Principles of Software Construction: Objects, Design, and Concurrency

Part 3: Concurrency

Introduction to concurrency, part 3

Concurrency primitives, libraries, and design patterns

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Administrivia

- HW 5b due today, 11:59EDT (framework & plugin implementation)
- Optional reading due today: JCiP Chatper 12

Key concepts from Tuesday

Lock splitting for increased concurrency

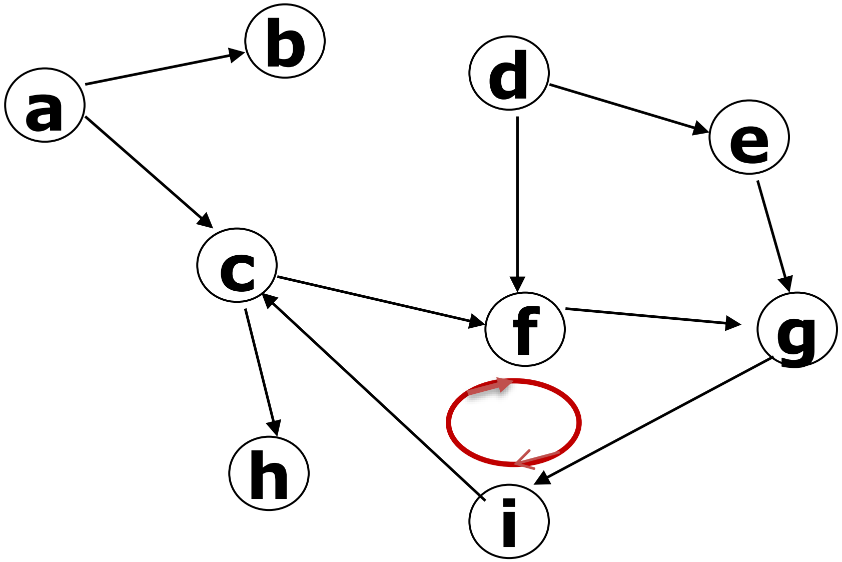
Review: what's the bug in this code?

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        synchronized(source) {
            synchronized(dest) {
                source.balance -= amount;
                dest.balance   += amount;
            }
        }
    }
    …
}
```

Avoiding deadlock

- The *waits-for graph* represents dependencies between threads
  - Each node in the graph represents a thread
  - An edge T1->T2 represents that thread T1 is waiting for a lock T2 owns
- Deadlock has occurred iff the waits-for graph contains a cycle
- One way to avoid deadlock: locking protocols that avoid cycles



Avoiding deadlock by ordering lock acquisition

```
public class BankAccount {
    private long balance;
    private final long id = SerialNumber.generateSerialNumber();

    public BankAccount(long balance) {
        this.balance = balance;
    }

    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        BankAccount first  = (source.id < dest.id) ? source : dest;
        BankAccount second = (first == source)     ? dest : source;
        synchronized (first) {
            synchronized (second) {
                source.balance -= amount;
                dest.balance += amount;
            }
        }
    }
}
```

Using a private lock to encapsulate synchronization

```
public class BankAccount {
    private long balance;
    private final long id = SerialNumber.generateSerialNumber();
    private final Object lock = new Object();

    public BankAccount(long balance) { this.balance = balance; }

    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        BankAccount first = source.id < dest.id ? source : dest;
        BankAccount second = first == source ? dest : source;
        synchronized (first.lock) {
            synchronized (second.lock) {
                source.balance -= amount;
                dest.balance += amount;
            }
        }
    }
}
```

Java Concurrency in Practice annotations

```
@ThreadSafe
public class BankAccount {
  @GuardedBy("lock")
  private long balance;
  private final long id = SerialNumber.generateSerialNumber();
  private final Object lock = new Object();

  public BankAccount(long balance) {
    this.balance = balance;
  }

  static void transferFrom(BankAccount source,
                           BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first.lock) {
        synchronized (second.lock) {
            source.balance -= amount;
            dest.balance += amount;
        } …
```

