` block are visible to other threads that later execute a `synchronized` block protected by the same lock. When used properly, intrinsic locking can make our programs thread-safe, but locking can be a relatively heavyweight operation when used to protect short code paths when threads frequently contend for the lock.

In "[Going atomic](#)," we looked at *atomic variables*, which provide atomic read-modify-write operations for safely updating shared variables without locks. Atomic variables have memory semantics similar to that of volatile variables, but because they can also be modified atomically, they can be used as the basis for lock-free concurrent algorithms.

A nonblocking counter

Counter in Listing 1 is thread-safe, but the need to use a lock irks some developers because of the performance cost involved. But the lock is needed because increment, though it looks like a single operation, is shorthand for three separate operations: fetch the value, add one to it, and write the value out. (Synchronization is also needed on the `getValue` method, to ensure that threads calling `getValue` see an up-to-date value. Simply ignoring the need for locking is not a good strategy, though many developers seem disturbingly willing to convince themselves that this approach is acceptable.)

When multiple threads ask for the same lock at the same time, one wins and acquires the lock, and the others block. JVMs typically implement blocking by suspending the blocked thread and rescheduling it later. The resulting context switches can cause a significant delay relative to the few instructions protected by the lock.



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Listing 1. A thread-safe counter using synchronization

```
public final class Counter {
    private long value = 0;

    public synchronized long getValue() {
        return value;
    }

    public synchronized long increment() {
        return ++value;
    }
}
```

`NonblockingCounter` in Listing 2 shows one of the simplest nonblocking algorithms: a counter that uses the `compareAndSet()` (CAS) method of `AtomicInteger`. The `compareAndSet()` method says "Update this variable to this new value, but fail if some other thread changed the value since I last looked." (See ["Going atomic"](#) for more explanation of atomic variables and compare-and-set.)

Listing 2. A nonblocking counter using 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;
    }
}
```

The atomic variable classes are called *atomic* because they provide for fine-grained atomic updates of numbers and object references, but they are also atomic in the sense that they are the basic building blocks for nonblocking algorithms. Nonblocking algorithms have been the subject of much research and study for over 20 years but have only become possible in the Java language as of Java 5.0.

Modern processors provide special instructions for atomically updating shared data that can detect interference from other threads, and `compareAndSet()` uses these instead of locking. (If all we wanted to do was increment the counter, `AtomicInteger` offers methods for incrementing, but they are based on `compareAndSet()` just like `NonblockingCounter.increment()`.)

The nonblocking version has several performance advantages over the lock-based version. It synchronizes at a finer level of granularity (an individual memory location) using a hardware primitive instead of the JVM locking code path, and losing threads can retry immediately rather than being suspended and rescheduled. The finer granularity reduces the chance that there will be contention, and the ability to retry without being descheduled reduces the cost of contention. Even with a few failed CAS operations, this approach is still likely to be faster than being rescheduled because of lock contention.

`NonblockingCounter` may be a simple example, but it illustrates a basic characteristic of all nonblocking algorithms -- some algorithmic step is executed speculatively, with the knowledge that it may have to be redone if the CAS is not successful. Nonblocking algorithms are often called *optimistic* because they proceed with the assumption that there will be no interference. If interference is detected, they back off and retry. In the case of the counter, the speculative step is the increment -- it fetches and adds one to the old value in the hopes that the value will not change while the update is being computed. If it is wrong, it has to fetch the value again and redo the increment computation.

A nonblocking stack

A less trivial example of a nonblocking algorithm is `ConcurrentStack` in Listing 3. The `push()` and `pop()` operations in `ConcurrentStack` are both structurally similar to `increment()` in `NonblockingCounter`, speculatively doing some work and hoping that the underlying assumptions have not been invalidated when it comes time to "commit" that work. The `push()` method observes the current

top node, constructs a new node to be pushed on the stack, and then, if the topmost node has not changed since the initial observation, installs the new node. If the CAS fails, it means that another thread has modified the stack, so the process starts again.

Listing 3. Nonblocking stack using Treiber's algorithm

