Practical Concurrent and Parallel Programming 3

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Plan for today

- Java Monitor pattern
- Defensive copying, VehicleTracker
- Standard collection classes not thread-safe
- Extending collection classes
- ConcurrentModificationException
- FutureTask<T>, asynchronous execution
- (Silly complications of checked exceptions)
- Building a scalable result cache

Comments on exercises

- Exercise schedule:
  - 1000-1200: 2A14
  - 1200-1400: **2A14 ← change!**

- True:
  - If program p fails when tested, then it is not thread-safe

- **False:**
  - If program p does not fail when tested, then it is thread-safe

NEVER reason like that

Java monitor pattern

An object following the *Java monitor pattern* encapsulates all its mutable state (in **`private`** fields) and guards it with the object's own intrinsic lock (**`synchronized`**).

Goetz p. 60

- Monitors invented 1974 by Hansen and Hoare
  - A way to encapsulate mutable state in concurrency
- Java monitor pattern implements monitors
  - If you use care and discipline!
  - Per Brinch Hansen critical of Java, 1999 paper
- Modern (Java) data structures are subtler ...
  - Illustrated by Goetz VehicleTracker example

LongCounter as monitor, and documenting thread-safety

- Use the @GuardedBy annotation on fields:

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

ThreadsafeLongCounter.java

- Compile files with

```
javac -cp ~/lib/jsr305-3.0.0.jar ThreadsafeLongCounter.java
```

- Annotations show the programmer's *intent*
  - Annotations are **not** checked by the Java compiler
  - Week 6 we see a tool for checking @GuardedBy

A class of mutable points

- MutablePoint, like java.awt.Point

Design mistake

Not thread-safe

```
class MutablePoint {
  public int x, y;
  public MutablePoint() {
    x = 0; y = 0;
  }
  public MutablePoint(MutablePoint p) {
    this.x = p.x; this.y = p.y;
  }
}
```

TestVehicleTracker.java

Goetz p. 64

- Q: Why not thread-safe?

