



The Hidden Art of Thread-Safe Programming: Exploring `java.util.concurrent`

Dr Heinz M. Kabutz

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Time for Q & A

- **Questions:**

1. **Why is it a hidden art?**
2. **Why is it not a science or engineering? What's artistic about it?**
3. **What are virtual threads?**

A Tale of `java.util.Vector`

- **One of the first classes in Java**
 - Part of Java 1.0
- **Designed thread-safe from concurrent updates**
 - Most methods synchronized, locking on "this"
 - But missed synchronization on read-only methods like `size()`

Java 1.0 Vector

- **size() could return stale values**

```
public class Vector1_0 {  
    protected int elementCount;  
  
    public final int size() {  
        return elementCount;  
    }  
  
    public final synchronized void addElement(Object obj) {  
        // ...  
    }  
}
```

Moving to Java 1.1

- Introduced a potential race condition

```
public class Vector1_1 implements Serializable {
    protected int elementCount;

    public final int size() {
        return elementCount;
    }

    public final synchronized void addElement(Object obj) {
        // ...
    }
}
```

Moving to Java 1.4

- **Fixed size() visibility and serialization race condition**

```
public class Vector1_4 implements Serializable {
    protected int elementCount;

    public synchronized int size() {
        return elementCount;
    }

    public synchronized void addElement(Object obj) { /* ... */ }

    private synchronized void writeObject(ObjectOutputStream s)
        throws IOException {
        s.defaultWriteObject();
    }
}
```

However, Java 1.4 Can Deadlock!

- **Often, fixing one type of bug, introduces others**

```
Vector v1 = new Vector();  
Vector v2 = new Vector();  
v1.addElement(v2);  
v2.addElement(v1);  
// serialize v1 and v2 from two different threads
```

- **Mentioned in The Java Specialists' Newsletter #184**

- **<https://www.javaspecialists.eu/archive/Issue184.html>**

Moving to Java 1.7

- **Fixed deadlock by calling writeFields() outside of lock**

```
public class Vector1_7 implements Serializable {  
    private void writeObject(ObjectOutputStream s) throws IOException {  
        final ObjectOutputStream.PutField fields = s.putFields();  
        final Object[] data;  
        synchronized (this) {  
            fields.put("capacityIncrement", capacityIncrement);  
            fields.put("elementCount", elementCount);  
            data = elementData.clone();  
        }  
        fields.put("elementData", data);  
        s.writeFields();  
    }  
}
```

New Potential Deadlock Added in Java 8

- **Should not call "alien methods" like accept() whilst locked**

```
public class Vector8<E> implements Serializable {
    public synchronized void forEach(Consumer<? super E> action) {
        Objects.requireNonNull(action);
        final int expectedModCount = modCount;
        final E[] elementData = (E[]) this.elementData;
        final int elementCount = this.elementCount;
        for (int i=0; modCount==expectedModCount && i<elementCount; i++) {
            action.accept(elementData[i]);
        }
        if (modCount != expectedModCount) {
            throw new ConcurrentModificationException();
        }
    }
}
```

Takeaways from Vector Bugs

- **Thread safety is subtle**
- **Tests don't always expose concurrency bugs**
 - **We need to know what to look for**



`java.util.concurrent` Teardown

Writing Correct Thread-Safe Code is a Challenge

- **The Java Memory Model is our rule book**
 - happens-before, ordering, access safety, etc.
 - However, we cannot test whether a class adheres to the JMM 100%
- **We run our code, and hope it works correctly**
 - Some bugs are very hard to detect

LockSupport Rare Lost unpark()

- **Bug 8074773**

- In JDK 7, class loading could consume the unpark()

- Extremely difficult to diagnose and discover, took a week of CPU time

- Recommended workaround was to force LockSupport to load early

```
static {  
    // Prevent rare disastrous classloading in first call to LockSupport.park.  
    // See: https://bugs.openjdk.java.net/browse/JDK-8074773  
    Class<?> ensureLoaded = LockSupport.class;  
}
```

- Since JDK 9, ConcurrentHashMap ensures LockSupport is loaded

So Why Study the `java.util.concurrent` Classes?