```
@ThreadSafe
@NotThreadSafe
@GuardedBy
@Immutable
```

Today

- Strategies for safety
- Java libraries for concurrency
- Building thread-safe data structures
  - Java primitives for concurrent coordination
- Program structure for concurrency

Policies for thread safety

1. **Thread-confined state** – mutate but don’t share
2. **Shared read-only state** – share but don’t mutate
3. **Shared thread-safe** – object synchronizes itself internally
4. **Shared guarded** – client synchronizes object(s) externally

1. Three kinds of thread-confined state

- **Stack-confined**
  - Primitive local variables are *never* shared between threads
  - Fast and cheap
- **Unshared object references**
  - The thread that creates an object must take action to share (“publish”)
  - e.g., put it in a shared collection, store it in a static variable
- **Thread-local variables**
  - Shared object with a separate value for each thread
  - Rarely needed but invaluable (e.g., for user ID or transaction ID)

```
class ThreadLocal<T> {
    ThreadLocal() ;    // Initial value for each thread is null
    static <S> ThreadLocal<S> withInitial(Supplier<S> supplier);

    void set(T value); // Sets value for current thread
    T get();           // Gets value for current thread
}
```

2. Shared read-only state

- Immutable data is always safe to share
- So is mutable data that isn't mutated

3. Shared thread-safe state

- Thread-safe objects that perform internal synchronization
- You can build your own, but not for the faint of heart
- You're better off using ones from `java.util.concurrent`
- `j.u.c` also provides skeletal implementations

4. Shared guarded state

- Shared objects that must be locked by user
  - Most examples in the last two lectures. e.g., `BankAccount`
- Can be error prone: burden is on user
- High concurrency can be difficult to achieve
  - Lock granularity is the entire object
- You’re generally better off avoiding guarded objects

Outline

I. Strategies for safety

II. Building thread-safe data structures

III. Java libraries for concurrency (`java.util.concurrent`)

`wait/notify` – a primitive for cooperation

The basic idea is simple…

- State (fields) are guarded by a lock
- Sometimes, a thread can't proceed till state is right
  - So it waits with `wait`
  - Automatically drops lock while waiting
- Thread that makes state right wakes waiting thread(s) with `notify`
  - Waking thread must hold lock when it calls `notify`
  - Waiting thread automatically acquires lock when it wakes up

But the devil is in the details

***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 waiting ensure **safety**
  - Condition may not be true when thread wakes up
  - 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 can cause extra wakeups
- Waiting thread can wake up without a `notify`(!)
  - Known as a *spurious wakeup*

Defining your own thread-safe objects

- Identify variables that represent the object's state
- Identify invariants that constrain the state variables
- Establish a policy for maintaining invariants

A toy example: Read-write locks (a.k.a. *shared/exclusive* locks)

Sample client code:

```
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();
}
```

A toy example: Read-write locks (implementation 1/2)

```
@ThreadSafe public class RwLock {
    /** Number of threads holding lock for read. */
    @GuardedBy("this") // Intrinsic lock on RwLock object
    private int numReaders = 0;

    /** Whether lock is held for write. */
    @GuardedBy("this")
    private boolean writeLocked = false;

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

A toy example: Read-write locks (implementation 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
    }
}
```

Advice for building thread-safe objects

- **Do as little as possible in synchronized region: get in, get out**
  - Obtain lock
  - Examine shared data
  - Transform as necessary
  - Drop the lock
- If you must do something slow, move it outside the synchronized region

Documentation

- Document a class's thread safety guarantees for its clients
- Document a class's synchronization policy for its maintainers
- Use `@ThreadSafe`, `@GuardedBy` annotations
  - And any prose that is required

Summary of our `RwLock` example

- Generally, avoid `wait/notify`
  - `Java.util.concurrent` provides better alternatives
- Never invoke `wait` outside a loop
  - Must check coordination condition after waking
- Generally use `notifyAll`, not `notify`
- Do not use our `RwLock` – it's just a toy

Outline

I. Strategies for safety
II. Building thread-safe data structures
III. Java libraries for concurrency (`java.util.concurrent`)

`java.util.concurrent` is BIG (1)

1. Atomic variables: `java.util.concurrent.atomic`
    - Support various atomic read-modify-write ops
2. Concurrent collections
    - Shared maps, sets, lists
3. Data exchange collections
    - Blocking queues, deques, etc.
4. Executor framework
    - Tasks, futures, thread pools, completion service, etc.
5. Synchronizers
    - Semaphores, cyclic barriers, countdown latches, etc.
6. Locks: `java.util.concurrent.locks`
    - Read-write locks, conditions, etc.

`java.util.concurrent` is BIG (2)

- Pre-packaged functionality: `java.util.Arrays`
  - Parallel sort, parallel prefix
- **Completable futures!**
  - Multistage asynchronous concurrent computations
- Flows
  - Publish/subscribe service
- And more
  - It just keeps growing

1. Overview of `java.util.concurrent.atomic`

- **`Atomic{Boolean,Integer,Long}`**
  - Boxed primitives that can be updated atomically
- **`AtomicReference<T>`**
  - Object reference that can be updated atomically
- **`Atomic{Integer,Long,Reference}Array`**
  - Array whose elements may be updated atomically
- **`Atomic{Integer,Long,Reference}FieldUpdater`**
  - Reflection-based utility enabling atomic updates to volatile fields
- **`LongAdder`, `DoubleAdder`**
  - Highly concurrent sums
- **`LongAccumulator`, `DoubleAccumulator`**
  - Generalization of `adder` to arbitrary functions (`max`, `min`, etc.)

Example: `AtomicLong`