Vehicle tracker as a monitor class

V1

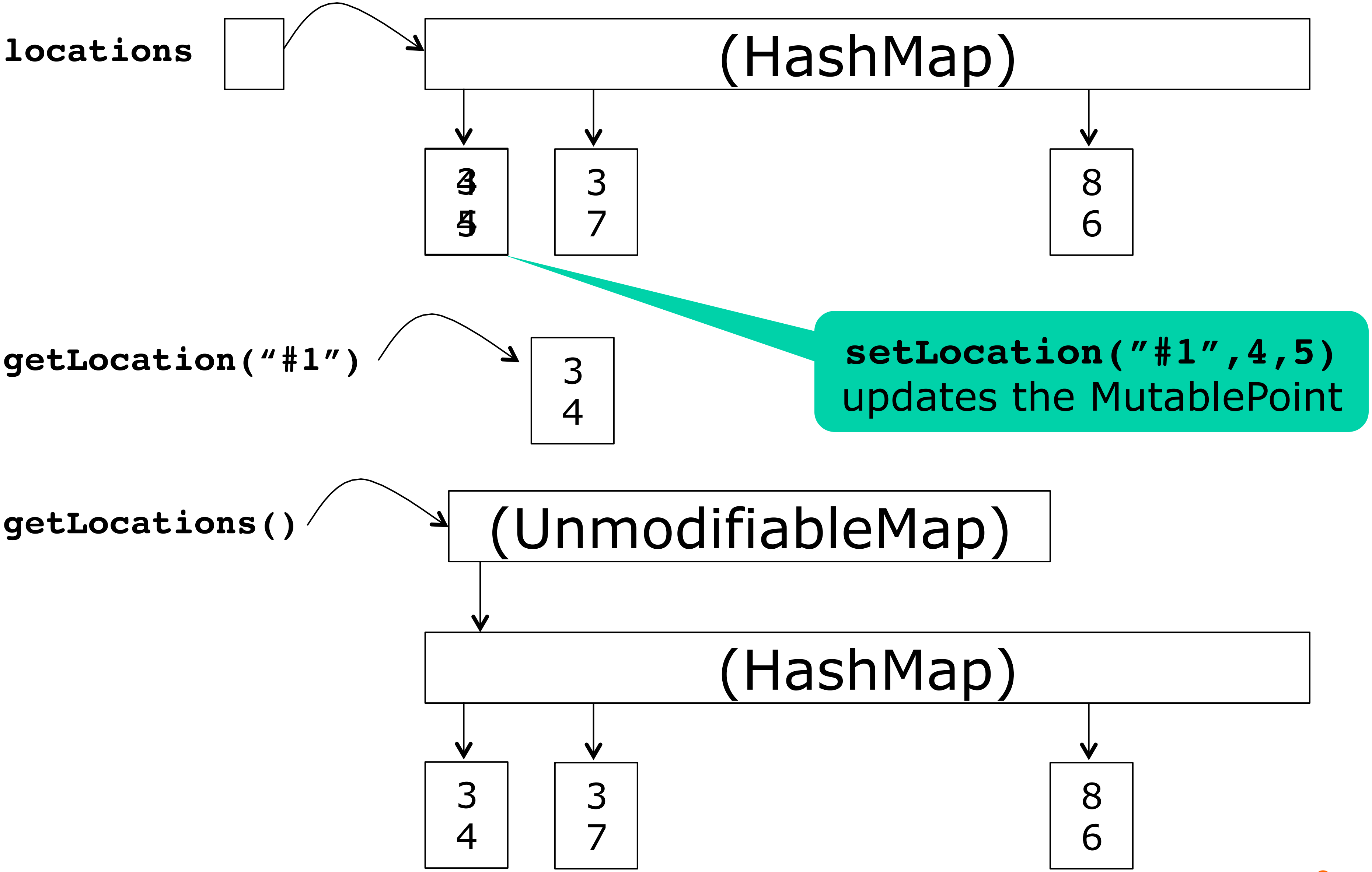
Goetz p. 63

TestVehicleTracker.java

```
class MonitorVehicleTracker {
  private final Map<String, MutablePoint> locations;
  public MonitorVehicleTracker(Map<String, MutablePoint> locations) {
    this.locations = deepCopy(locations);
  }
  public synchronized Map<String, MutablePoint> getLocations() {
    return deepCopy(locations);
  }
  public synchronized MutablePoint getLocation(String id) {
    MutablePoint loc = locations.get(id);
    return loc == null ? null : new MutablePoint(loc);
  }
  public synchronized void setLocation(String id, int x, int y) {
    MutablePoint loc = locations.get(id);
    loc.x = x;
    loc.y = y;
  }
  private static Map<String, MutablePoint> deepCopy(Map<String, MutablePoint> m) {
    Map<String, MutablePoint> result = new HashMap<String, MutablePoint>();
    for (String id : m.keySet())
      result.put(id, new MutablePoint(m.get(id)));
    return Collections.unmodifiableMap(result);
  }
}
```

- Protects its state in field locations
- But why all that copying?

MonitorVehiclerTracker memory



A class of immutable points

- Immutable Point class:

```
class Point {
  public final int x, y;
  public Point(int x, int y) {
    this.x = x; this.y = y;
  }
}
```

