Practical Concurrent and Parallel Programming 2

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Plan for today

- ”concurrent” and ”parallel”, what difference?
- Using threads for performance
- Processes, threads, tasks
- Atomically updating multiple fields
- Visibility of writes between threads
- java.util.concurrent.atomic.AtomicLong
- Safe publication
- Thread and stack confinement
- Immutability

Exercises

- Last week, problems with LearnIT, now fixed

- Hand-ins this week:
  - Must put yourself into a group, maybe 1-person
  - Your hand-in will automatically count for the group

- Last week's exercises:
  - Too easy?
  - Too hard?
  - Too time-consuming?
  - Too confusing?
  - Any particular problems?

Why "concurrent" and "parallel"?

- Informally both mean "at the same time"
- But some people distinguish
  - Concurrent: related to correctness
  - Parallel: related to performance
- Soccer (*fodbold*) analogy, by P. Panangaden
  - The referee (*dommer*) is concerned with concurrency: the soccer rules must be followed
  - The coach (*træner*) is concerned with parallelism: the best possible use of the team's 11 players

- This course is concerned with correctness as well as performance: concurrent and parallel

Recall: Creating a thread, Java 1-7

- A Thread **`t`** is created from a Runnable
- The thread's behavior is in the **`run`** method

NB!

```
final LongCounter lc = new LongCounter();
Thread t =
  new Thread(
    new Runnable() {
      public void run() {
        while (true)
          lc.increment();
      }
    }
  );
```

An anonymous inner class, and an instance of it

When started, the thread will do this: increment forever

New: Java 8 allows simpler syntax

- Java 8 anonymous functions may look better

```
final LongCounter lc = new LongCounter();
Thread t = new Thread(
    () ->
      {
        while (true)
          lc.increment();
      }
  );
```

An anonymous **`void`** function

Function body

- Use this if you want, else forget about it
- In Java 8, the **`final`** is sometimes not needed
  - If the captured variable (**`lc`**) is *effectively final*
  - That is, not assigned after initialization

Using threads for performance
Example: Count primes 2 3 5 7 11 …

- Count primes in 0…9999999

```
static long countSequential(int range) {
  long count = 0;
  final int from = 0, to = range;
  for (int i=from; i<to; i++)
    if (isPrime(i))
      count++;
  return count;
}
```

Result is 664579

TestCountPrimes.java

- Takes 6.4 sec to compute on 1 CPU core
- Why not use all my computer's 4 (x 2) cores?
  - Eg. use two threads t1 and t2 and divide the work: t1: 0…4999999 and t2: 5000000…9999999

Using two threads to count primes

```
final LongCounter lc = new LongCounter();
final int from1 = 0, to1 = perThread;
Thread t1 = new Thread(new Runnable() { public void run() {
  for (int i=from1; i<to1; i++)
    if (isPrime(i))
      lc.increment();
}});
final int from2 = perThread, to2 = perThread * 2;
Thread t2 = new Thread(new Runnable() { public void run() {
  for (int i=from2; i<to2; i++)
    if (isPrime(i))
      lc.increment();
}});
t1.start(); t2.start();
```

Same code twice, bad practice

- Takes 4.2 sec real time, so already faster
- Q: Why not just use a **`long count`** variable?
- Q: What if we want to use 10 threads?

Using N threads to count primes

```
final LongCounter lc = new LongCounter();
Thread[] threads = new Thread[threadCount];
for (int t=0; t<threadCount; t++) {
  final int from = perThread * t,
    to = (t+1==threadCount) ? range : perThread * (t+1);
  threads[t] = new Thread(new Runnable() { public void run()
    for (int i=from; i<to; i++)
      if (isPrime(i))
        lc.increment();
    }});
}
for (int t=0; t<threadCount; t++)
  threads[t].start();
```

Last thread has **to==range**

Thread processes segment [from,to)

- Takes 1.8 sec real time with **threadCount** 10
  - Approx 3.3 times faster than sequential solution
  - Q: Why not 4 times, or 10 times faster?
  - Q: What if we just put **to=perThread * (t+1)**?

