# Threads and Locks, Part 2

CSCI 5828: Foundations of Software Engineering
Lecture 10 — 09/24/2015

# Goals

- Cover the material presented in Chapter 2 of our concurrency textbook
  - In particular, selected material from Days 2 and 3
- java.util.concurrent
  - ReentrantLock
  - AtomicVariables
  - Thread Pools
  - Producer Consumer Example
    - Warning: the book expects you to download a 10GB file that expands to be 51 GB in order to run these examples!
    - I’ve done this for you. (You’re welcome. 😃)

# What’s the easy way?

- Last lecture, we looked at “doing concurrency the hard way”
  - So, what’s the easy way?
- We are not necessarily going to answer that question in this lecture
  - But, we are going to look at the java.util.concurrency library to help make it ***less painful*** to create concurrent software
    - <http://docs.oracle.com/javase/7/docs/api/java/util/concurrent/package-summary.html>
- As we move forward, we’ll look at other models and techniques that all attempt to reduce the complexity associated with concurrent programming
  - However, each new model/technique will introduce its own set of accidental difficulties, such as having to learn Clojure. 😃

# Synchronized Keyword => Intrinsic Locks

- We've been using the **synchronized** keyword to try to address the problems we've been seeing in our concurrent programs so far
- The problem with this keyword is that it makes use of an inflexible lock that our book calls **intrinsic locks**
  - It is inflexible because
    - A thread blocked on an intrinsic lock cannot be interrupted
      - It's all or nothing
    - A thread blocked on an intrinsic lock cannot have a time out
    - There's only one type of intrinsic lock (*reentrant*) and only one way to acquire it (*with the synchronized keyword*)

# java.util.concurrent.locks.ReentrantLock

- The ReentrantLock class from java.util.concurrent.locks allows us to gain the benefit of fine-grained locking without having to use the synchronized keyword
- To use them, you first instantiate a lock (and stash it somewhere)
  - Lock lock = new ReentrantLock();
- Then you follow this pattern
  - `lock.lock();`
  - `try {`
    - `«use shared resource»`
  - `} finally {`
    - `lock.unlock();`
  - `}`

# First benefit: Abstraction (I)

- Note this line of code carefully: `Lock lock = new ReentrantLock();`
- The concrete class is `ReentrantLock`. Our variable is of type `Lock`
  - This gives us a nice abstraction with the following methods
    - `lock()` — acquire the lock and block if needed
    - `lockInterruptibly()` — acquire the lock, block if needed, allow interruption
    - `newCondition()` —bind a Condition to this lock
    - `tryLock()` and `tryLock(…)` —acquire the lock without blocking or with a timeout
    - `unlock()` — release the lock

# First benefit: Abstraction

- Currently `java.util.concurrent.locks` provide us with two locks
  - `ReentrantLock` and `ReentrantReadWriteLock`
- But the interface `Lock` allows us to write code that is not dependent on the concrete classes and could change if better options are added in the future
- This abstraction also addresses the problem of having only one way to acquire an intrinsic lock
  - The `Lock` interface gives us four different ways of acquiring a lock
    - blocking, non-blocking, with a time out, and with the option of being interrupted
- This flexibility allows us to design concurrent systems with more powerful constructs and avoid the problems we saw in Lecture 9

# Second Benefit: Thread Interruption

- The book has two programs to demonstrate the ability (or lack thereof) to interrupt threads that are blocked on locks
  - With an intrinsic lock, there's no way to do it
    - if a thread becomes blocked and the semantics of your program will never allow it to become unblocked
      - then it's stuck until you kill the JVM
  - With the `Lock` interface, you simply acquire it with the `lockInterruptibly()` method and then `Thread.interrupt()` behaves as you would expect
  - DEMO

# Third Benefit: Timeouts (I)

- With the Lock interface, you have the option of calling `tryLock()`
  - This is a nonblocking call that returns TRUE if the lock is acquired
  - `if (lock.tryLock()) {`
    - `Lock acquired`
  - `} else {`
    - `Lock not acquired; act accordingly`
  - `}`
- You also have the option to specify a timeout (from nanoseconds to days!)
  - `if (lock.tryLock(50L, TimeUnit.SECONDS)) {`
    - `Lock acquired`
  - `} else {`
    - `Timeout occurred; act accordingly`
  - `}`