TestVehicleTracker.java

Goetz p. 64

- Automatically thread-safe

Thread safety by delegation and immutable points

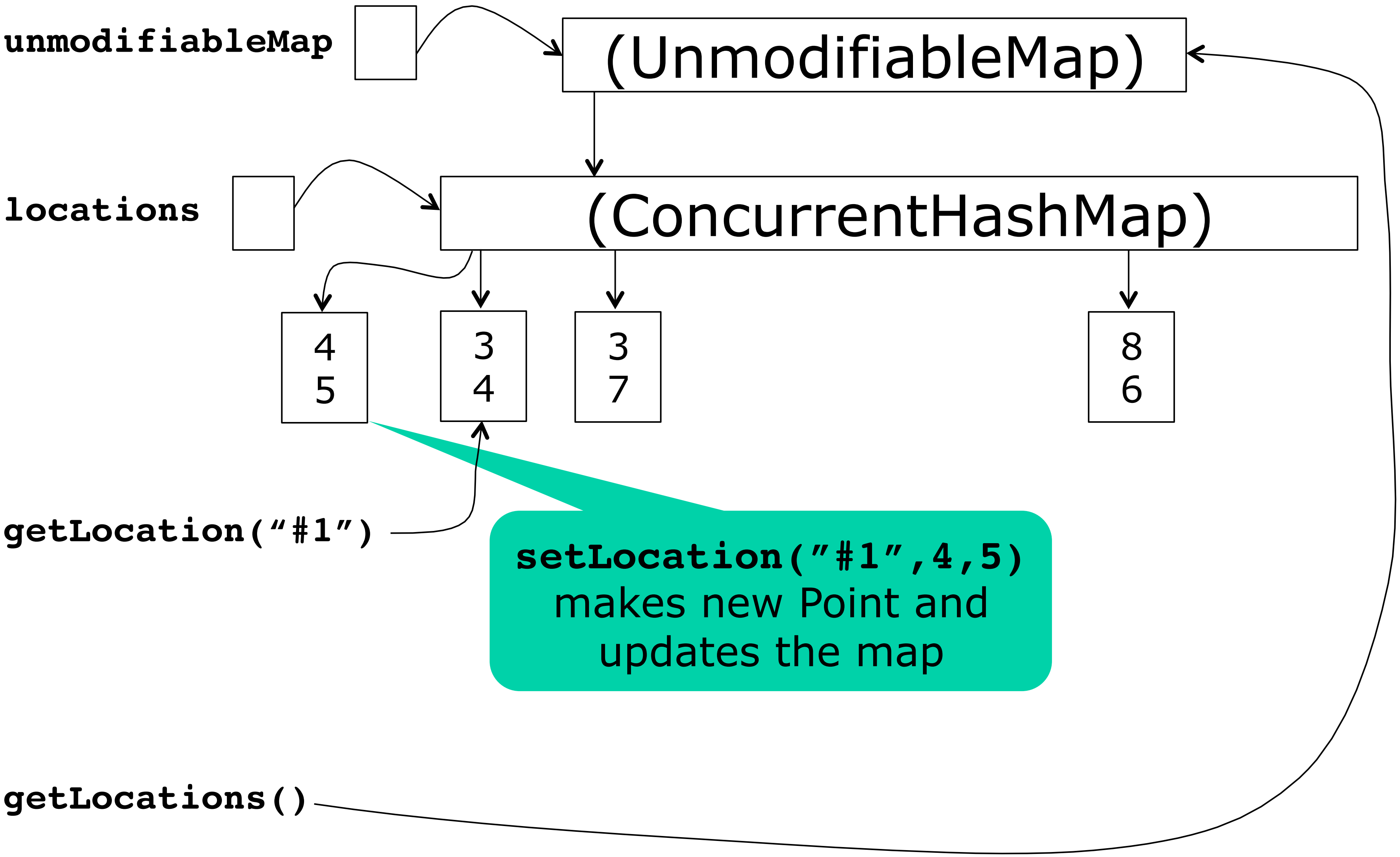
V2

Goetz p. 65

```
class DelegatingVehicleTracker {
  private final ConcurrentMap<String, Point> locations;
  private final Map<String, Point> unmodifiableMap;
  public DelegatingVehicleTracker(Map<String, Point> points) {
    locations = new ConcurrentHashMap<String, Point>(points);
    unmodifiableMap = Collections.unmodifiableMap(locations);
  }
  public Map<String, Point> getLocations() {
    return unmodifiableMap;
  }
  public Point getLocation(String id) {
    return locations.get(id);
  }
  public void setLocation(String id, int x, int y) {
    locations.replace(id, new Point(x, y));
  }
}
```

- No defensive copying any longer
  - Less mutability can give better performance!
- Q: Why not just cast **`locations`** to an interface without setters?

