Practical Concurrent and Parallel Programming 2

Riko Jacob
IT University of Copenhagen

Friday 2018-09-07

Exercises

- There are 13 sets of weekly exercises
- At least 11 can be handed in towards the exam
- Hand in the solutions through LearnIT
- You can work in teams of 1,2 or 3 students
- The teaching assistants provide joint feedback
- Hand-ins: ≥6 must be submitted, ≥5 approved
  - otherwise you cannot take the course examination
  - failing to get 5 approved costs an exam attempt (!!)
- Exercise may be approved even if not fully solved
  - It is possible to resubmit
  - Make your best effort: two serious attempts=one solved
  - What is important is that **you learn**

Standard weekly plan

- Lectures Fridays in Auditorium 1
  Corresponding exercise assignment is ready
- Exercise Lab: Wednesdays, 2A54
  - Two slots: 12-14 and 14-16
  - First 15 minutes: Announcements wrt exercises
- Exercise hand-in: 6.5 days after lecture
  - That is, the following Thursday at 23:55
  - Feedback by 14 days after lecture
  - Retry-hand-in: 20.5 days after lecture
- Until December 8, Exam hand-in Dec 12
  (except fall break, Week 41, 16-20 Oct)

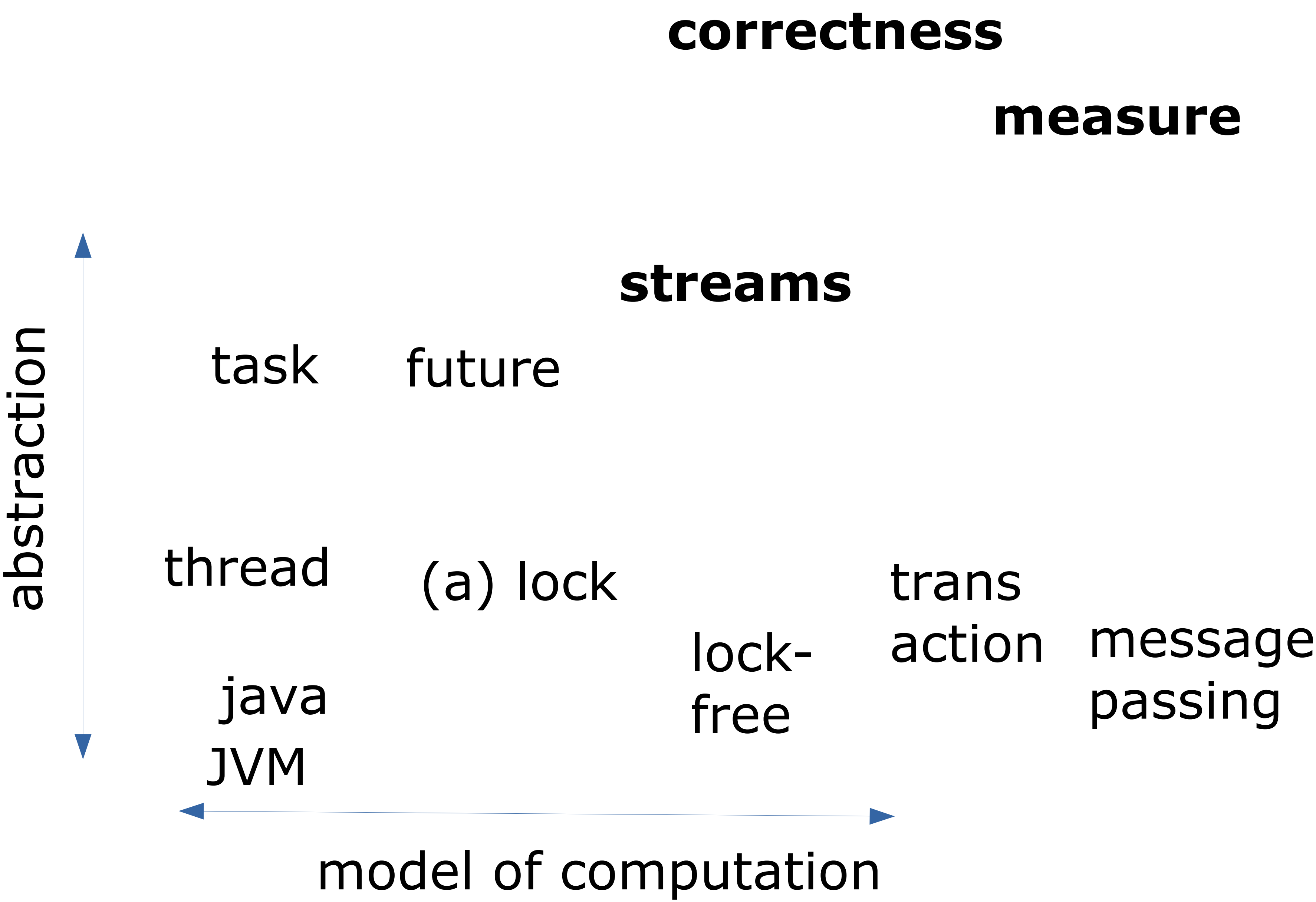
Exercises

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

Plan for today

- Threads for performance
- Primitive atomic operations: AtomicLong, ...
- Immutability, **`final`**, and safe publication
- Java monitor pattern
- Standard collection classes not thread-safe
- FutureTask<T> and asynchronous execution
- Building a scalable result cache

Based on slides by
Peter Sestoft


correctness
measure
streams
task
future
thread
(a) lock
trans
action
lock-
free
message
passing
java
JVM
abstraction
model of computation

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

TestCountPrimes.java

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

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(() -> {
    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 3**
- Use Java 8 parallel streams instead, **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
- Use *tasks* and Java “executors”, **week 5**
- More advice on scalability, **week 7**
- How to avoid locking, **week 10 and 11**

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

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

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:

```
for (int t=0; t<threadCount; t++) {
  threads[t] =
    new Thread(() -> {
      for (int i=2; i<range; i++) {
        long[] result = factorizer.getFactors(i);
      }
    });
  threads[t].start();
}
```

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 (**`p`**, **`factors`**) are never shared between 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 make it thread-safe?

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 a thread-safe LongCounter class

Caching computed results

- Fibonacci numbers:
  F(0) = F(1) = 1
  F(N) = F(N-1) + F(N-2) for N>1
- F(N) is exponential
- Naïve recursive implementation:
  F(N) operations
- Iterative / dynamic programming with memoization: O(N) operations
- Serial java 8:
  HashMap.computeIfAbsent(...)

Bad attempt to cache last factorization

```
class TooSynchrCachingFactorizer implements Factorizer {
  private long lastNumber = 1;
  private long[] lastFactors = new long[] { 1 };
  // 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?

Atomic operations

- We want to *atomically* update *both* **`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

Atomic update without excess locking

```
class CachingFactorizer implements Factorizer {
  private long lastNumber = 6;
  private long[] lastFactors = new long[] { 2,3 };
  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

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`**!!!

Wrong

Alternative: Wrap 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();
  }
}
```

The fields cannot change between test and return

Like Goetz p. 49

- Immutable, so automatically thread-safe

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

```
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 update

Like Goetz p. 50

- Only one mutable field, atomic update
- Easy to implement, easy to see it is correct
- Allocates many OneValueCache objects: Bad?
  - 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

- Immutable design:
  - Each object has one state
  - Each state an object

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
  - **Non-updatability** can be checked by the compiler
  - **Visibility** from other threads of the fields' values after the 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 locking or MemoryBarrier
  - Seems a little dangerous?

