Principles of Software Construction: Objects, Design, and Concurrency

Concurrency Part II: Safety

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Administrivia

- HW 5b due tonight
  - Submit by 9am tomorrow (Wednesday) for “Best Framework” consideration
- No class on Thursday
  - Happy Carnival!

Last Tuesday

- Concurrency hazards:
  - Safety
  - Liveness
  - Performance
- Java primitives for ensuring visibility and atomicity
  - Synchronized access
  - jcip annotations: `@ThreadSafe, @NotThreadSafe, @GuardedBy`
  - Stateless objects are always thread safe

Enforcing atomicity: Intrinsic locks

- `synchronized(lock) { … }` synchronizes entire code block on object `lock`; cannot forget to unlock
- The `synchronized` modifier on a method is equivalent to `synchronized(this) { … }` around the entire method body
- Every Java object can serve as a lock
- At most one thread may own the lock (mutual exclusion)
  - `synchronized` blocks guarded by the same lock execute atomically w.r.t. one another

Non atomicity and thread (un)safety

- Stateful factorizer
  - Susceptible to *lost updates*
  - The ++count operation is not atomic (read-modify-write)

```
@NotThreadSafe
public class UnsafeCountingFactorizer implements Servlet {
    private long count = 0;

    public long getCount() { return count; }

    public void service(ServletRequest req, ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        ++count;
        encodeIntoResponse(resp, factors);
    }
}
```

Fixing the stateful factorizer

```
@ThreadSafe
public class UnsafeCountingFactorizer
        implements Servlet {
    @GuardedBy(“this”)
    private long count = 0;

    public long getCount() {
        synchronized(this){
            return count;
        }
    }

    public void service(ServletRequest req,
                        ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        synchronized(this) {
            ++count;
        }
        encodeIntoResponse(resp, factors);
    }
}
```

For each mutable state variable that may be accessed by more than one thread, **all** accesses to that variable must be performed with the **same** lock held. In this case, we say that the variable is **guarded by** that lock.

Fixing the stateful factorizer

```
@ThreadSafe
public class UnsafeCountingFactorizer
        implements Servlet {
    @GuardedBy("this")
    private long count = 0;

    public synchronized long getCount() {
            return count;
    }

    public void service(ServletRequest req,
                        ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        synchronized(this) {
            ++count;
        }
        encodeIntoResponse(resp, factors);
    }
}
```

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Fixing the stateful factorizer

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@ThreadSafe
public class UnsafeCountingFactorizer
        implements Servlet {
    @GuardedBy("this")
    private long count = 0;

    public synchronized long getCount() {
            return count;
    }

    public synchronized void service(
                    ServletRequest req,
                    ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
            ++count;
        encodeIntoResponse(resp, factors);
    }
}
```

For each mutable state variable that may be accessed by more than one thread, **all** accesses to that variable must be performed with the **same** lock held. In this case, we say that the variable is **guarded by** that lock.

What’s the difference?

```java
public synchronized void service(ServletRequest req,
                                 ServletResponse resp) {
    BigInteger i = extractFromRequest(req);
    BigInteger[] factors = factor(i);
        ++count;
    encodeIntoResponse(resp, factors);
}
```

```java
public void service(ServletRequest req,
                    ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        synchronized(this) {
            ++count;
        }
        encodeIntoResponse(resp, factors);
    }
```

Private locks

```
@ThreadSafe
public class UnsafeCountingFactorizer
        implements Servlet {
    private final Object lock = new Object();
    @GuardedBy("lock")
    private long count = 0;

    public long getCount() {
        synchronized(lock){
            return count;
        }
    }

    public void service(ServletRequest req,
                        ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        synchronized(lock) {
            ++count;
        }
        encodeIntoResponse(resp, factors);
    }
}
```

For each mutable state variable that may be accessed by more than one thread, **all** accesses to that variable must be performed with the **same** lock held. In this case, we say that the variable is **guarded by** that lock.

Could this deadlock?