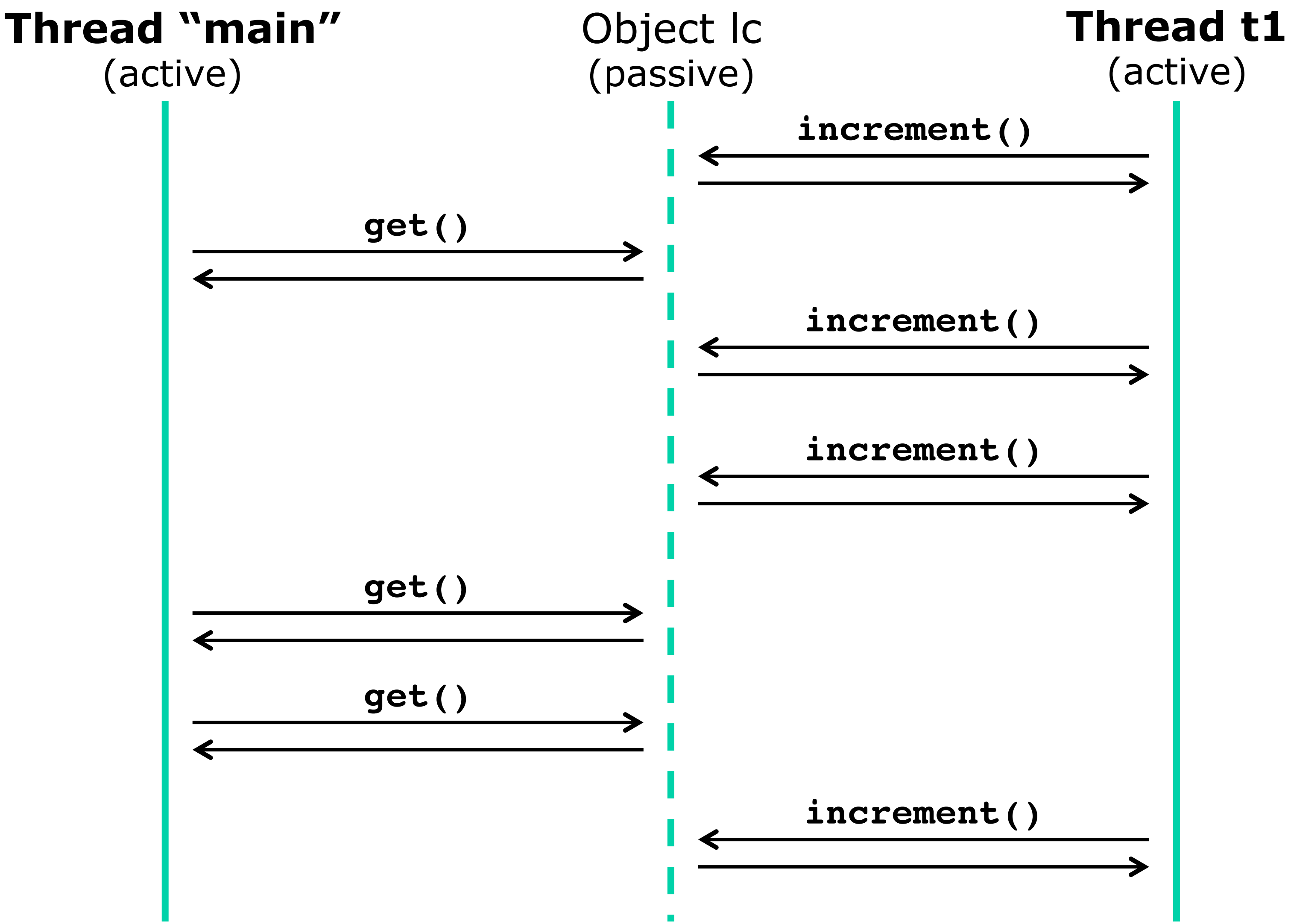
Reflections: threads for performance

- This code can be made better in many ways
  - Eg better distribution of work on the 10 threads
  - Eg less use of the synchronized LongCounter
- Proper performance measurements, **week 4**
- Very bad idea to use many (> 500) threads
  - Each thread takes much memory for the stack
  - Each thread slows down the garbage collector
- Better use *tasks* and Java “executors”, **week 5**
- More advice on scalability, **week 7**
- How to avoid locking, **week 11 and 12**
- (Prime numbers used as example for simplicity)