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 just anybody
- Must *defensively clone* the array when passing a reference to other parts of the program
- This is a problem in sequential code too, but much worse in concurrent code
  - Minimize Mutability!
- PCPP is an advert for functional programming

The classic collection classes are not threadsafe

```
final Collection<Integer> coll = new HashSet<Integer>();
final int itemCount = 100_000;
Thread addEven = new Thread(new Runnable() { public void run() {
  for (int i=0; i<itemCount; i++)
    coll.add(2 * i);
}});
Thread addOdd = new Thread(new Runnable() { public void run() {
  for (int i=0; i<itemCount; i++)
    coll.add(2 * i + 1);
}});
```

TestCollection.java

- May give wrong results or obscure exceptions:

```
There are 169563 items, should be 200000
```

```
"Thread-0" ClassCastException: java.util.HashMap$Node cannot be
cast to java.util.HashMap$TreeNode
```

- Wrap as synchronized coll. for thread safety

```
final Collection<Integer> coll
  = Collections.synchronizedCollection(new HashSet<Integer>());
```

Collections in a concurrent context

- Preferably use a modern concurrent collection class from java.util.concurrent.*
  - Operations **`get`**, **`put`**, **`remove`** … are thread-safe
  - But iterators and **`for`** are only *weakly consistent:*
    - they may proceed concurrently with other operations
    - they will never throw `ConcurrentModificationException`
    - they are guaranteed to traverse elements as they existed upon construction exactly once, and may (but are not guaranteed to) reflect any modifications subsequent to construction.

Java 8 class library documentation

- Or else wrap collection as synchronized
- Or synchronize accesses yourself
- Or make a thread-local copy of the collection and iterate over that

Callable<T> versus Runnable

- A Runnable is one method that returns nothing

```
public interface Runnable {
  public void run();
}
```

unit -> unit

- A java.util.concurrent.Callable<T> returns a T:

```
public interface Callable<T> {
  public T call() throws Exception;
}
```

unit -> T

```
Callable<String> getWiki = new Callable<String>() {
  public String call() throws Exception {
    return getContents("http://www.wikipedia.org/", 10);
}};
// Call the Callable, block till it returns:
try { String homepage = getWiki.call(); ... }
catch (Exception exn) { throw new RuntimeException(exn); }
```

TestCallable.java

Synchronous FutureTask<T>

```
Callable<String> getWiki = new Callable<String>() {
  public String call() throws Exception {
    return getContents("http://www.wikipedia.org/", 10);
}};
FutureTask<String> fut = new FutureTask<String>(getWiki);
fut.run();
try {
  String homepage = fut.get();
  System.out.println(homepage);
}
catch (Exception exn) { throw new RuntimeException(exn); }
```

Run **call()** on "main" thread

Get result of **call()**

- A FutureTask<T>
  - Produces a T
  - Is created from a Callable<T>
  - Above we run it synchronously on the main thread
  - More useful to run asynchronously on other thread