DelegatingVehicleTracker memory



V3

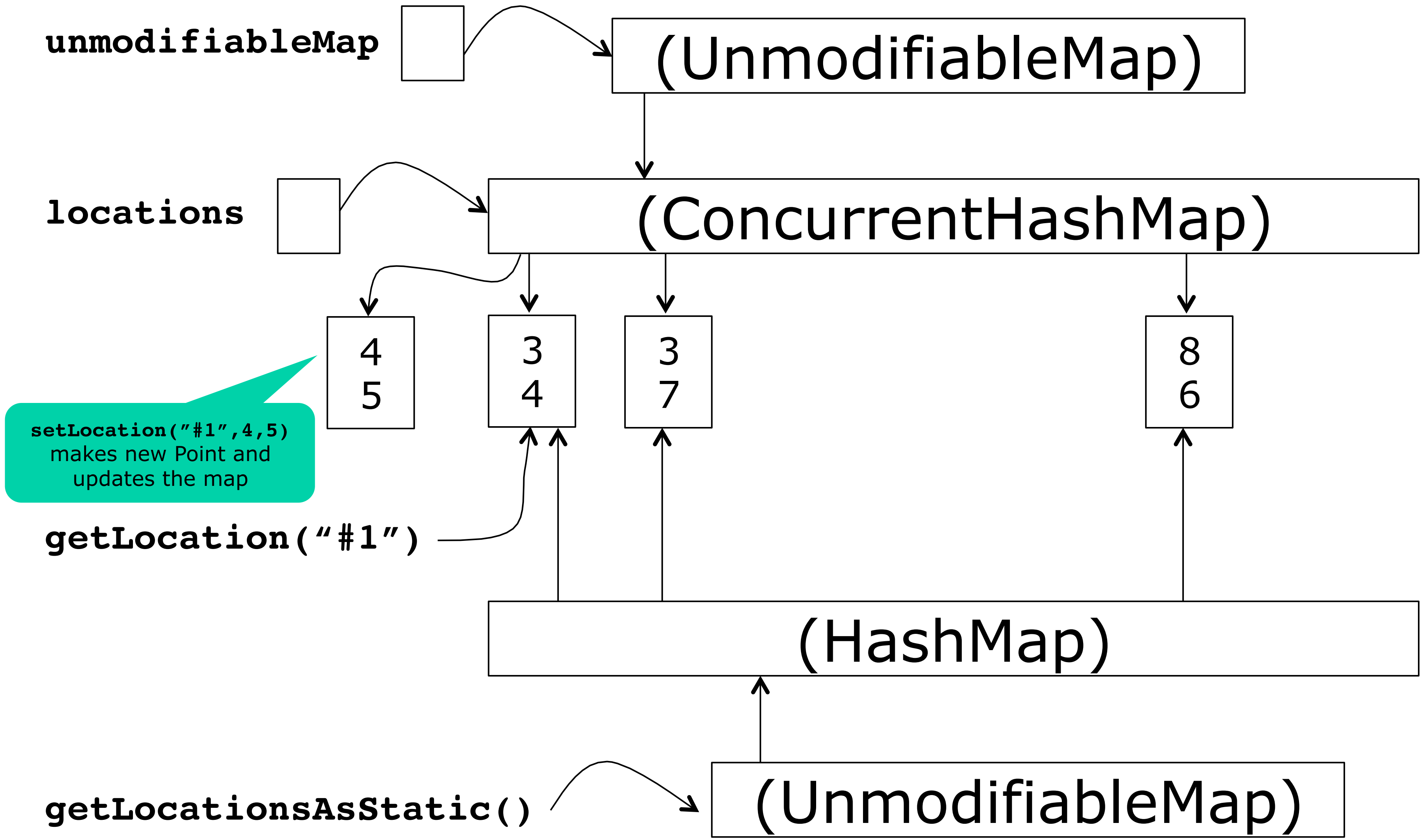
Alternative getLocations()

- Returns unmodifiable view
  - of static copy of hashmap,
  - referring to the existing immutable points

Goetz p. 66

```
public Map<String, Point> getLocationsAsStatic() {
  return Collections.unmodifiableMap(new HashMap<String, Point>(locations));
}
```

DelegatingVehicleTracker memory with static getLocations result



Immutability is GOOD

- Can speed up some operations
- Can simplify thread-safety
- Microsoft .NET has new immutable collections
  - http://msdn.microsoft.com/en-us/library/dn385366%28v=vs.110%29.aspx
  - http://blogs.msdn.com/b/bclteam/archive/2012/12/18/preview-of-immutable-collections-released-on-nuget.aspx
- Different from unmodifiable collections
  - No underlying modifiable collection
  - Enumeration is safe, including thread-safe
- Java 8 does not have immutable collections

Safe mutable point class

- Mutable point as monitor

```
public class SafePoint {
  private int x, y;
  private SafePoint(int[] a) { this(a[0], a[1]); }
  public SafePoint(SafePoint p) { this(p.get()); }
  public SafePoint(int x, int y) { this.set(x, y); }
  public synchronized int[] get() {
    return new int[]{x, y};
  }
  public synchronized void set(int x, int y) {
    this.x = x; this.y = y;
  }
}
```