Processes, threads, and tasks

- An operating system **process** running Java is
  - a Java Virtual Machine that executes code
  - an object heap, managed by a garbage collector
  - one or more running Java threads
- A Java **thread**
  - has its own method call stack, takes much memory
  - shares the object heap with other threads
- A **task** (or future) (or actor)
  - does not have a call stack, so takes little memory
  - is run by an executor, using a thread pool, week 5

Java threads communicate through mutable shared state



Last week's LongCounter

Why synchronize just to read data?

```
class LongCounter {
  private long count = 0;
  public synchronized void increment() {
    count = count + 1;
  }
  public synchronized long get() {
    return count;
  } }
```

Why needed?

TestLongCounter.java

- The **`synchronized`** keyword has **two** effects:
  - **Mutual exclusion**: only one thread can hold a lock (execute a synchronized method or block) at a time
  - **Visibility** of memory writes: All writes by thread A before releasing a lock (exit synchr) are visible to thread B after acquiring the lock (enter synchr)

Visibility is really important

WARNING: Useless

```
class MutableInteger {
  private int value = 0;
  public void set(int value) { this.value = value; }
  public int get() { return value; }
}
```

TestMutableInteger.java

- Looks OK, no needed for synchronization?
- But thread t may loop forever in this scenario:

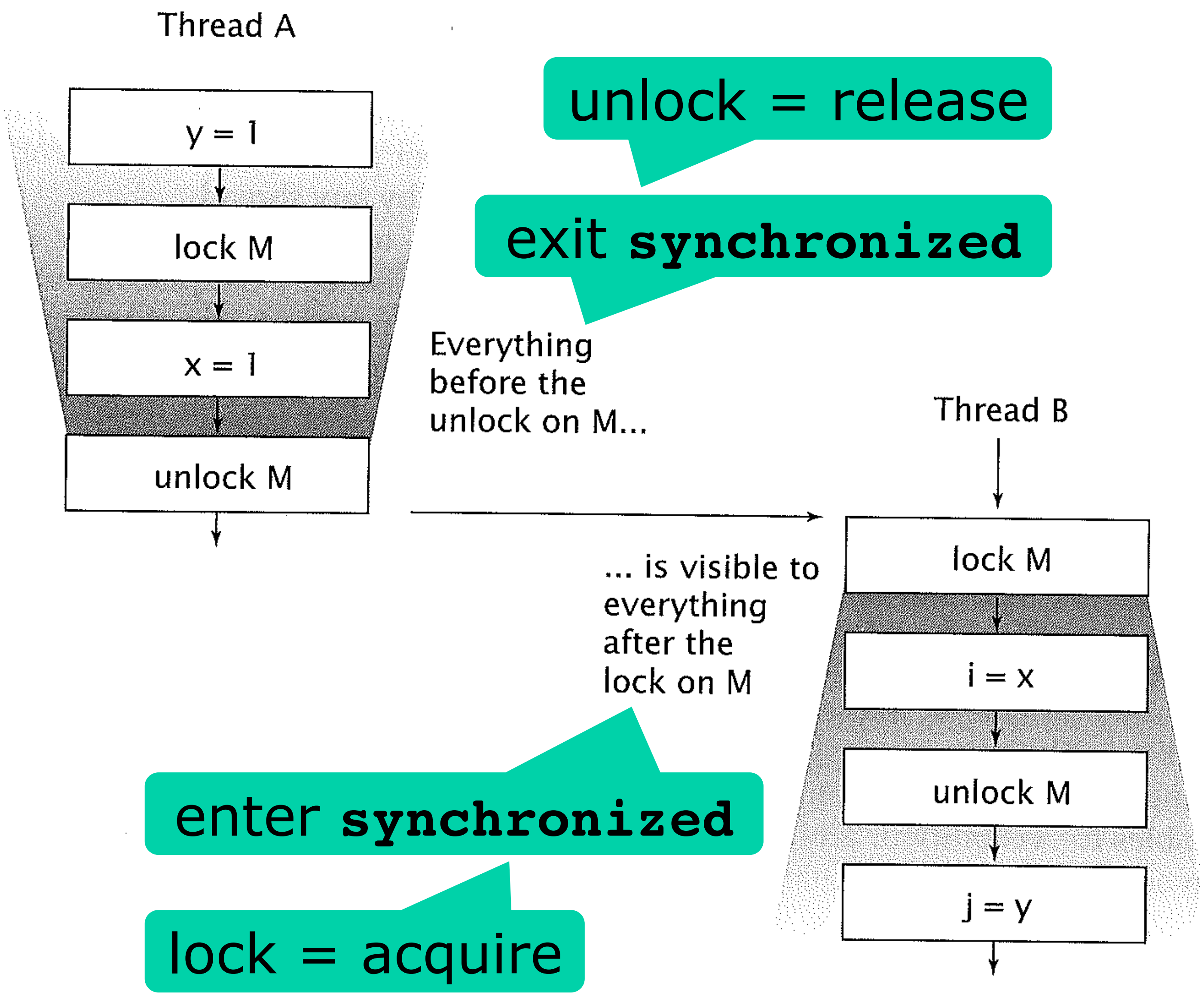
```
Thread t = new Thread(new Runnable() { public void run() {
  while (mi.get() == 0) { }
}});
t.start();
...
mi.set(42);
```