Similar to .NET System.Threading.Tasks.Task<T>

Asynchronous FutureTask<T>

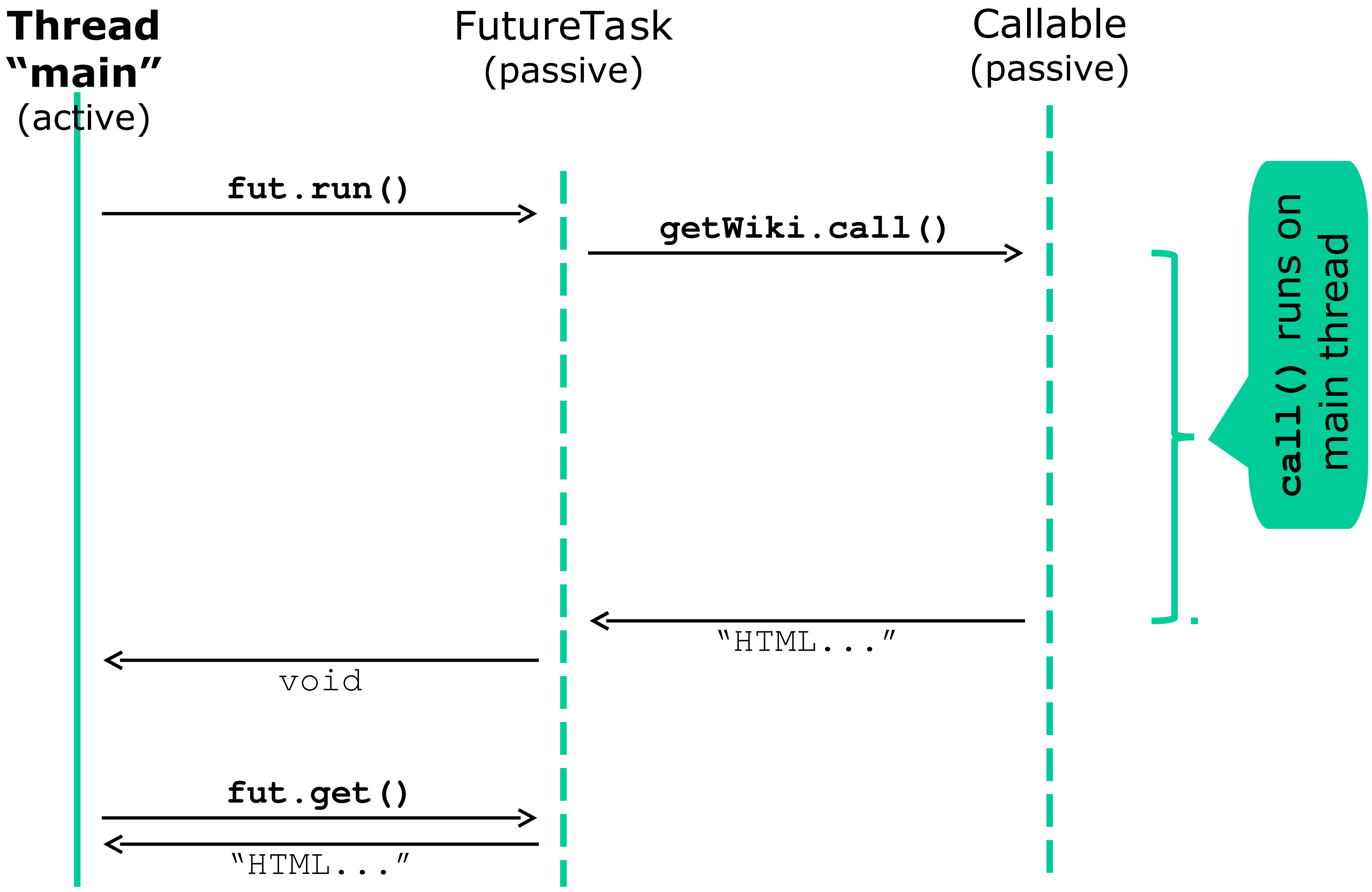
```
Callable<String> getWiki = new Callable<String>() {
  public String call() throws Exception {
    return getContents("http://www.wikipedia.org/", 10);
}};
FutureTask<String> fut = new FutureTask<String>(getWiki);
Thread t = new Thread(fut);
t.start();
try {
  String homepage = fut.get();
  System.out.println(homepage);
}
catch (Exception exn) { throw new RuntimeException(exn); }
```