```
public class ConcurrentStack<E> {
    AtomicReference<Node<E>> head = new AtomicReference<Node<E>>();

    public void push(E item) {
        Node<E> newHead = new Node<E>(item);
        Node<E> oldHead;
        do {
            oldHead = head.get();
            newHead.next = oldHead;
        } while (!head.compareAndSet(oldHead, newHead));
    }

    public E pop() {
        Node<E> oldHead;
        Node<E> newHead;
        do {
            oldHead = head.get();
            if (oldHead == null)
                return null;
            newHead = oldHead.next;
        } while (!head.compareAndSet(oldHead, newHead));
        return oldHead.item;
    }

    static class Node<E> {
        final E item;
        Node<E> next;

        public Node(E item) { this.item = item; }
    }
}
```

Performance considerations

Under light to moderate contention, nonblocking algorithms tend to outperform blocking ones because most of the time the CAS succeeds on the first try, and the penalty for contention when it does occur does not involve thread suspension and context switching, just a few more iterations of the loop. An uncontended CAS is less expensive than an uncontended lock acquisition (this statement has to be true because an uncontended lock acquisition involves a CAS plus additional processing), and a contended CAS involves a shorter delay than a contended lock acquisition.

Under high contention -- when many threads are pounding on a single memory location -- lock-based algorithms start to offer better throughput than nonblocking ones because when a thread blocks, it stops pounding and patiently waits its turn, avoiding further contention. However, contention levels this high are uncommon, as most of the time threads interleave thread-local computation with operations that contend for shared data, giving other threads a chance at the shared data. (Contention levels this high also indicate that reexamining your algorithm with an eye towards less shared data is in order.) The graph in ["Going atomic"](#) was somewhat confusing in this regard, as the program being measured was so unrealistically contention-intensive that it appeared that locks were a win for even small numbers of threads.

A nonblocking linked list

The examples so far -- counter and stack -- are very simple nonblocking algorithms and are easy to follow once you grasp the pattern of using CAS in a loop. For more sophisticated data structures, nonblocking algorithms are much more complicated than these simple examples because modifying a linked list, tree, or hash table can involve updating more than one pointer. CAS enables atomic conditional updates on a single pointer, but not on two. So to construct a nonblocking linked list, tree, or hash table, we need to find a way to update multiple pointers with CAS without leaving the data structure in an inconsistent state.

Inserting an element at the tail of a linked list typically involves updating two pointers: the "tail" pointer that always refers to the last element in the list and the "next" pointer from the previous last element to the newly inserted element. Because two pointers need to be updated, two CASes are needed. Updating two pointers in separate CAS operations introduces two potential problems that need to be considered:

what happens if the first CAS succeeds but the second fails, and what happens if another thread attempts to access the list between the first and second CAS.

The "trick" to building nonblocking algorithms for nontrivial data structures is to make sure that the data structure is always in a consistent state, even between the time that a thread starts modifying the data structure and the time it finishes, and to make sure that other threads can tell not only whether the first thread has finished its update or is still in the middle of it, but also what operations would be required to complete the update if the first thread went AWOL. If a thread arrives on the scene to find the data structure in the middle of an update, it can "help" the thread already performing the update by finishing the update for it, and then proceeding with its own operation. When the first thread gets around to trying to finish its own update, it will realize that the work is no longer necessary and just return because the CAS will detect the interference (in this case, constructive interference) from the helping thread.

This "help thy neighbor" requirement is needed to make the data structure resistant to the failure of individual threads. If a thread arrived to find the data structure in mid-update by another thread and just waited until that thread finished its update, it could wait forever if the other thread fails in the middle of its operation. Even in the absence of failure, this approach would offer poor performance because the newly arriving thread would have to yield the processor, incurring a context switch, or wait for its quantum to expire, which is even worse.

LinkedList in Listing 4 shows the insertion operation for the Michael-Scott nonblocking queue algorithm, which is implemented by ConcurrentLinkedList:

Listing 4. Insertion in the Michael-Scott nonblocking queue algorithm

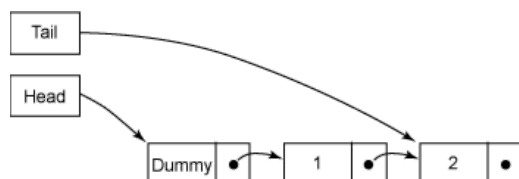
```
public class LinkedList <E> {
    private static class Node <E> {
        final E item;
        final AtomicReference<Node<E>> next;

        Node(E item, Node<E> next) {
            this.item = item;
            this.next = new AtomicReference<Node<E>>(next);
        }
    }

    private AtomicReference<Node<E>> head
        = new AtomicReference<Node<E>>(new Node<E>(null, null));
    private AtomicReference<Node<E>> tail = head;