Loop while zero

This write by thread "main" may be forever invisible to thread t

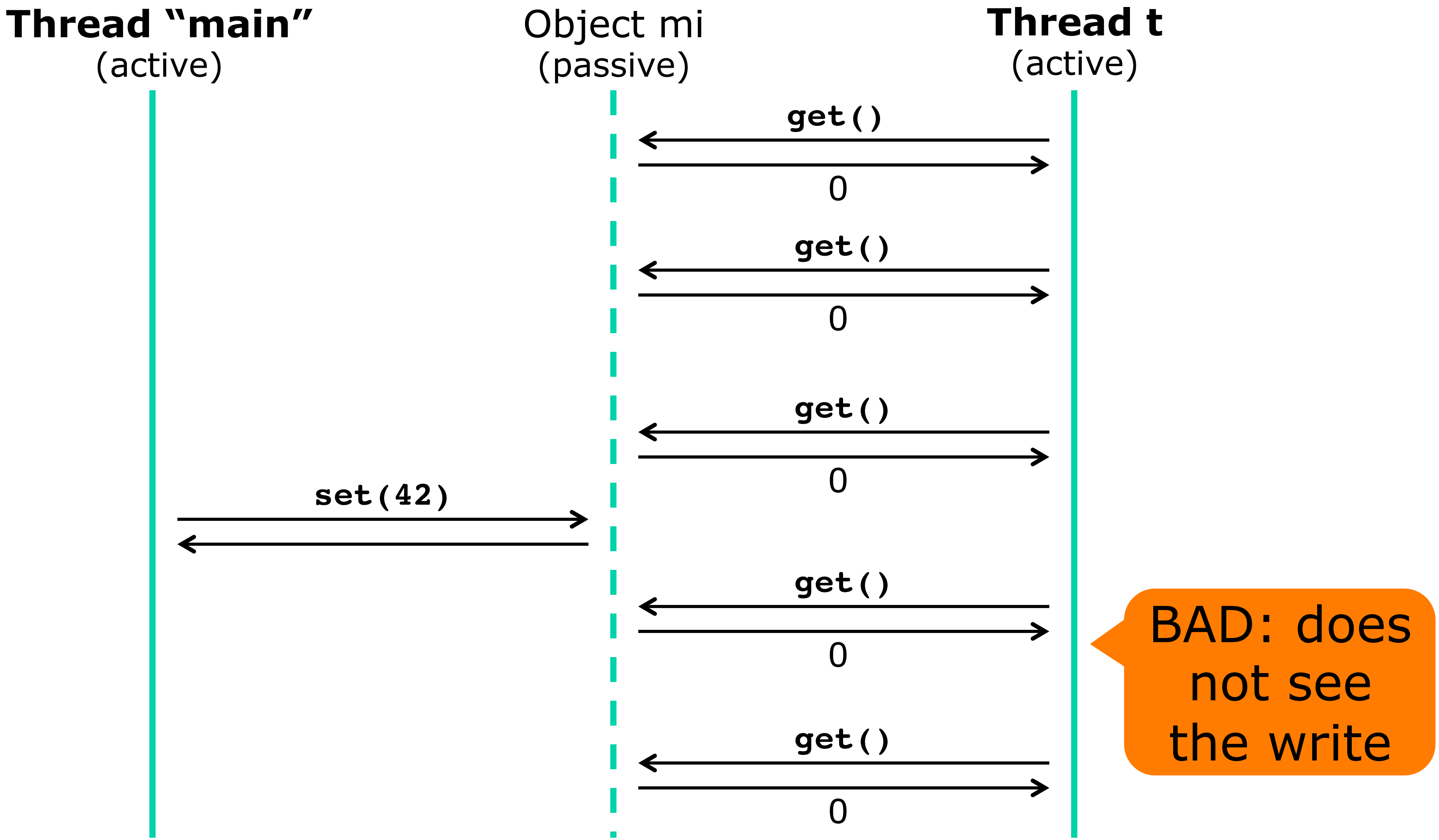
- Two possible fixes:
  - Add **synchronized** to methods **get** and **set**, OR
  - Add **volatile** to field **value**