```
class AtomicLong {  // We used this in generateSerialNumber()
    long get();
    void set(long newValue);
    long getAndSet(long newValue);
    long getAndAdd(long delta);
    long getAndIncrement();
    boolean compareAndSet(long expectedValue, long newValue);
    long getAndUpdate(LongUnaryOperator updateFunction);
    long updateAndGet(LongUnaryOperator updateFunction);
    …
}
```

2. Concurrent collections

- Provide high performance and scalability

Unsynchronized	**Concurrent**
`HashMap`	`ConcurrentHashMap`
`HashSet`	`ConcurrentHashSet`
`TreeMap`	`ConcurrentSkipListMap`
`TreeSet`	`ConcurrentSkipListSet`

You can’t prevent concurrent use of a concurrent collection

- This works for synchronized collections…

```
Map<String, String> syncMap =
    Collections.synchronizedMap(new HashMap<>());
synchronized(syncMap) {
   if (!syncMap.containsKey("foo"))
       syncMap.put("foo", "bar");
}
```

- But ***not*** for concurrent collections
  - They do their own internal synchronization
  - Never synchronize on a concurrent collection!

Instead, use **atomic read-modify-write methods**

- `V putIfAbsent(K key, V value);`
- `boolean remove(Object key, Object value);`
- `V replace(K key, V value);`
- `boolean replace(K key, V oldValue, V newValue);`
- `V compute(K key, BiFunction<...> remappingFn);`
- `V computeIfAbsent(K key, Function<...> mappingFn);`
- `V computeIfPresent (K key, BiFunction<...> remapFn);`
- `V merge(K key, V value, BiFunction<...> remapFn);`

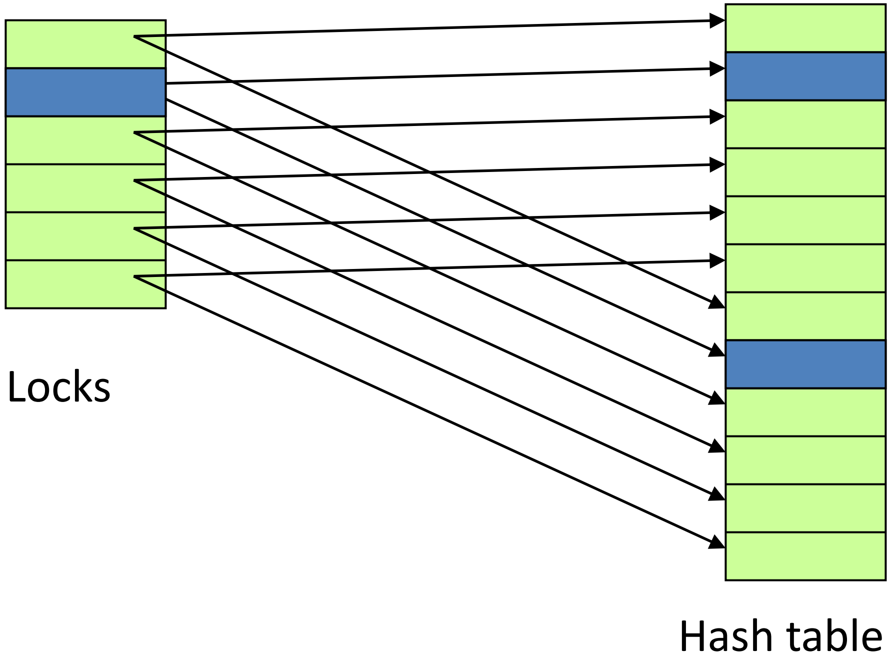
Concurrent collection example: canonicalizing map