- **Brian Goetz, JCiP:**
 - If you need to implement a state-dependent class the best strategy is usually to build upon an existing library class such as `Semaphore`, `BlockingQueue`, or `CountDownLatch`.
- **By studying `java.util.concurrent` in detail, we learn**
 - What is available
 - How to write robust, thread-safe classes

Good vs Bad Code

- **We all make mistakes**

- In German, we say: „Vertrauen ist gut, Kontrolle ist besser!“

- Test Driven Development

- Super difficult with multi-threaded code

- Java Concurrency Stress can help: github.com/openjdk/jcstress

- **Best to rely on well-known synchronizers**

- And then, use those that are most commonly used

- Favour `ConcurrentHashMap` over `ConcurrentSkipListMap`

- Favour `LinkedBlockingQueue` over `LinkedBlockingDeque`

Contributing Bug Reports

- **Anybody can report a Java bug: <https://bugreport.java.com>**
 - I've reported quite a few javaspecialists.eu/about/jdk-contributions/
 - Most of these were in little used classes
 - 1 in `ThreadLocalRandom` (fixed in Java 21+9)
 - 1 in `ConcurrentSkipListMap` (fixed in Java 24)
 - 1 in `ArrayBlockingQueue` (fixed in Java 24)
 - 2 in `LinkedTransferQueue` (fixed in Java 1.8.0+70 and 26)
 - 5 in `LinkedBlockingDeque` (all fixed in Java 26)
 - The less used a class is, the higher the chance of bugs

Eat Your Own Dogfood Collections

- **How many new instances of each in the JDK**
 - **213: ConcurrentHashMap**
 - **11-24: CopyOnWriteArrayList, ConcurrentLinkedQueue, ConcurrentLinkedDeque, FutureTask, LinkedBlockingQueue**
 - **2-6: CountdownLatch, ArrayBlockingQueue, SynchronousQueue, ConcurrentSkipListSet**
 - **1: ConcurrentSkipListMap, LinkedBlockingDeque, LinkedTransferQueue, Semaphore**
 - **0: CopyOnWriteArraySet, CyclicBarrier, Exchanger, Phaser, PriorityBlockingQueue**

Let's Say That Again

- **Use extremely common thread-safe classes**
 - **ConcurrentHashMap**
 - **LinkedBlockingQueue**
 - **ConcurrentLinkedQueue**
- **I only found bugs in rarely used classes**

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Lessons from Striped64

LongAdder vs AtomicLong

- **Let's do a quick comparison of incrementing 100m times**
 - **AtomicLong vs LongAdder (Striped64) (Demo1)**

```
IntStream.range(0, 100_000_000)
    .parallel()
    .forEach(_ -> atomicLong.getAndIncrement());
```

```
IntStream.range(0, 100_000_000)
    .parallel()
    .forEach(_ -> longAdder.increment());
```

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Demo

- **Magic? Let's look at how LongAdder / Striped64 works**

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Takeaways

- **Best way to deal with contention is to not have any**

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Changing Hardware Landscape

Changing Hardware Landscape

- **Started coding Java in 1997**
 - **64 MB of RAM, single core, 233 MHz, 32-bit**
 - **And that was one of the better machines in the company in 1997**
 - **My laptop has 96 GB of RAM, 12 cores, 38 GPU cores, 3.7GHz, 64-bit**
- **Memory was scarce**
 - **Could not imagine creating a collection with billions of entries**
 - **Only platform threads - limited to thousands**