    public boolean put(E item) {
        Node<E> newNode = new Node<E>(item, null);
        while (true) {
            Node<E> curTail = tail.get();
            Node<E> residue = curTail.next.get();
            if (curTail == tail.get()) {
                if (residue == null) /* A */ {
                    if (curTail.next.compareAndSet(null, newNode)) /* C */ {
                        tail.compareAndSet(curTail, newNode) /* D */ ;
                        return true;
                    }
                } else {
                    tail.compareAndSet(curTail, residue) /* B */;
                }
            }
        }
    }
}
```

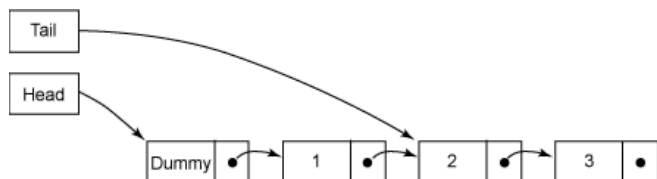
Like many queue algorithms, an empty queue consists of a single dummy node. The head pointer always points to the dummy node; the tail pointer always points to either the last node or the second-to-last node. Figure 1 illustrates a queue with two elements under normal conditions:



As Listing 4 shows, inserting an element involves two pointer updates, both of which are done with CAS: linking the new node from the current last node on the queue (C) and swinging the tail pointer to point to the new last node (D). If the first of these fails, then the queue state is unchanged, and the inserting

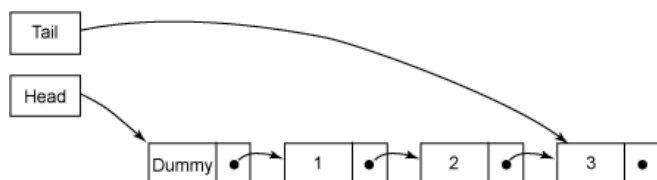
thread retries until it succeeds. Once that operation succeeds, the insertion is considered to have taken effect, and other threads can see the modification. It still remains to swing the tail pointer to point to the new node, but this task can be considered "cleanup" because any thread that arrives on the scene can tell whether such cleanup is needed and knows how to do it.

The queue is always in one of two states: the normal, or quiescent, state ([Figure 1](#) and [Figure 3](#)) or the intermediate state ([Figure 2](#)). The queue is in the quiescent state before an insertion operation and after the second CAS (D) succeeds; it is in the intermediate state after the first CAS (C) succeeds. In the quiescent state, the next field of the link node pointed to by the tail is always null; in the intermediate state, it is always non-null. Any thread can tell which state the queue is in by comparing `tail.next` to null, which is the key to enabling threads to help other threads "finish" their operation.



The insertion operation first checks to see if the queue is in the intermediate state before attempting to insert a new element (A), as shown in [Listing 4](#). If it is, then some other thread must already be in the middle of inserting an element, between steps (C) and (D). Rather than wait for the other thread to finish, the current thread can "help" it out by finishing the operation for it by moving the tail pointer forward (B). It keeps checking the tail pointer and advancing it if necessary until the queue is in the quiescent state, at which point it can begin its own insertion.

The first CAS (C) could fail because two threads are contending for access to the current last element of the queue; in this case, no change has taken effect, and any threads that lose the CAS reload the tail pointer and try again. If the second CAS (D) fails, the inserting thread does not need to retry -- because another thread has completed the operation for it in step (B)!



Nonblocking algorithms under the hood

If you dive into the JVM and OS, you'll find nonblocking algorithms everywhere. The garbage collector uses them to accelerate concurrent and parallel garbage collection; the scheduler uses them to efficiently schedule threads and processes and to implement intrinsic locking. In Mustang (Java 6.0), the lock-based `SynchronousQueue` algorithm is being replaced with a new nonblocking version. Few developers use `SynchronousQueue` directly, but it is used as the work queue for thread pools constructed with the `Executors.newCachedThreadPool()` factory. Benchmark tests comparing cached thread pool performance show that the new nonblocking synchronous queue implementation offers close to three times the speed over the current implementation. And further improvements are planned for the release following Mustang, codenamed Dolphin.

Summary

Nonblocking algorithms tend to be far more complicated than lock-based ones. Developing nonblocking algorithms is a rather specialized discipline, and it can be extremely difficult to prove their correctness. But many of the advances in concurrent performance across Java versions come from the use of nonblocking algorithms, and as concurrent performance becomes even more important, expect to see more nonblocking algorithms used in future releases of the Java platform.

Resources

Learn

"[Going atomic](#)" (developerWorks, Brian Goetz, November 2004): Describes the atomic variable classes added in Java 5.0 and the compare-and-swap operation.

"[Simple, Fast, and Practical Non-Blocking and Blocking Concurrent Queues](#)" (Maged M. Michael and Michael L. Scott, Symposium on Principles of Distributed Computing, 1996): Details the construction of the nonblocking linked queue algorithm illustrated in [Listing 4](#) of this article.

[Java Concurrency in Practice](#) (Addison-Wesley Professional, Brian Goetz, Tim Peierls, Joshua Bloch, Joseph Bowbeer, David Holmes, and Doug Lea, June 2006): A how-to manual for developing concurrent programs in the Java language, including constructing and composing thread-safe classes and programs, avoiding liveness hazards, managing performance, and testing concurrent applications.

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