Goetz p. 69

V4

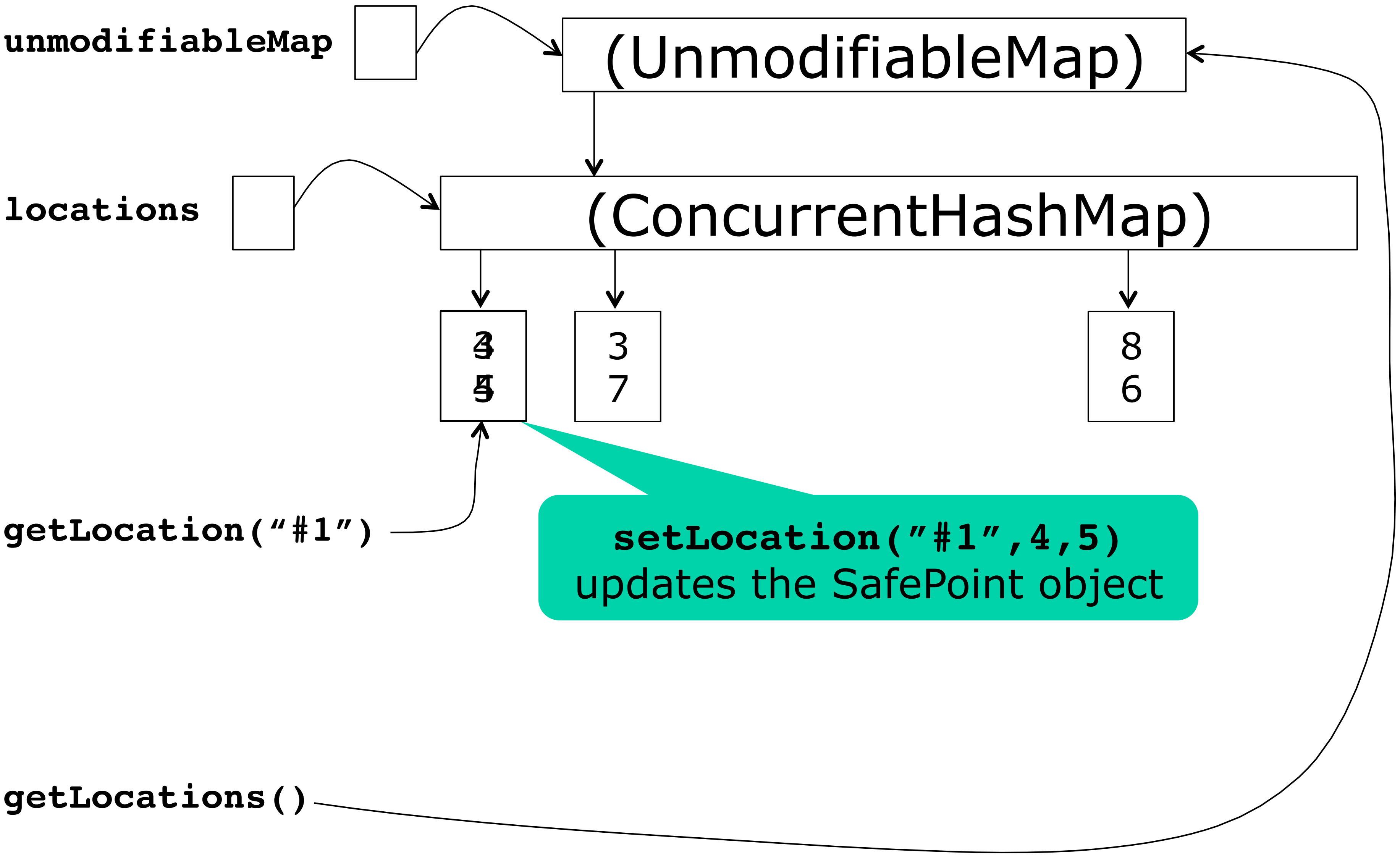
Safe publishing vehicle tracker

Goetz p. 70

```
public class PublishingVehicleTracker {
  private final Map<String, SafePoint> locations;
  private final Map<String, SafePoint> unmodifiableMap;

  public PublishingVehicleTracker(Map<String, SafePoint> locations) {
    this.locations
      = new ConcurrentHashMap<String, SafePoint>(locations);
    this.unmodifiableMap = Collections.unmodifiableMap(this.locations);
  }
  public Map<String, SafePoint> getLocations() {
    return unmodifiableMap;
  }
  public SafePoint getLocation(String id) {
    return locations.get(id);
  }
  public void setLocation(String id, int x, int y) {
    locations.get(id).set(x, y);
  }
}
```

SafePublishingVehicleTracker memory



Which VehicleTracker is best?