Create and start thread running **`call()`**

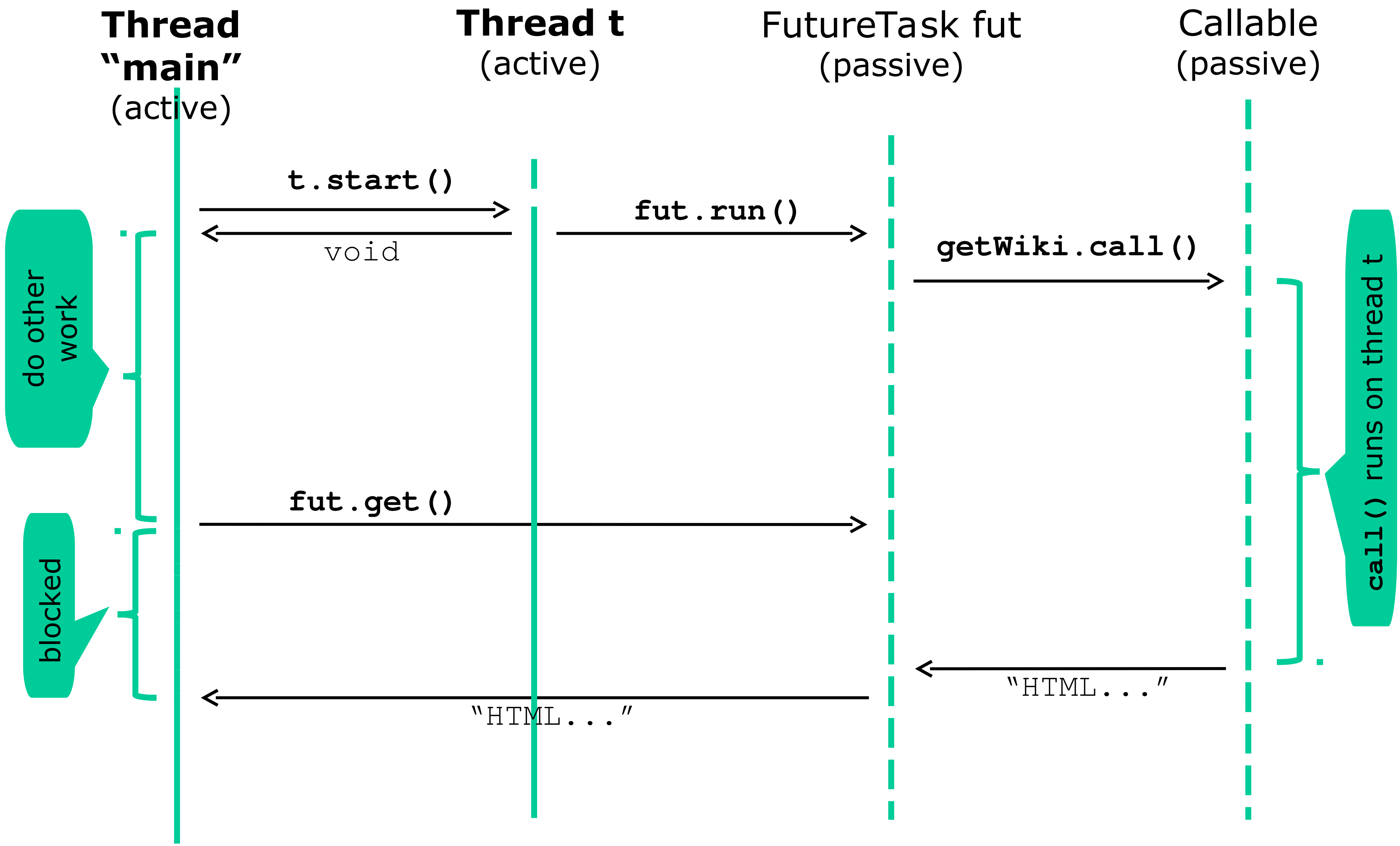
Block until **`call()`** completes

- The "main" thread can do other work between **`t.start()`** and **`fut.get()`**
- FutureTask can also be run as a *task*, week 5

Synchronous FutureTask



Asynchronous FutureTask



Those @$%&!!! checked exceptions

- Our exception handling is simple but gross:

If **call()** throws **exn**, then **get()** throws ExecutionException(**exn**)

… and then we further wrap a RuntimeException(…) around that

```
try { String homepage = fut.get(); ... }
catch (Exception exn) { throw new RuntimeException(exn); }
```

- Goetz has a better, more complex, approach:

```
try { String homepage = fut.get(); ... }
catch (ExecutionException exn) {
  Throwable cause = exn.getCause();
  if (cause instanceof IOException)
    throw (IOException)cause;
  else
    throw launderThrowable(cause);
}
```