# Third Benefit: Timeouts (II)

- The book provides an example of the Dining Philosophers program that makes use of timeouts
  - We don't have to worry about acquiring chopsticks in the same order
    - We instead adopt the following strategy
      - acquire a lock on the left chopstick
      - acquire a lock on the right chopstick using tryLock() with a timeout
        - If that fails, release the lock on the left chopstick and try again
- This works BUT you can have a problem with ***LIVELOCK***
  - Live lock is the situation in which a program does not make progress because the threads lock, time out, and then immediately lock again
    - You spend your time dealing with locks and not performing work

# Note: Skipping Hand-over-Hand Locking

- The book has an example of using ReentrantLocks to allow multiple threads to access a linked list at the same time
    - including allowing multiple insertions to occur without damaging the overall structure of the list
    - and allowing iteration and other operations to occur in parallel on the list
- I'm going to skip this example as it is fairly low-level
    - The key idea is how the locks are acquired as a thread moves through the list
        - You acquire a lock on node i and then try to acquire a lock on node i+1
            - Once you have the lock on node i+1, you can release the lock on node i

# Fourth Benefit: Condition Variables (I)

- Condition Variables are used when your thread's logic involves waiting for an event to occur (or a condition to become true) before it does its work
  - If the event has not happened or the condition is false, we want the thread to block and not consume the scheduler's time
- Coding this logic can be quite challenging
  - You may have a lot of threads waiting for the condition to become true
    - As a result, you need a queue or a collection class to hold the threads while they are waiting
    - When the condition becomes true, you need a way to "wake up" the threads that are waiting, and let them try to do their work
- Condition variables make coding this type of logic straightforward

# Fourth Benefit: Condition Variables (II)

- To work with a conditional variable, you follow this pattern
  - `ReentrantLock lock = new ReentrantLock();`
  - `Condition condition = lock.newCondition();`
  - `lock.lock()`
  - `try {`
    - `while (!«condition is true») { condition.await(); }`
    - `«use shared resources»`
  - `} finally { lock.unlock(); }`
- The key to this pattern is that the variable and the condition are tied together
  - The thread has to acquire the lock and then check the condition
  - If the condition is false, it needs to wait. The call to await() blocks the thread and **unlocks the lock** *atomically*, allowing other threads to access the shared resources

# Fourth Benefit: Condition Variables (III)

- To work with a conditional variable, you follow this pattern
  - `ReentrantLock lock = new ReentrantLock();`
  - `Condition condition = lock.newCondition();`
  - `lock.lock()`
  - `try {`
    - `while (!«condition is true») { condition.await(); }`
    - `«use shared resources»`
  - `} finally { lock.unlock(); }`
- The key to this pattern is that the variable and the condition are tied together
  - If **some other thread** performs work that may have changed the condition, it calls signal() or signalAll() on the condition. The former wakes up a single thread that was blocked on the condition; the latter wakes them all up
    - If signalAll() is used, **all of the threads** battle to **reacquire the lock**

# Fourth Benefit: Condition Variables (IV)

- To work with a conditional variable, you follow this pattern
    - `ReentrantLock lock = new ReentrantLock();`
    - `Condition condition = lock.newCondition();`
    - `lock.lock()`
    - `try {`
        - `while (!«condition is true») { condition.await(); }`
        - `«use shared resources»`
    - `} finally { lock.unlock(); }`
- The key to this pattern is that the variable and the condition are tied together
    - It is thus **guaranteed** that when await() returns, the thread once again has acquired the lock. It then checks the condition to see if it is indeed true.
        - If so, it performs its work and releases the lock. If not, it blocks once again with a call to await()

# Fourth Benefit: Condition Variables (V)

- The book provides an example of using a Condition Variable to provide a solution to the dining philosopher that
  - a) avoids deadlock
  - b) enables significantly more concurrency than previous solutions
- With the previous solutions, it was highly likely that only one philosopher was able to eat at a time
  - All the other philosophers have one chopstick and are waiting for the other one to become available
- With this solution, at least two philosophers can be eating at one time. That number goes up, if we increase the number of philosophers that are sitting around the table