```java
public class Widget {
    public synchronized void doSomething() {
        ...
    }
}

public class LoggingWidget extends Widget {
    public synchronized void doSomething() {
        System.out.println(toString() + ": calling doSomething");
        super.doSomething();
    }
}
```

No: Intrinsic locks are reentrant

- A thread can lock the same object again while already holding a lock on that object

```java
public class Widget {
    public synchronized void doSomething() {...}
}

public class LoggingWidget extends Widget {
    public synchronized void doSomething() {
        System.out.println(toString() + ": calling doSomething");
        super.doSomething();
    }
}
```

Cooperative thread termination

How long would you expect this to run?

```
public class StopThread {
    private static boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
    }
}
```

What could have gone wrong?

- **In the absence of synchronization, there is no guarantee as to when, if ever, one thread will see changes made by another!**

- VMs can and do perform this optimization (“hoisting”):

```
while (!done)
    /* do something */ ;
```

becomes:

```
if (!done)
    while (true)
        /* do something */ ;
```

How do you fix it?

```
public class StopThread {
    @GuardedBy("StopThread.class")
    private static boolean stopRequested;

    private static synchronized void requestStop() {
        stopRequested = true;
    }

    private static synchronized boolean stopRequested() {
        return stopRequested;
    }

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested())
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        requestStop();
    }
}
```

You can do better (?)

`volatile` *is synchronization without mutual exclusion*

```
public class StopThread {
    private static volatile boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(1);
        stopRequested = true;
    }
}
```

forces all accesses (read or write) to the volatile variable to occur in main memory, effectively keeping the volatile variable out of CPU caches.

https://stackoverflow.com/questions/3519664/difference-between-volatile-and-synchronized-in-java

Volatile keyword

- Tells compiler and runtime that variable is shared and operations on it should not be reordered with other memory ops
  - A read of a volatile variable **always returns the most recent write by any thread**

- Volatile is **not a substitute for synchronization**
  - Volatile variables can only guarantee visibility
  - Locking can guarantee both visibility and atomicity

Summary: Synchronization

- **Ideally, avoid shared mutable state**
- If you can't avoid it, synchronize properly
  - Failure to do so causes safety and liveness failures
  - **If you don't sync properly, your program won't work**
- Even atomic operations require synchronization
  - e.g., `stopRequested = true`
  - And some things that look atomic aren't (e.g., `val++`)

JAVA PRIMITIVES: WAIT, NOTIFY, AND TERMINATION

Guarded methods

- What to do on a method if the precondition is not fulfilled (e.g., transfer money from bank account with insufficient funds)
  - throw exception (**balking**)
  - wait until precondition is fulfilled (**guarded suspension**)
  - wait and timeout (combination of balking and guarded suspension)

Example: Balking

- If there are multiple calls to the job method, only one will proceed while the other calls will return with nothing.

```
public class BalkingExample {
    private boolean jobInProgress = false;

    public void job() {
        synchronized (this) {
            if (jobInProgress) { return; }
            jobInProgress = true;
        }
        // Code to execute job goes here
}

    void jobCompleted() {
        synchronized (this) {
            jobInProgress = false;
        }
    }
}
```

Guarded suspension

- Block execution until a given condition is true
- For example,
  - pull element from queue, but wait on an empty queue
  - transfer money from bank account as soon sufficient funds are there
- Blocking as (often simpler) alternative to callback

Monitor Mechanics in Java

- Object.wait() – suspends the current thread's execution, releasing locks
- Object.wait(timeout) – suspends the current thread's execution for up to *timeout* milliseconds
- Object.notify() – resumes one of the waiting threads
- See documentation for exact semantics

Example: Guarded Suspension

- Loop until condition is satisfied
  - wasteful, since it executes continuously while waiting