- All are thread-safe
  - Some due to defensive copying
  - Some due to immutability and unmodifiability
- Different meanings of setLocation:
  - setLocation **does not** affect prior getLocation/s:
    - MonitorVehicleTracker (V1)
    - DelegatingVehicleTracker with getLocationsStatic (V3)
  - setLocation **does** affect prior getLocation/s:
    - DelegatingVehicleTracker (V2)
    - SafePublishingVehicleTracker (V4)
- Performance depends on the usage
  - More setLocation calls than getLocations calls
  - Number of results returned by getLocations

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- **Standard collection classes not threadsafe**
- **Extending collection classes**
- ConcurrentModificationException
- FutureTask<T> and asynchronous execution
- (Silly complications of checked exceptions)
- Building a scalable result cache

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);
}});
```

TestCollections.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>());
```

Adding putIfAbsent to ArrayList<T>

Not thread-safe

```
class FirstBadListHelper<E> {
  public List<E> list = Collections.synchronizedList(new ArrayList<E>());
  public boolean putIfAbsent(E x) {
    boolean absent = !list.contains(x);
    if (absent)
      list.add(x);
    return absent;
  }
}
```

test, then …

… act

- Non-atomic test-then-act is not thread-safe
- But this is not thread-safe either. Q: Why?

Not thread-safe

```
class SecondBadListHelper<E> {
  public List<E> list = Collections.synchronizedList(new ArrayList<E>());
  public synchronized boolean putIfAbsent(E x) {
    boolean absent = !list.contains(x);
    if (absent)
      list.add(x);
    return absent;
  }
}
```

Goetz p. 72

Client side locking for putIfAbsent

```
class GoodListHelper<E> {
  public List<E> list = Collections.synchronizedList(new ArrayList<E>());

  public boolean putIfAbsent(E x) {
    synchronized (list) {
      boolean absent = !list.contains(x);
      if (absent)
        list.add(x);
      return absent;
    }
  }
}
```

Atomic test-then-act

Goetz p. 72

- Discuss:
  - Is the test-then-act guaranteed atomic?
  - What could undermine the atomicity?

Using composition is safer – and more work

```
final class BetterArrayList<E> implements List<E> {
  private List<E> list = new ArrayList<E>();

  public synchronized boolean putIfAbsent(E x) {
    boolean absent = !list.contains(x);
    if (absent)
      list.add(x);
    return absent;
  }

  public synchronized boolean add(E item) {
    return list.add(item);
  }

  ... approx. 30 other ArrayList<E> methods with synchronized added ...
}
```

TestListHelper.java

- Q: Are operations now guaranteed atomic?
- Better use java.util.concurrent.* collections
  - If you need to make updates concurrently

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ConcurrentModificationException

```
ArrayList<String> universities = new ArrayList<String>();
universities.add("Copenhagen University");
universities.add("KVL");
universities.add("Aarhus University");
for (String name : universities) {
  System.out.println(name);
  if (name.equals("KVL"))
    universities.remove(name);
}
```

Should not change the collection while iterating

```
Copenhagen University
KVL
Exception ... java.util.ConcurrentModificationException
```

Even when no thread concurrency

- The “fail-early” mechanism is not thread-safe!
- Do not rely on it in a concurrent context
  - ... instead ...

Java 8 documentation on iteration

- Collections.synchronizedList() says:

It is imperative that the user manually synchronize on the returned collection when traversing it via `Iterator`, `Spliterator` or `Stream`:

```
Collection c = Collections.synchronizedCollection(myCollection);
   ...
synchronized (c) {
    Iterator i = c.iterator(); // Must be in the synchronized block
    while (i.hasNext())
       foo(i.next());
}
```

Failure to follow this advice may result in non-deterministic behavior.

```
Collection c = Collections.synchronizedCollection(myCollection);
synchronized (c) {
  for (T item : c)
    foo(item);
}
```

Same as above code:
`for` creates an Iterator

- All access to myCollection must be through c

Collections in a concurrent context

- Preferably use a modern concurrent collection in java.util.concurrent.*
  - Iterators and **`for`** are *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