# java.util.concurrent.atomic

- The java.util.concurrent.atomic package contains classes that "support lock-free thread-safe programming on single variables"
  - They provide an easy way to implement single variables that need to be shared between multiple threads and you want to avoid the use of locks to enable maximum concurrency
    - A common use case includes variables that need to be incremented or decremented as events occur without "losing" any of those operations due to race conditions
    - Another use case is the ability to share object references across threads, such that a change in the reference is seen by all threads
      - No "memory barrier" issues, the change is guaranteed to be visible in all threads
- The book updates the counter example using an AtomicInteger. **DEMO**

# Thread Pools

- It takes time to create threads
  - For servers, you want to avoid having to create threads on demand
    - It will slow you down, if you have to wait for a thread to spin up each time you receive a connection
    - Code that creates threads on demand, typically do not have logic to prevent creating one thread per request
      - If that's true and you get 1000s of requests, your code will blindly create 1000s of threads, which will bring your machine to its knees
- A much better strategy is to use a thread pool
  - You create all of the threads you are going to use up front
  - When you need a request to be handled, you wrap it up in a Runnable and hand it to the pool
    - If a thread is available, it executes immediately; otherwise it waits

# Using Thread Pools

- The code to create a thread pool is straightforward
    - `public class Task implements Runnable …`
    - `…`
    - `int threadPoolSize = Runtime.getRuntime().availableProcessors() * 2;`
    - `ExecutorService executor = Executors.newFixedThreadPool(threadPoolSize);`
    - `…`
    - `executor.execute(new Task(…));`
- You figure out how large you want your thread pool to be
    - You then create a new thread pool (called an ExecutorService in Java) and pass in that size; when you need something done, call execute()
- How many threads should you allocate
    - *Are your tasks computationally intensive?* => **one thread per core**
    - *Are your tasks mainly performing I/O?* => **lots of threads!**

# Producer-Consumer Example (I)

- The book makes use of a large data file (51 GB!) to provide a real world example of an application that can see performance gains with concurrency
  - The file contains the latest set of articles on Wikipedia
    - The programs operate on the first 100K pages contained within this file
  - I also discovered that Java would sometimes run out of memory when processing the XML file. To give the JVM more memory, I would execute the program with this command
    - env MAVEN_OPTS="-Xms2048m -Xmx4096m" mvn -q -e exec:java
  - This gives the program 2 to 4 GB of memory to use if needed

# Producer-Consumer Example (II)

- The first program, WordCount, is a single threaded version of the program
  - It shows how long it takes to parse the first 100K pages of the XML file
  - On my machine, it averaged **2.69 minutes** across several runs
- Nothing special about this program
  - The heavy lifting occurs in the `Pages.java` class, which does the work of parsing the XML file, looking for `<page>` tags
  - it extracts the title and text of each page and ignores all other elements in the XML file
    - When it has a complete page, it stops and returns it to the main routine, which then counts the words on that page
- I modified the program to *print the top 25 terms* that it finds in the first 100K pages and to *print out the time it took to parse the 100K pages in minutes*.

