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

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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 java.io.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 java.io.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(java.io.ObjectOutputStream s)
            throws java.io.IOException {
        final java.io.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
- Better 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 LinkedTransferQueue (fixed in Java 1.8.0+70)
    - 1 in ThreadLocalRandom (fixed in Java 21+9)
    - 1 in ConcurrentSkipListMap (fixed in Java 24)
    - 1 in ArrayBlockingQueue (fixed in Java 24)
    - 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

Before we continue ...

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Lessons from Striped64

LongAdder vs AtomicLong

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

```
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
  - 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
- Demo: ManyReadLocks

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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
  - Quick demo

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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
- Demo LockSplittingDemo

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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?**
- **Demo WeaklyConsistentViaWeakReferences**

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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),
```

- **Demo DCLOnSteroidsCOWDemo**

Conclusion

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