```
private final ConcurrentMap<T,T> map = new ConcurrentHashMap<>();

public T intern(T t) {
    String previousValue = map.putIfAbsent(t, t);
    return previousValue == null ? t : previousValue;
}
```

`java.util.concurrent.ConcurrentHashMap`

- Uses **many** techniques used to achieve high concurrency
  - Over 6,000 lines of code
- The simplest of these is *lock striping*
  - Multiple locks, each dedicated to a region of hash table



Aside: the producer-consumer pattern

- Goal: Decouple the producer and the consumer of some data
- Consequences:
  - Removes code dependency between producers and consumers
  - Producers and consumers can produce and consume at different rates

3. Data exchange collections summary

Hold elements for processing by another thread (producer/consumer)

- `BlockingQueue` – Supports blocking ops
  - `ArrayBlockingQueue`, `LinkedBlockingQueue`
  - `PriorityBlockingQueue`, `DelayQueue`
  - `SynchronousQueue`
- `BlockingDeque` – Supports blocking ops
  - `LinkedBlockingDeque`
- `TransferQueue` – `BlockingQueue` in which producers may wait for consumers to receive elements
  - `LinkedTransferQueue`

Summary of `BlockingQueue` methods

	Throws exception	*Special value*	*Blocks*	*Times out*
Insert	`add(e)`	`offer(e)`	`put(e)`	`offer(e, time, unit)`
Remove	`remove()`	`poll()`	`take()`	`poll(time, unit)`
Examine	`element()`	`peek()`	n/a	n/a

Summary of `BlockingDeque` methods

First element (head) methods

	Throws exception	*Returns null*	*Blocks*	*Times out*
Insert	`addFirst(e)`	`offerFirst(e)`	`putFirst(e)`	`offerFirst(e, time, unit)`
Remove	`removeFirst()`	`pollFirst()`	`takeFirst()`	`pollFirst(time,unit)`
Examine	`getFirst()`	`peekFirst()`	n/a	n/a

Last element (tail) methods

	Throws exception	*Returns null*	*Blocks*	*Times out*
Insert	`addLast(e)`	`offerLast(e)`	`putLast(e)`	`offerLast(e, time, unit)`
Remove	`removeLast()`	`pollLast()`	`takeLast()`	`pollLast(time,unit)`
Examine	`getLast()`	`peekLast()`	n/a	n/a

4. Executor framework overview

- Flexible interface-based task execution facility
- Key abstractions
  - `Runnable`, `Callable<T>` - kinds of tasks
- `Executor` – thing that executes tasks
- `Future<T>` – a promise to give you a T
- Executor service – `Executor` that
  - Lets you manage termination
  - Can produce `Future` instances

`Executors` – your one-stop shop for executor services

- `Executors.new`**`SingleThreadExecutor`**`()`
    - A single background thread
- `new`**`FixedThreadPool`**`(int nThreads)`
    - A fixed number of background threads
- `Executors.new`**`CachedThreadPool`**`()`
    - Grows in response to demand

A very simple (but useful) executor service example

- Background execution of a long-lived worker thread
  - To start the worker thread:

```
ExecutorService executor =
  Executors.newSingleThreadExecutor();
```

  - To submit a task for execution:

```
executor.execute(runnable);
```

  - To terminate gracefully:

```
executor.shutdown(); // Allows tasks to finish
```

Other things you can do with an executor service

- Wait for a task to complete

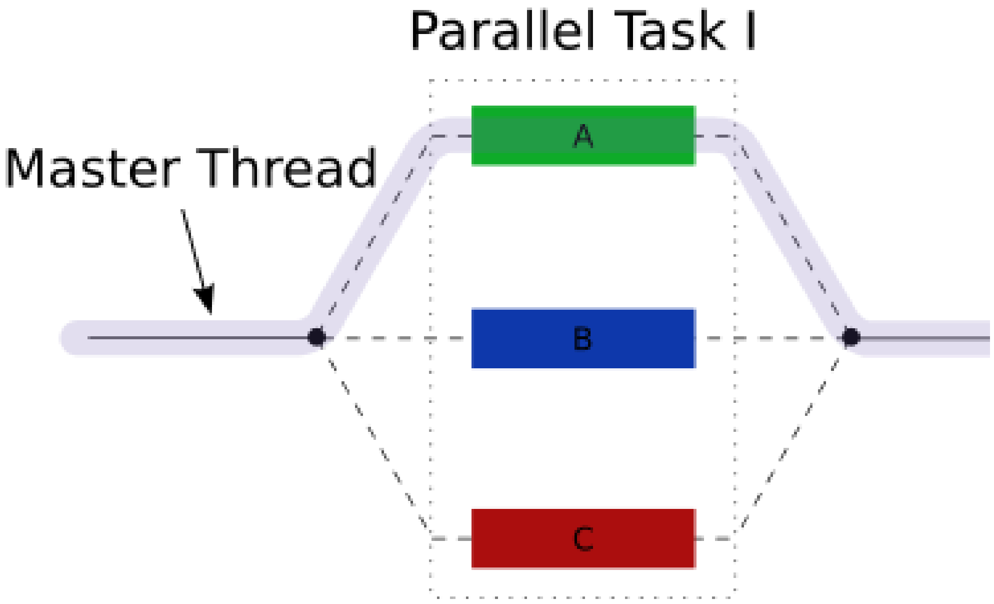
  `Foo foo = executorSvc.submit(callable).get();`
- Wait for any or all of a collection of tasks to complete

  `invoke{Any,All}(Collection<Callable<T>> tasks)`
- Retrieve results as tasks complete

  `ExecutorCompletionService`
- Schedule tasks for execution a time in the future

  `ScheduledThreadPoolExecutor`
- etc., ad infinitum

The fork-join pattern



```
if (my portion of the work is small)
    do the work directly
else
    split my work into pieces
    recursively process the pieces
```

`ForkJoinPool`: executor service for `ForkJoinTask`

Dynamic, fine-grained parallelism with recursive task splitting

```
class SumOfSquaresTask extends RecursiveAction {
   final long[] a; final int lo, hi; long sum;
   SumOfSquaresTask(long[] array, int low, int high) {
       a = array; lo = low; hi = high;
   }

   protected void compute() {
       if (h - l < THRESHOLD) {
           for (int i = l; i < h; ++i)
               sum += a[i] * a[i];
       } else {
           int mid = (lo + hi) >>> 1;
           SumOfSquaresTask left = new SumOfSquaresTask(a, lo, mid);
           left.fork(); // pushes task
           SumOfSquaresTask right = new SumOfSquaresTask(a, mid, hi);
           right.compute();
           right.join(); // pops/runs or helps or waits
           sum = left.sum + right.sum;
       }
   }
}
```

5. Overview of synchronizers

- `CountDownLatch`
  - One or more threads to wait for others to count down
- `CyclicBarrier`
  - a set of threads wait for each other to be ready
- `Semaphore`
  - Like a lock with a maximum number of holders (“permits”)
- Phaser – Cyclic barrier on steroids
- AbstractQueuedSynchronizer – roll your own!

6. Overview of `java.util.concurrency.locks` (1/2)

- `ReentrantReadWriteLock`
  - Shared/Exclusive mode locks with tons of options
    - Fairness policy
    - Lock downgrading
    - Interruption of lock acquisition
    - Condition support
    - Instrumentation
- `ReentrantLock`
  - Like Java's intrinsic locks
  - But with more bells and whistles

Overview of `java.util.concurrency.locks` (2/2)

- `Condition`
  - `wait/notify/notifyAll` with multiple wait sets per object
- `AbstractQueuedSynchronizer`
  - Skeletal implementation of locks relying on FIFO wait queue
- `AbstractOwnableSynchronizer`, `AbstractQueuedLongSynchronizer`
  - Fancier skeletal implementations

`ReentrantReadWriteLock` example

Does this look vaguely familiar?

```
private final ReentrantReadWriteLock rwl =
        new ReentrantReadWriteLock();

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

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

Summary

- `java.util.concurrent` is big and complex
- But it's well designed and engineered
  - Easy to do simple things
  - Possible to do complex things
- Executor framework does for execution what collections did for aggregation
- This lecture just scratched the surface
  - But you know the lay of the land and the javadoc is good
- **Always better to use j.u.c than to roll your own!**