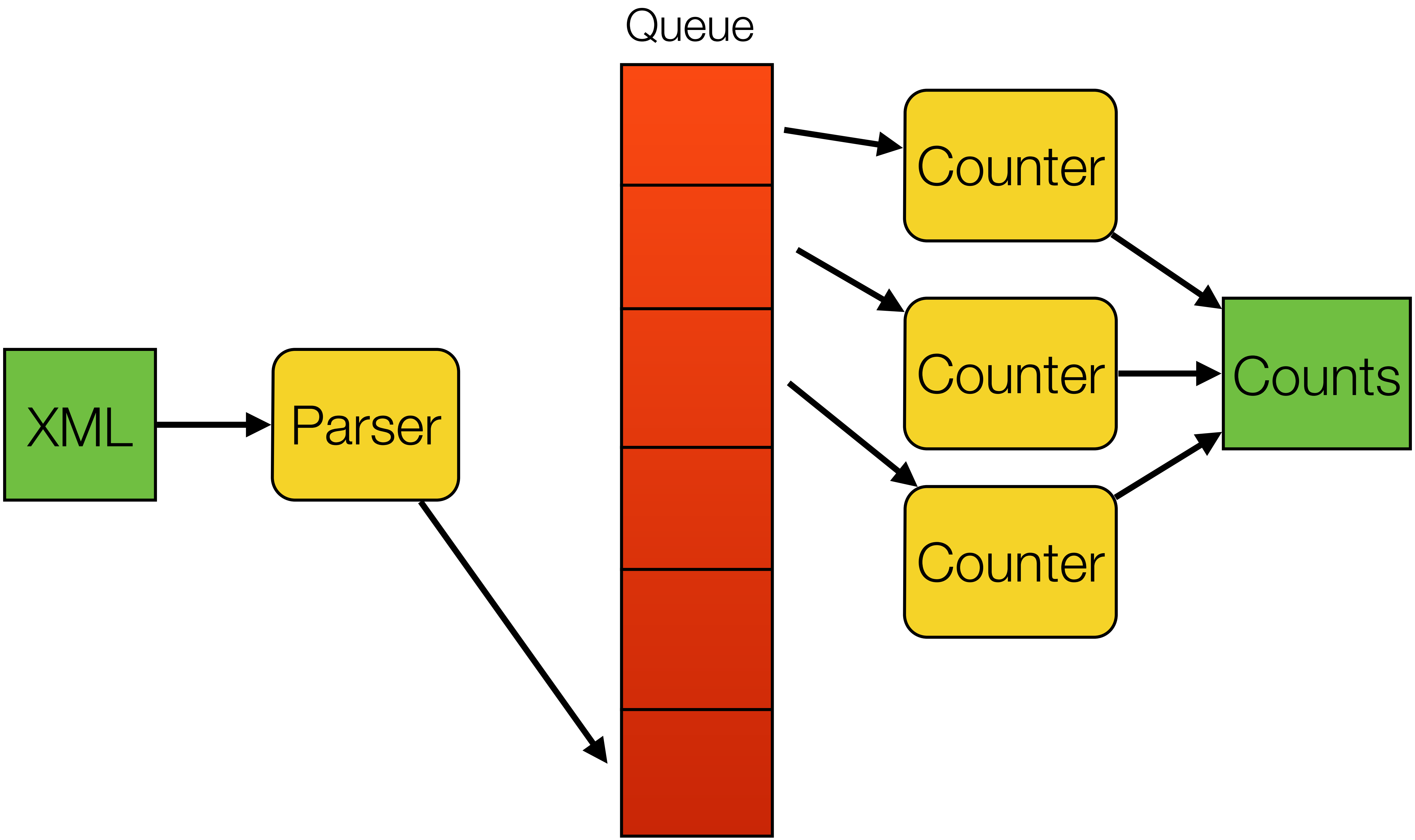
# Producer-Consumer Example (III)

- The first attempt to make this program concurrent adopts a typical producer/consumer architecture
  - The parser is in one thread, sticking pages into a bounded queue
    - 100 pages max
  - The consumer is in another thread pulling pages from the queue and counting them
    - A “poison pill” page is inserted into the queue when the parser is done
      - The consumer processes pages until it finds the poison pill and then it terminates
- The program now averages **2.45 minutes** per run; this is a (slight) improvement but not by much. `top` doesn’t report much in the way of concurrency, the CPU utilization is only 112% for most of the run; the queue provides some separation of work but not by much

# What's taking so long?

- What about queue size? Let's try increasing the queue's size from 100 to 1000? Maybe the producer got blocked on a full queue?
  - **No impact**, processing time is still **2.42 minutes** (on average)
- Let's determine if the producer is the problem
  - Let's modify the consumer to pull pages off the queue without counting them
    - It takes about 18.3 seconds to parse 100 thousands pages
- So, in order to speed this program up, we need to see if we can make the counting side (i.e. consumers) of the equation more concurrent

# The new approach



# Producer-Consumer Example (IV)

- We need to create multiple consumers and have them work together to pull pages off the queue and count the words in parallel
  - The problem here is that we will have a shared resource between the consumers => the hash table that stores the counts for each word
- We will protect the hash table with a static lock shared by all consumers
  - How did we do?
    - Two threads => **5 minutes;** ~160% CPU utilization
    - Three threads => **10 minutes**; ~180% CPU utilization
- There's too much contention for the lock that guards the hash table, we're seeing a slow down not a speed up!