Bugs at the Limits

- **Oodles of memory and virtual threads**
 - Bug in `LinkedBlockingDeque` allowed us to fill it with too many items
 - `size()` returned a negative value
 - www.javaspecialists.eu/archive/Issue328.html
 - Fixed in Java 26
 - Bug in `ReentrantReadWriteLock` ran out of read locks after 65536
 - Resulted in Error being thrown
 - Could not have conceived a system with that many threads
 - Fixed in Java 25
- **Demo2: ManyReadLocks**



StartingGun Synchronizer

StartingGun Synchronizer

- **Let's say we have a service that takes time to be started**
 - Any other part of the system that depends on it should wait
 - But we do not want to deal with `InterruptedException`
 - Once all the data is set up, we call `ready()`, awaking waiting threads

```
public interface StartingGun {  
    void awaitUninterruptibly();  
    void ready();  
}
```

Using `synchronized` and `wait()/notifyAll()`

```
public class StartingGunMonitor implements StartingGun {
    private boolean ready = false;
    public synchronized void awaitUninterruptibly() {
        boolean interrupted = Thread.interrupted();
        while (!ready) {
            try {
                wait(); // not fully compatible with older Loom versions
            } catch (InterruptedException e) {
                interrupted = true;
            }
        }
        if (interrupted) Thread.currentThread().interrupt();
    }
    public synchronized void ready() { ready = true; notifyAll(); }
}
```

Basing StartingGun on CountdownLatch

```
public class StartingGunCountDownLatch implements StartingGun {
    private final CountdownLatch latch = new CountdownLatch(1);
    public void awaitUninterruptibly() {
        var interrupted = Thread.interrupted();
        while (true) {
            try {
                latch.await();
                break;
            } catch (InterruptedException e) {
                interrupted = true;
            }
        }
        if (interrupted) Thread.currentThread().interrupt();
    }
    public void ready() { latch.countDown(); }
}
```

Issues With These Approaches

- **Synchronized `wait()` not fully compatible with virtual threads**
 - Fixed in Java 24
- **Both times, `interrupt` would cause `InterruptedException`**
 - We hide it, but we still pay the cost of creating the exception
- **Another way is to copy what `CountDownLatch` does**
 - Demo3



Lock Splitting: LinkedBlockingQueue

LinkedBlockingQueue Design

- **Single lock would cause `put()/take()` contention**
- **Has separate `putLock` and `takeLock` `ReentrantLock`**
 - We can `put()` and `take()` from a single queue at the same time
 - Has higher throughput for the SPSC case
 - And surprises for the SPMC case
 - Subtleties regarding visibility due to two locks
 - Use `AtomicInteger` count as a volatile synchronizer
- **Demo4 `LockSplittingDemo`**



Weakly Consistent Iterators – `ArrayBlockingQueue`

ArrayBlockingQueue Circular Array Queue

- **Weakly consistent iteration**

- **ArrayDeque would cause a ConcurrentModificationException**

```
var queue = new ArrayBlockingQueue<Integer>(10);
Collections.addAll(queue, 1, 2, 3, 4, 5);
var iterator = queue.iterator();
for (int i = 0; i < 3; i++) System.out.println(iterator.next()); // 1, 2, 3
Collections.addAll(queue, 6, 7, 8, 9, 10);
iterator.forEachRemaining(System.out::println); // 4, 5, 6, 7, 8, 9, 10
```

- **However, what if we circle completely around the array?**

- **ArrayBlockingQueue has to notify its current iterators**

- **But how?**

- **Demo5 WeaklyConsistentViaWeakReferences**  [JavaSpecialists.eu](https://www.javaspecialists.eu)



Double-Checked-Locking – CopyOnWriteArrayList

CopyOnWriteArrayList DCL

- In several places, checks before locking

```
public boolean remove(Object o) {  
    Object[] snapshot = getArray();  
    int index = indexOfRange(o, snapshot, 0, snapshot.length);  
    return index >= 0 && remove(o, snapshot, index);  
}  
// also addIfAbsent(E e),
```

- Demo6 DCLOnSteroidsCOWDemo



Conclusion

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