Visibility by synchronization



Goetz p. 37

Communication through mutable shared state fails if no visibility



The volatile field modifier

- The **`volatile`** field modifier can be used to ensure visibility (but not mutual exclusion)

```
class MutableInteger {
  private volatile int value = 0;
  public void set(int value) { this.value = value; }
  public int get() { return value; }
}
```

OK

- All writes by thread A before writing a **`volatile`** field are visible to thread B when, and after, reading the **`volatile`** field
- Note: A single **`volatile`** write+read makes writes to all other fields visible also!
  - A bit mysterious, but a consequence of the implementation
  - This is Java semantics; C and C++ volatile is different

Goetz advice on volatile

Use volatile variables only when they simplify your synchronization policy; avoid it when verifying correctness would require subtle reasoning about visibility.

Locking can guarantee both visibility and atomicity; volatile variables can only guarantee visibility.

Goetz p. 38, 39

- Rule 1: Use **`synchronized`**
- Rule 2: If circumstances are right, and you are an expert, maybe use **`volatile`** instead
- Rule 3: There are few experts

That was Java.
What about C# and .NET?

- C# Language Specification 17.3.4 *Volatile Fields*
- CLI Ecma-335 standard section I.12.6.7:
  - "A volatile write has *release* semantics ... the write is guaranteed to happen *after* any memory references *prior* to the write instruction in the CIL instruction sequence"
  - "volatile read has *acquire* semantics ... the read is guaranteed to occur *prior* to any references to memory that occur *after* the read instruction in the CIL instruction sequence"

- So same as Java: volatile write+read has the visibility effect of lock release+acquire
  - (but not the mutual exclusion effect, of course)

Ways to ensure visibility

- Unlocking followed by locking the same lock
- Writing a volatile field and then reading it
- Calling one method on a concurrent collection and another method on same coll.
  - java.util.concurrent.*
- Calling one method on an atomic variable and then another method on same variable
  - java.util.concurrent.atomic.*
- Finishing a constructor that initializes final or volatile fields
- Calling **`t.start()`** before anything in thread **`t`**
- Anything in thread **`t`** before **`t.join()`** returns

(Java Language Specification 8 §17.4, and the Javadoc for concurrent collection classes etc, give the full and rather complicated details; week 11)

Goetz examples use servlets

```
public class StatelessFactorizer implements Servlet {
  public void service(ServletRequest req, ServletResponse resp) {
    BigInteger i = extractFromRequest(req);
    BigInteger[] factors = factor(i);
    encodeIntoResponse(resp, factors);
  }
}
```

Goetz p. 19

- Because a webserver is naturally concurrent
  - So servlets should be thread-safe
- We use similar, simpler examples:

```
class StatelessFactorizer implements Factorizer {
  public long[] getFactors(long p) {
    long[] factors = PrimeFactors.compute(p);
    return factors;
  }
}
```