# Producer-Consumer Example (V)

- Since synchronization is slowing us down, perhaps we can avoid explicit locking and use a hash table designed for concurrent access
  - `java.util.concurrent.ConcurrentHashMap` may do the trick!
- This data structure tries to allow parallel reads and writes on the hash table without explicit locking
  - To do this correctly, however, in the presence of multiple threads, we have to adopt a different style of use
    - When we have an update, we loop until one of these conditions is true
      - The map has not seen this word before and we set the count to 1
      - The map has seen this word and we successfully increment by 1
    - To do this, we use `putIfAbsent()` and `replace()` rather than `put()`

# Producer-Consumer Example (VI)

- The insertion code into the `ConcurrentHashMap` looks like this

```
private void countWord(String word) {
  while (true) {
    Integer currentCount = counts.get(word);
    if (currentCount == null) {
      if (counts.putIfAbsent(word, 1) == null) {
        break;
      }
    } else if (counts.replace(word, currentCount, currentCount + 1)) {
      break;
    }
  }
}
```

- The loop is there since at any point some other thread may update counts out from underneath us!
  - e.g. `currentCount == null`, but `putIfAbsent() != null`

# Producer-Consumer Example (VII)

- The results?
  - 2 consumers: **3.4 minutes**, 210% CPU utilization
  - 3 consumers: **2.86 minutes**, 330% CPU utilization
  - 4 consumers: **3 minutes**, 400% CPU utilization
  - 8 consumers: **4.87 minutes**, 520% CPU utilization
- We can get **some** speed up, but we *still run into contention issues*
  - We're seeing **livelock** in action, the threads are active (leading to higher CPU utilization) but they keep failing to update the hash table and so they are spinning around the loop, not making progress
- To get **faster** speedups, we need to ***reduce the contention close to zero***

# Producer-Consumer Example (VIII)

- The final solution is to have **each consumer thread maintain its own counts separate from all other threads**
  - We can use a regular `HashTable;` no need for locks since there will be no contention with this data structure; **one** `HashTable` **per Consumer**
  - When the consumer is done counting words for its pages, it then merges its counts into a shared `ConcurrentHashMap` in the same way as the previous solution
    - There might be some contention near the end of the run as each Consumer performs its merge, but for most of the run, there will be NO contention while counting

# Producer-Consumer Example (IX)

- The results?
  - 2 consumers: **77 SECONDS**, 224% CPU utilization
  - 3 consumers: **53.8 SECONDS**, 350% CPU utilization
  - 4 consumers: **42.6 SECONDS**, 500% CPU utilization
  - 8 consumers: **24.6 SECONDS**, 850% CPU utilization
- We don't see a strict linear speed-up with increased cores BUT
  - this solution (with 8 threads) is ~9x faster than the single threaded version!
  - this solution (with 8 threads) is ~10x faster than the previous version
- Not bad!

# There's more!

- We've covered most of the major classes of functionality hiding in java.util.concurrent
  - BUT there is still more to see
    - Futures
    - CountdownLatch and CyclicBarrier
    - ForkJoinPool (work stealing)
- We'll return to java.util.concurrent later in the semester
  - For now, we'll forge on and look at the functional approach to concurrency, the actor model, and more

# Summary

- We reviewed a wide range of functionality provided by the java.util.concurrent library
  - ReentrantLock
  - AtomicVariables
  - Thread Pools
  - Producer Consumer Example
- These constructs help to reduce the sting of programming with Threads and Locks and make it easier to write and reason about concurrent programs