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Callable<T> versus Runnable

- A Runnable contains a **`void`** method:

```
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()`**

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

- 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
  - Possible because it implements Runnable

Asynchronous FutureTask<T>

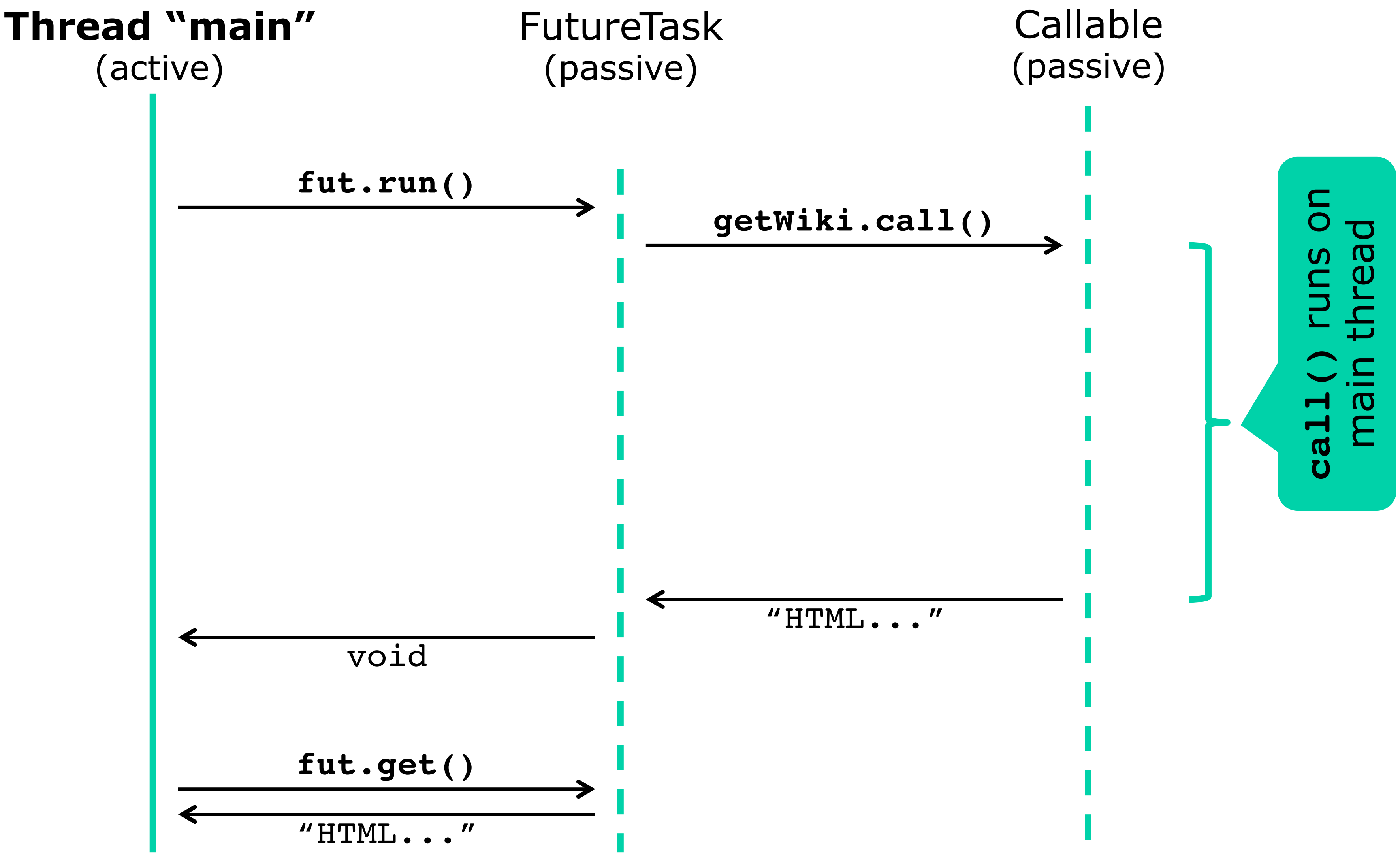
```
Callable<String> getWiki = new Callable<String>() {
  public String call() throws Exception {
    return getContents("http://www.wikipedia.org/", 10);
}};
FutureTask<String> fut = new FutureTask<String>(getWiki);
Thread t = new Thread(fut);
t.start();
try {
  String homepage = fut.get();
  System.out.println(homepage);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