TestFactorizer.java

A "server" for computing prime factors 2 3 5 7 11 … of a number

- Could replace the example by this

```
interface Factorizer {
  public long[] getFactors(long p);
  public long getCount();
}
```

- Call the server from multiple threads:

```
final Factorizer factorizer = new StatelessFactorizer();
for (int t=0; t<threadCount; t++) {
  threads[t] = new Thread(new Runnable() { public void run()
    for (int i=2; i<range; i++) {
      long[] result = factorizer.getFactors(i);
    }
}});
```

Stateless objects are thread-safe

```
class StatelessFactorizer implements Factorizer {
  public long[] getFactors(long p) {
    long[] factors = PrimeFactors.compute(p);
    return factors;
  }
  public long getCount() { return 0; }
}
```

Like Goetz p. 18

- Local variables are never shared btw threads
  - two getFactors calls can execute at the same time

Bad attempt to count calls

```
class UnsafeCountingFactorizer implements Factorizer {
  private long count = 0;
  public long[] getFactors(long p) {
    long[] factors = PrimeFactors.compute(p);
    count++;
    return factors;
  }
  public long getCount() { return count; }
}
```

Like Goetz p. 19

- Not thread-safe
- Q: Why?
- Q: How could we repair the code?

Thread-safe server counting calls

```
class CountingFactorizer implements Factorizer {
  private final AtomicLong count = new AtomicLong(0);
  public long[] getFactors(long p) {
    long[] factors = PrimeFactors.compute(p);
    count.incrementAndGet();
    return factors;
  }
  public long getCount() { return count.get(); }
}
```

Like Goetz p. 23

- java.util.concurrent.atomic.AtomicLong supports atomic thread-safe arithmetics
- Similar to an improved LongCounter class

Bad attempt to cache last factorization

```
class TooSynchronizedCachingFactorizer implements Factorizer
  private long lastNumber = 1;
  private long[] lastFactors = new long[0];
  // Invariant: product(lastFactors) == lastNumber

  public synchronized long[] getFactors(long p) {
    if (p == lastNumber)
      return lastFactors.clone();
    else {
      long[] factors = PrimeFactors.compute(p);
      lastNumber = p;
      lastFactors = factors;
      return factors;
} } }
```

cache

Like Goetz p. 26

Without synchronized the two fields could be written by different threads

- Bad performance: no parallelism at all
- Q: Why? Q: What is an invariant?