```java
public void guardedJoy() {
    // Simple loop guard. Wastes
    // processor time. Don't do this!
    while (!joy) {
    }
    System.out.println("Joy has been achieved!");
}
```

Example: Guarded Suspension

- More efficient: invoke Object.wait to suspend current thread

```
public synchronized guardedJoy() {
    while(!joy) {
        try {
         wait();
     } catch (InterruptedException e) {}
    }
    System.out.println("Joy and efficiency have been achieved!");
}
```

- When wait is invoked, the thread releases the lock and suspends execution. The invocation of wait does not return until another thread has issued a notification

```
public synchronized notifyJoy() {
    joy = true;
    notifyAll();
}
```

Never invoke wait outside a loop!

- Loop tests condition before and after waiting
- Test before skips `wait` if condition already holds
  - Necessary to ensure **liveness**
  - Without it, thread can wait forever!
- Testing after `wait` ensures **safety**
  - Condition may not be true when thread wakens
  - If thread proceeds with action, it can destroy invariants!

All of your waits should look like this

```
synchronized (obj) {
    while (<condition does not hold>) {
        obj.wait();
    }

    ... // Perform action appropriate to condition
}
```

Why can a thread wake from a `wait` when condition does not hold?

- Another thread can slip in between `notify` & wake
- Another thread can invoke `notify` accidentally or maliciously when condition does not hold
  - This is a flaw in java locking design!
  - Can work around flaw by using private lock object
- Notifier can be liberal in waking threads
  - Using `notifyAll` is good practice, but causes this
- Waiting thread can wake up without a `notify`(!)
  - Known as a *spurious wakeup*

Guarded Suspension vs Balking

- Guarded suspension:
  - Typically only when you know that a method call will be suspended for a finite and reasonable period of time
  - If suspended for too long, the overall program will slow down
- Balking:
  - Typically only when you know that the method call suspension will be indefinite or for an unacceptably long period

Monitor Example

```
class SimpleBoundedCounter {
  protected long count = MIN;
  public synchronized long count() { return count; }
  public synchronized void inc() throws InterruptedException {
       awaitUnderMax(); setCount(count + 1);
  }
  public synchronized void dec() throws InterruptedException {
       awaitOverMin(); setCount(count - 1);
  }
  protected void setCount(long newValue) { // PRE: lock held
       count = newValue;
       notifyAll(); // wake up any thread depending on new value
  }
  protected void awaitUnderMax() throws InterruptedException {
       while (count == MAX) wait();
  }
  protected void awaitOverMin() throws InterruptedException {
       while (count == MIN) wait();
  }
}
```

Interruption

- Difficult to kill threads once started, but may politely ask to stop (thread.interrupt())
- Long-running threads should regularly check whether they have been interrupted
- Threads waiting with wait() throw exceptions if interrupted
- Read documentation

```
public class Thread {
    public void interrupt() { ... }
    public boolean isInterrupted() { ... }
    ...
}
```

Interruption Example

```java
class PrimeProducer extends Thread {
    private final BlockingQueue<BigInteger> queue;
    PrimeProducer(BlockingQueue<BigInteger> queue) {
        this.queue = queue;
    }
    public void run() {
        try {
            BigInteger p = BigInteger.ONE;
            while (!Thread.currentThread().isInterrupted())
                queue.put(p = p.nextProbablePrime());
        } catch (InterruptedException consumed) {
            /* Allow thread to exit */
        }
    }
    public void cancel() { interrupt(); }
}
```

For details, see Java Concurrency In Practice, Chapter 7

BUILDING HIGHER LEVEL CONCURRENCY MECHANISMS

Beyond Java Primitives

- Java Primitives (synchronized, wait, notify) are low level mechanisms
- For most tasks better higher-level abstractions exist
- Writing own abstractions is possible, but potentially dangerous – use libraries written by experts

Example: read-write locks (API)

Also known as shared/exclusive mode locks