Rethrow "expected" **call()** exceptions

Turn others into unchecked exceptions

Like Goetz p. 97

Goetz's launderThrowable method

unchecked — checked

```
public static RuntimeException launderThrowable(Throwable t) {
  if (t instanceof RuntimeException)
    return (RuntimeException) t;
  else if (t instanceof Error)
    throw (Error) t;
  else
    throw new IllegalStateException("Not unchecked", t);
}
```

Goetz p. 98

- Make a checked exception into an unchecked
  - without adding unreasonable layers of wrapping
  - cannot just **`throw cause;`** in previous slide's code
- Mostly an administrative mess
  - caused by the Java's "checked exceptions" design
  - thus not a problem in C#/.NET

Goetz's scalable result cache

- Wrapping a computation so that it caches results and reuses them
  - Example: Given URL, computation fetches webpage
  - If URL is requested again, cache returns webpage

- Versions of Goetz's result cache ("Memoizer")
  - M1: lock-based, not scalable
  - M2: ConcurrentMap, large risk of computing twice
  - M3: use FutureTask, small risk of computing twice
  - M4: use putIfAbsent, no risk of computing twice
  - M5: use computeIfAbsent (Java 8), no risk of ...
    - See also Exercise 2.4.7

Goetz's scalable result cache

Goetz p. 103

- Interface representing functions from A to V

```
interface Computable <A, V> {
  V compute(A arg) throws InterruptedException;
}
```

A -> V

- Example 1: Our prime factorizer

TestCache.java

```
class Factorizer implements Computable<Long, long[]> {
  public long[] compute(Long wrappedP) {
    long p = wrappedP;
    ...
} }
```

- Example 2: Fetching a web page

```
class FetchWebpage implements Computable<String, String> {
  public String compute(String url) {
    ... create Http connection, fetch webpage ...
} }
```

Thread-safe but non-scalable cache

M1

```
class Memoizer1<A, V> implements Computable<A, V> {
  private final Map<A, V> cache = new HashMap<A, V>();
  private final Computable<A, V> c;

  public Memoizer1(Computable<A, V> c) { this.c = c; }

  public synchronized V compute(A arg) throws InterruptedEx... {
    V result = cache.get(arg);
    if (result == null) {
      result = c.compute(arg);
      cache.put(arg, result);
    }
    return result;
  }
}
```

If not in cache, compute and put

Goetz p. 103

```
Computable<Long, long[]> factorizer = new Factorizer(),
  cachingFactorizer = new Memoizer1<Long,long[]>(factorizer);
long[] factors = cachingFactorizer.compute(7182763656381322L);
```

- Q: Why not scalable?
- Q: Would it work to wrap as synchronizedMap?

Thread-safe scalable cache, using concurrent hashmap

M2

```
class Memoizer2<A, V> implements Computable<A, V> {
  private final Map<A, V> cache = new ConcurrentHashMap<A, V>();
  private final Computable<A, V> c;

  public Memoizer2(Computable<A, V> c) { this.c = c; }

  public V compute(A arg) throws InterruptedException {
    V result = cache.get(arg);
    if (result == null) {
      result = c.compute(arg);
      cache.put(arg, result);
    }
    return result;
  }
}
```

Goetz p. 105

- But large risk of computing same thing twice
  - Argument put in cache only after computing result
    - so cache may be updated long after **compute(arg)** call