Atomic operations

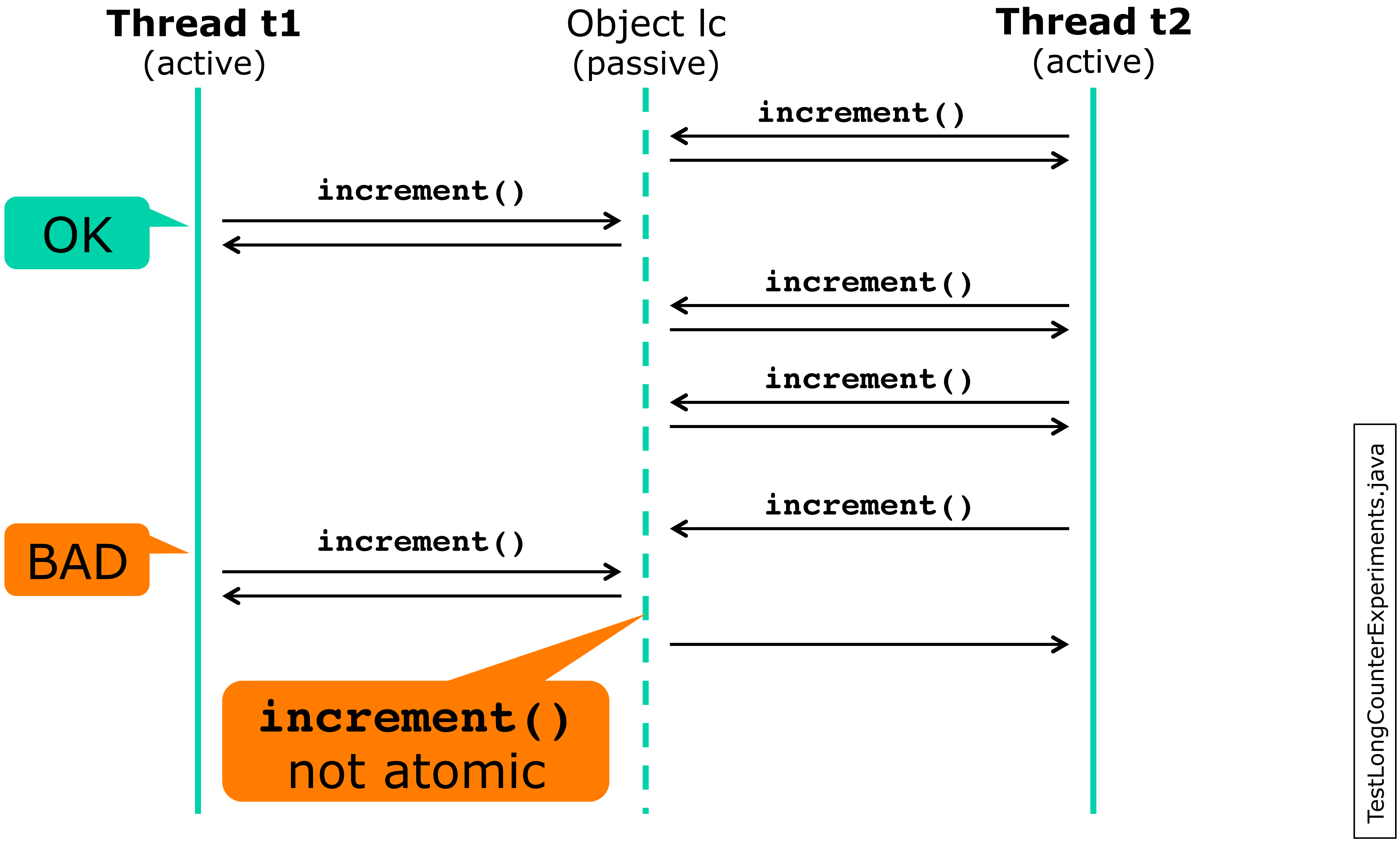
- We want to *atomically* update **`lastNumber`** and **`lastFactors`**

Operations A and B are *atomic* with respect to each other if, from the perspective of a thread executing A, when another thread executes B, either all of B has executed or none of it has.

An *atomic operation* is one that is atomic with respect to all operations, including itself, that operate on the same state.

Goetz p. 22, 25

Lack of atomicity: overlapping reads and writes



Atomic update without excess locking

```
class CachingFactorizer implements Factorizer {
  private long lastNumber = 0;
  private long[] lastFactors = new long[0];
  public long[] getFactors(long p) {
    long[] factors = null;
    synchronized (this) {
      if (p == lastNumber)
        factors = lastFactors.clone();
    }
    if (factors == null) {
      factors = PrimeFactors.compute(p);
      synchronized (this) {
        lastNumber = p;
        lastFactors = factors.clone();
      }
    }
    return factors;
} }
```

Atomic test-then-act

Atomic write of both fields

Like Goetz p. 31

- Correct but subtle

Using locks for atomicity

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. Then the variable is *guarded* by that lock.

For every invariant that involves more than one variable, *all* the variables involved in that invariant must be guarded by the *same* lock.

Goetz p. 28, 29

- Common mis-reading and mis-reasoning:
  - The *purpose* of **`synchronized`** is to get atomicity
  - So **`synchronized`** roughly means "**`atomic`**"
  - True only if **all other** accesses are **`synchronized`**!!!

Wrapping the state in an immutable object

```
class OneValueCache {
  private final long lastNumber;
  private final long[] lastFactors;
  public OneValueCache(long p, long[] factors) {
    this.lastNumber = p;
    this.lastFactors = factors.clone();
  }
  public long[] getFactors(long p) {
    if (lastFactors == null || lastNumber != p)
      return null;
    else
      return lastFactors.clone();
  }
}
```

NB!