```
private final RwLock lock = new RwLock();

lock.readLock();
try {
    // Do stuff that requires read (shared) lock
} finally {
    lock.unlock();
}

lock.writeLock();
try {
    // Do stuff that requires write (exclusive) lock
} finally {
    lock.unlock();
}
```

Example: read-write locks (Impl. 1/2)

```
public class RwLock {
    // State fields are protected by RwLock's intrinsic lock

    /** Num threads holding lock for read. */
    private int numReaders = 0;

    /** Whether lock is held for write. */
    private boolean writeLocked = false;

    public synchronized void readLock() throws InterruptedException {
        while (writeLocked) {
            wait();
        }
        numReaders++;
    }
```

Example: read-write locks (Impl. 2/2)

```
    public synchronized void writeLock() throws InterruptedException {
        while (numReaders != 0 || writeLocked) {
            wait();
        }
        writeLocked = true;
    }

    public synchronized void unlock() {
        if (numReaders > 0) {
            numReaders--;
        } else if (writeLocked) {
            writeLocked = false;
        } else {
            throw new IllegalStateException("Lock not held");
        }
        notifyAll(); // Wake any waiters
    }
}
```

Caveat: `RwLock` is just a toy!

- It has poor fairness properties
  - Readers can starve writers!
- `java.util.concurrent` provides an industrial strength `ReadWriteLock`
- More generally, avoid `wait/notify`
  - In the early days it was all you had
  - Nowadays, higher level concurrency utils are better

Summary

- Concurrency for exploiting multiple processors, simplifying modeling, simplifying asynchronous events
- Safety, liveness and performance hazards matter
- Synchronization on any Java object; volatile ensures visibility
- Wait/notify for guards, interruption for cancelation – building blocks for higher level abstractions

THREAD SAFETY: DESIGN TRADEOFFS

Recall: Synchronization for Safety

- If multiple threads access the same mutable state variable without appropriate synchronization, the program is broken.
- There are three ways to fix it:
  - **Don't share** the state variable across threads;
  - Make the state variable **immutable**; or
  - Use **synchronization** whenever accessing the state variable.

Thread Confinement

- Ensure variables are not shared across threads (concurrency version of encapsulation)
- Stack confinement:
  – Object only reachable through local variables (never leaves method) → accessible only by one thread
  – Primitive local variables always thread-local
- Confinement across methods/in classes needs to be done carefully (see immutability)

Example: Thread Confinement

- Shared ark object
- TreeSet is not thread safe but it's local → can't leak
- Defensive copying on AnimalPair

```
public int loadTheArk(Collection<Animal> candidates) {
    SortedSet<Animal> animals;
    int numPairs = 0;
    Animal candidate = null;
    // animals confined to method, don't let them escape!
    animals = new TreeSet<Animal>(new SpeciesGenderComparator());
    animals.addAll(candidates);
    for (Animal a : animals) {
        if (candidate == null || !candidate.isPotentialMate(a))
            candidate = a;
        else {
            ark.load(new AnimalPair(candidate, a));
            ++numPairs;
            candidate = null;
        }
    }
    return numPairs;
}
```

Confinement with ThreadLocal

- ThreadLocal holds a separate value for each cache (essentially Map<Thread,T>)
  - create variables that can only be read and written by the same thread
  - if two threads are executing the same code, and the code has a reference to a ThreadLocal variable, then the two threads cannot see each other's ThreadLocal variables

Example: ThreadLocal

```
public static class MyRunnable implements Runnable {
    private ThreadLocal<Integer> threadLocal = new ThreadLocal<Integer>();

    @Override
    public void run() {
        threadLocal.set((int) (Math.random() * 100D));

        System.out.println(threadLocal.get());
    }
}

public static void main(String[] args) throws InterruptedException {
    MyRunnable sharedRunnableInstance = new MyRunnable();