How Memoizer2 can duplicate work

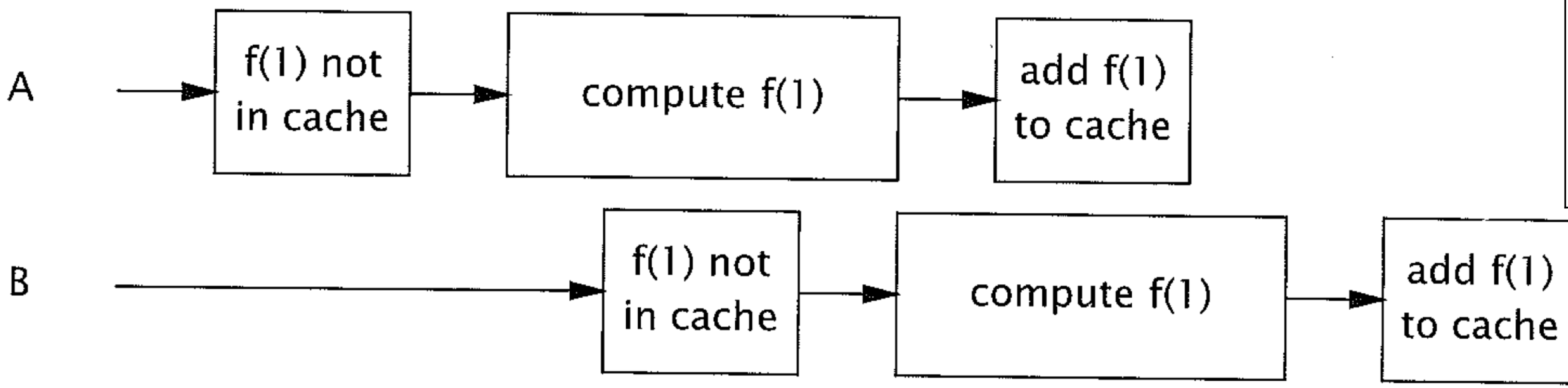


FIGURE 5.3. Two threads computing the same value when using `Memoizer2`.

Goetz p. 105

- Better approach, Memoizer3:
  - Create a FutureTask for **`arg`**
  - Add the FutureTask to cache immediately at **`arg`**
  - Run the future on the calling thread
  - Return **`fut.get()`**

Thread-safe scalable cache using FutureTask<V>, v. 3

M3

Goetz p. 106

```
class Memoizer3<A, V> implements Computable<A, V> {
  private final Map<A, Future<V>> cache
    = new ConcurrentHashMap<A, Future<V>>();
  private final Computable<A, V> c;

  public V compute(final A arg) throws InterruptedException {
    Future<V> f = cache.get(arg);
    if (f == null) {
      Callable<V> eval = new Callable<V>() {
         public V call() throws InterruptedException {
           return c.compute(arg);
      }};
      FutureTask<V> ft = new FutureTask<V>(eval);
      cache.put(arg, ft);
      f = ft;
      ft.run();
    }
    try { return f.get(); }
    catch (ExecutionException e) { throw launderThrowable(...); }

  }
```