Like Goetz p. 49

Nothing can change between test and return

Q: Why?

- Immutable, so automatically thread-safe

Make the state a single field, referring to an immutable object

NB!

```
class VolatileCachingFactorizer implements Factorizer {
  private volatile OneValueCache cache
    = new OneValueCache(0, null);
  public long[] getFactors(long p) {
    long[] factors = cache.getFactors(p);
    if (factors == null) {
      factors = PrimeFactors.compute(p);
      cache = new OneValueCache(p, factors);
    }
    return factors;
  }
}
```

Single-field state, atomic assignment

Atomic assignment

Like Goetz p. 50

- Only one mutable field, atomic assignment
- Easy to implement, easy to see it is correct
- Drawback: cost of creating cache objects
  - Not a problem with modern garbage collectors

Immutability

- OOP: An object has state, held by its fields
  - Fields should be **`private`** for encapsulation
  - It is common to define getters and setters
- But mutable state causes lots of problems
  - So make fields **`final`** and remove the setters

Immutable objects are always thread-safe.

An object is *immutable* if:
- Its state cannot be modified after construction
- All its fields are **`final`**
- It is properly constructed (**`this`** does not escape)

Goetz p. 46, 47

Bloch: Effective Java, item 15

Item 15: Minimize mutability

An immutable class is simply a class whose instances cannot be modified. All of the information contained in each instance is provided when it is created and is fixed for the lifetime of the object. The Java platform libraries contain many immutable classes, including `String`, the boxed primitive classes, and `BigInteger` and `BigDecimal`. There are many good reasons for this: Immutable classes are easier to design, implement, and use than mutable classes. They are less prone to error and are more secure.

To make a class immutable, follow these five rules:

1. **Don't provide any methods that modify the object's state** (known as *mutators*).
2. **Ensure that the class can't be extended.** This prevents careless or malicious subclasses from compromising the immutable behavior of the class by behaving as if the object's state has changed. Preventing subclassing is generally ac- c d
3. M forced by the system. Also, it is necessary to ensure correct behavior if a reference to a newly created instance is passed from one thread to another without synchronization, as spelled out in the *memory model* [JLS, 17.5; Goetz06 16].
4. **Make all fields private.** This prevents clients from obtaining access to muta-

Classes should be immutable unless there's a very good reason to make them mutable. Immutable classes provide many advantages, and their only disadvan-

Josh Bloch designed the Java collection classes

A serious Java (or C#) developer should own and use this book

Bloch p. 73

Safe publication: visibility

- The **`final`** field modifier has two effects
  - **Un-updatability** can be checked by the compiler
  - **Visibility** from other threads of the fields' values after the OneValueCache constructor returns
- So **`final`** has visibility effect like **`volatile`**
- Without **`final`** or synchronization, another thread may not see the given field values

- That was Java. What about C#/.NET?
  - No visibility effect of **`readonly`** field modifier
  - So must be ensured by volatile or synchronization
  - Seems a little dangerous?

Avoiding shared mutable state

- Avoiding sharing between threads:
  - Ad hoc thread confinement: Swing GUI components are accessed only by the GUI thread
  - Thread confinement via ThreadLocal objects
  - Stack confinement: Local variables are never shared between threads
- Avoiding mutable state:
  - Make fields final as far as possible
  - Replace multiple mutable fields by a single mutable reference to an immutable object

Why .clone() in the factorizers?

```
public long[] getFactors(long p) {
  ...
  factors = lastFactors.clone();
  ...
  lastFactors = factors.clone();
  ...
}
```

- Because Java array elements are mutable
- So unsafe to share an array with anybody
- Must defensively clone the array when passing a reference to some other part of the program
- This is a problem in sequential code too, only much worse in concurrent code
  – Minimize Mutability! More about this next week ...

This week

- Reading
  - Goetz et al chapters 2 and 3
  - Bloch item 15
- Exercises
  - Mandatory hand-in Thursday at 23:55
  - Goals: Understand and use multiple threads for performance; visibility of concurrent writes; atomicity by locking; advantages of immutability
- Reading for next week
  - Goetz chapters 4 and 5