    Thread thread1 = new Thread(sharedRunnableInstance);
    Thread thread2 = new Thread(sharedRunnableInstance);

    thread1.start();
    thread2.start();

    thread1.join(); // wait for thread 1 to terminate
    thread2.join(); // wait for thread 2 to terminate
}
```


From: http://tutorials.jenkov.com/java-concurrency/threadlocal.html

Immutable Objects

- Immutable objects can be shared freely
- Remember:
  - Fields initialized in constructor
  - Fields final
  - Defensive copying if mutable objects used internally

Synchronization

- **Thread-safe** objects vs **guarded**:
  - Thread-safe objects perform synchronization internally (clients can always call safely)
  - Guarded objects require clients to acquire lock for safe calls
- Thread-safe objects are easier to use (harder to misuse), but guarded objects can be more flexible

Designing Thread-Safe Objects

- Identify variables that represent the object’s state
  - may be distributed across multiple objects
- Identify invariants that constraint the state variables
  - important to understand invariants to ensure atomicity of operations
- Establish a policy for managing concurrent access to state

What would you change here?

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("this")
    private final Set<Person> mySet = new HashSet<Person>();

    @GuardedBy("this")
    private Person last = null;

    public synchronized void addPerson(Person p) {
        mySet.add(p);
    }

    public synchronized boolean containsPerson(Person p) {
        return mySet.contains(p);
    }

    public synchronized void setLast(Person p) {
        this.last = p;
    }
}
```

Coarse-Grained Thread-Safety

- Synchronize all access to all state with the object

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("this")
    private final Set<Person> mySet = new HashSet<Person>();

    @GuardedBy("this")
    private Person last = null;

    public synchronized void addPerson(Person p) {
        mySet.add(p);
    }

    public synchronized boolean containsPerson(Person p) {
        return mySet.contains(p);
    }

    public synchronized void setLast(Person p) {
        this.last = p;
    }
}
```

Fine-Grained Thread-Safety

- "Lock splitting": Separate state into independent regions with different locks

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("myset")
    private final Set<Person> mySet = new HashSet<Person>();

    @GuardedBy("this")
    private Person last = null;

    public void addPerson(Person p) {
        synchronized (mySet) {
            mySet.add(p);
        }
    }

    public boolean containsPerson(Person p) {
        synchronized (mySet) {
            return mySet.contains(p);
        }
    }

    public synchronized void setLast(Person p) {
        this.last = p;
    }
}
```

Private Locks: Any object can serve as lock

```
@ThreadSafe
public class PersonSet {
    @GuardedBy("myset")
    private final Set<Person> mySet = new HashSet<Person>();

    private final Object myLock = new Object();
    @GuardedBy("myLock")
    private Person last = null;

    public void addPerson(Person p) {
        synchronized (mySet) {
            mySet.add(p);
        }
    }

    public synchronized boolean containsPerson(Person p) {
        synchronized (mySet) {
            return mySet.contains(p);
        }
    }

    public void setLast(Person p) {
        synchronized (myLock) {
            this.last = p;
        }
    }
}
```

Delegating thread-safety to well designed classes

- Recall previous CountingFactorizer

```
@NotThreadSafe
public class CountingFactorizer implements Servlet {
    private long count = 0;

    public long getCount() { return count; }

    public void service(ServletRequest req, ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        ++count;
        encodeIntoResponse(resp, factors);
    }
}
```

Delegating thread-safety to well designed classes

- Replace long counter with an AtomicLong

```
@ThreadSafe
public class CountingFactorizer implements Servlet {
    private final AtomicLong count = new AtomicLong(0);

    public long getCount() { return count.get(); }

    public void service(ServletRequest req, ServletResponse resp) {
        BigInteger i = extractFromRequest(req);
        BigInteger[] factors = factor(i);
        count.incrementAndGet();
        encodeIntoResponse(resp, factors);
    }
}
```