If arg not in cache …

… make future, add to cache …

… run it on calling thread

Block until completed

Memoizer3 can still duplicate work

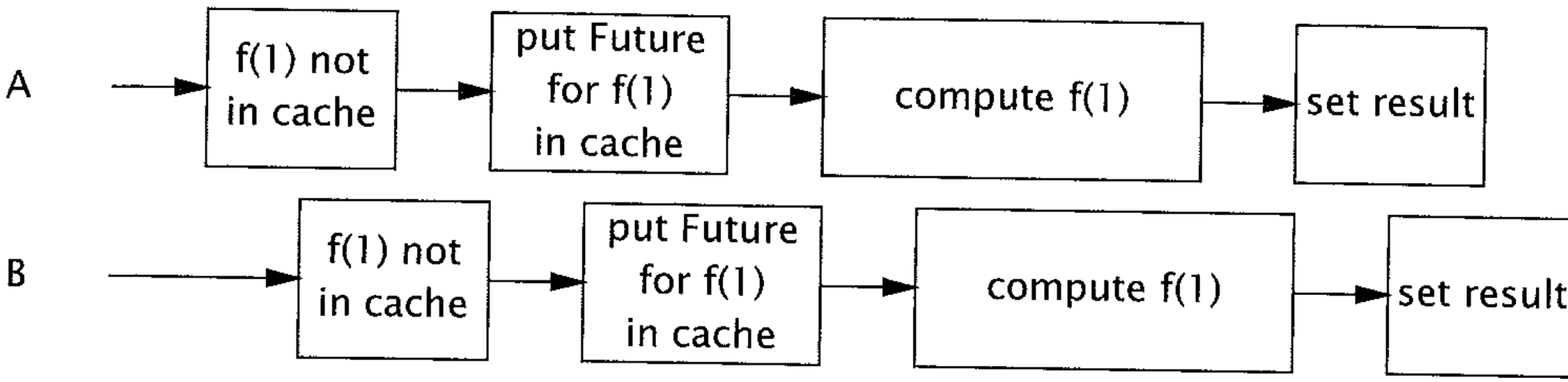


FIGURE 5.4. Unlucky timing that could cause `Memoizer3` to calculate the same value twice.

Goetz p. 107

- Better approach, Memoizer4:
  - Fast initial check for **`arg`** cache
  - If not, create a future for the computation
  - Atomic put-if-absent may add future to cache
  - Run the future on the calling thread
  - Return **`fut.get()`**

Thread-safe scalable cache using FutureTask<V>, v. 4

M4

TestCache.java

```
class Memoizer4<A, V> implements Computable<A, V> {
  private final Map<A, Future<V>> cache
    = new ConcurrentHashMap<A, Future<V>>();
  private final Computable<A, V> c;
  public V compute(final A arg) throws InterruptedException {
    Future<V> f = cache.get(arg);
    if (f == null) {
      Callable<V> eval = new Callable<V>() {
         public V call() throws InterruptedException {
           return c.compute(arg);
      }};
      FutureTask<V> ft = new FutureTask<V>(eval);
      f = cache.putIfAbsent(arg, ft);
      if (f == null) {
        f = ft; ft.run();
      }
    }
    try { return f.get(); }
    catch (ExecutionException e) { throw launderThrowable(...); }

  }
```

Fast test: If arg not in cache ...

... make future

... atomic put-if-absent

... run on calling thread if not added to cache before

The technique used in Memoizer4

- Suggestion by Bloch item 69:
  - Make a fast (non-atomic) test for arg in cache
  - If not there, create a future object
  - Then atomically put-if-absent (arg, future)
    - If the arg was added in the meantime, do not add
    - Otherwise, add (arg, future) and run the future
- May wastefully create a future, but only rarely
  - The garbage collector will remove it
- Java 8 has computeIfAbsent, can avoid the two-stage test (see next slide)

Thread-safe scalable cache using FutureTask<V>, v. 5 (Java 8)

M5

TestCache.java

```
class Memoizer5<A, V> implements Computable<A, V> {
  private final Map<A, Future<V>> cache
    = new ConcurrentHashMap<A, Future<V>>();
  private final Computable<A, V> c;
  public V compute(final A arg) throws InterruptedException {
    final AtomicReference<FutureTask<V>> ftr = new ...();
    Future<V> f = cache.computeIfAbsent(arg, (A argv) -> {
        Callable<V> eval = new Callable<V>() {
            public V call() throws InterruptedException {
              return c.compute(argv);
            }};
        ftr.set(new FutureTask<V>(eval));
        return ftr.get();
      });
    if (ftr.get() != null)
      ftr.get().run();
    try { return f.get(); }
    catch (ExecutionException e) { throw launderThrowable(...); }

  }
```

make future

... run on calling thread if not already in cache

This week

- Reading
  - Goetz et al chapters 4 and 5
  - Bloch item 15
- Exercises
  - Hand-in Thursday at 23:55
  - Goals: Build a threadsafe class, use built-in collection classes, use the “future” concept
- Read before for next week’s lecture
  - Sestoft: Microbenchmarks in Java and C# http://www.itu.dk/people/sestoft/papers/benchmarking.pdf
  - Optional: McKenney chapter 3