Synchronize only relevant method parts

- Design heuristic:
  - **Get in, get done, and get out**
    - Obtain lock
    - Examine shared data
    - Transform as necessary
    - Drop lock
  - **If you must do something slow, move it outside synchronized region**

Example: What to synchronize?

```
@ThreadSafe
public class AttributeStore {
    @GuardedBy("this")
    private final Map<String, String>
                attributes = new HashMap<String, String>();

    public synchronized boolean userLocationMatches(String name,
                                                    String regexp) {
        String key = "users." + name + ".location";
        String location = attributes.get(key);
        if (location == null)
            return false;
        else
            return Pattern.matches(regexp, location);
    }
}
```

Narrowing lock scope

```
@ThreadSafe
public class BetterAttributeStore {
    @GuardedBy("this")
    private final Map<String, String>
                attributes = new HashMap<String, String>();

    public boolean userLocationMatches(String name, String regexp) {
        String key = "users." + name + ".location";
        String location;
        synchronized (this) {
            location = attributes.get(key);
        }
        if (location == null)
            return false;
        else
            return Pattern.matches(regexp, location);
    }
}
```

Fine-Grained vs Coarse-Grained Tradeoffs

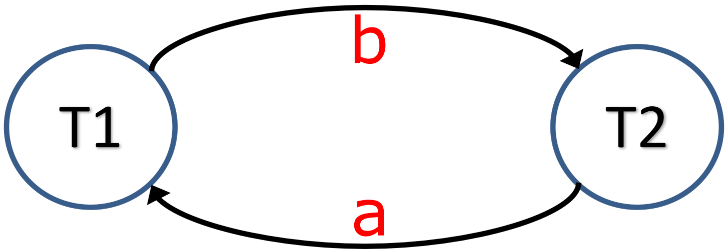
- Coarse-Grained is simpler
- Fine-Grained allows concurrent access to different parts of the state
- When invariants span multiple variants, fine-grained locking needs to ensure that all relevant parts are using the same lock or are locked together
- Acquiring multiple locks requires care to avoid deadlocks

Over vs Undersynchronization

- Undersynchronization -> safety hazard
- Oversynchronization -> liveness hazard and reduced performance

Avoiding deadlock

- Deadlock caused by a cycle in waits-for graph
  - T1: `synchronized(a){ synchronized(b){ … } }`
  - T2: `synchronized(b){ synchronized(a){ … } }`



- To avoid these deadlocks:
  - When threads have to hold multiple locks at the same time, **all threads obtain locks in same order**

Summary of policies:

- **Thread-confined.** A thread-confined object is owned exclusively by and confined to one thread, and can be modified by its owning thread.
- **Shared read-only.** A shared read-only object can be accessed concurrently by multiple threads without additional synchronization, but cannot be modified by any thread. Shared read-only objects include immutable and effectively immutable objects.
- **Shared thread-safe.** A thread-safe object performs synchronization internally, so multiple threads can freely access it through its public interface without further synchronization.
- **Guarded.** A guarded object can be accessed only with a specific lock held. Guarded objects include those that are encapsulated within other thread-safe objects and published objects that are known to be guarded by a specific lock.

Tradeoffs

- Strategies:
  - Don't share the state variable across threads;
  - Make the state variable immutable; or
  - Use synchronization whenever accessing the state variable.
    - Thread-safe vs guarded
    - Coarse-grained vs fine-grained synchronization
- When to choose which strategy?
  - Avoid synchronization if possible
  - Choose simplicity over performance where possible

Documentation

- Document a class's thread safety guarantees for its clients
- Document its synchronization policy for its maintainers.
- @ThreadSafe, @GuardedBy annotations not standard but useful

Recommended Readings

- Goetz et al. Java Concurrency In Practice. Pearson Education, 2006, Chapters 2-5, 11
- Lea, Douglas. Concurrent programming in Java: design principles and patterns. Addison-Wesley Professional, 2000.