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

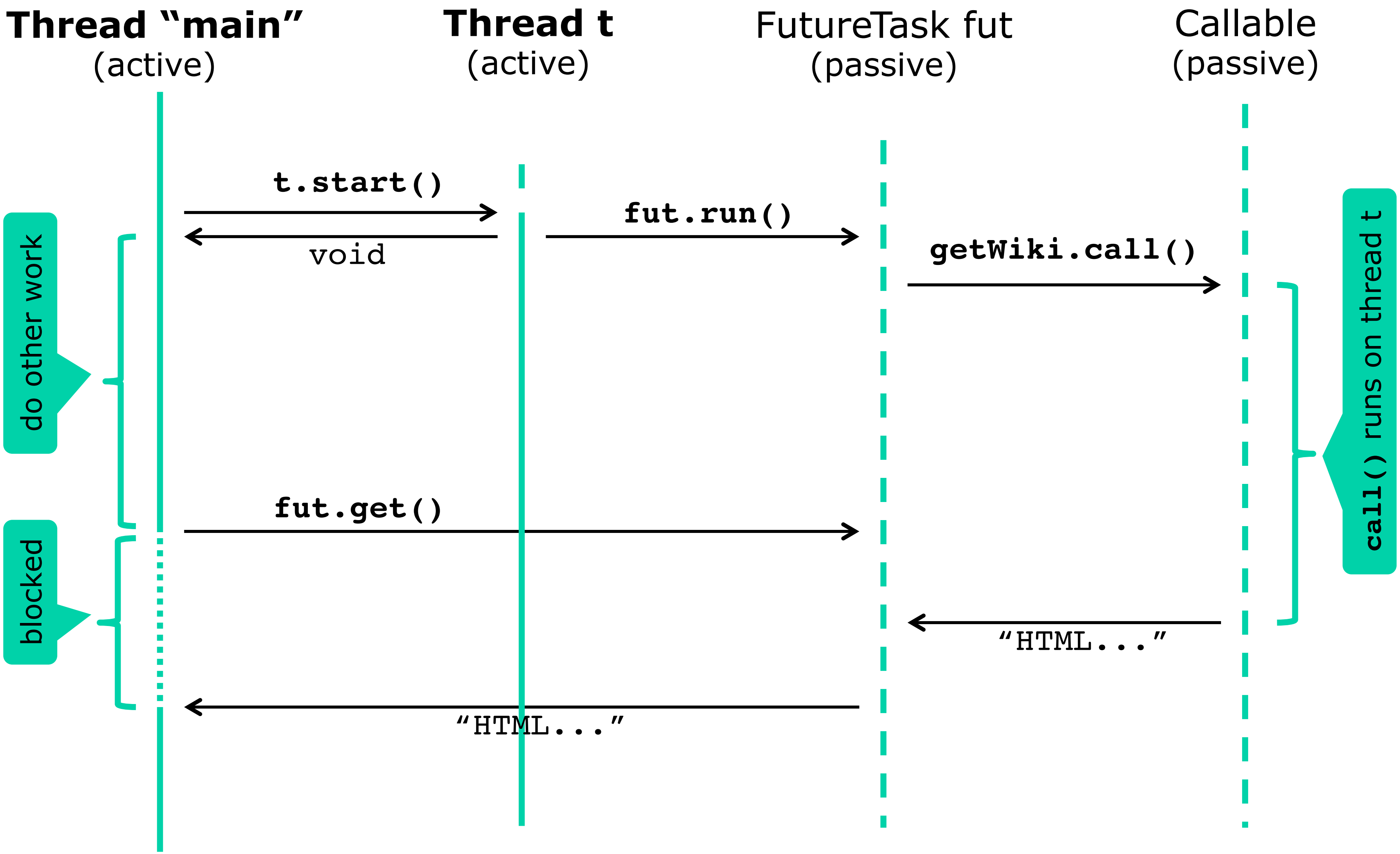
Block until **`call()`** completes

- 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

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- **Building a scalable result cache**

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 ...
} }
```

C1

Thread-safe but non-scalable cache

```
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?

Thread-safe scalable cache, using concurrent hashmap

C2

```
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

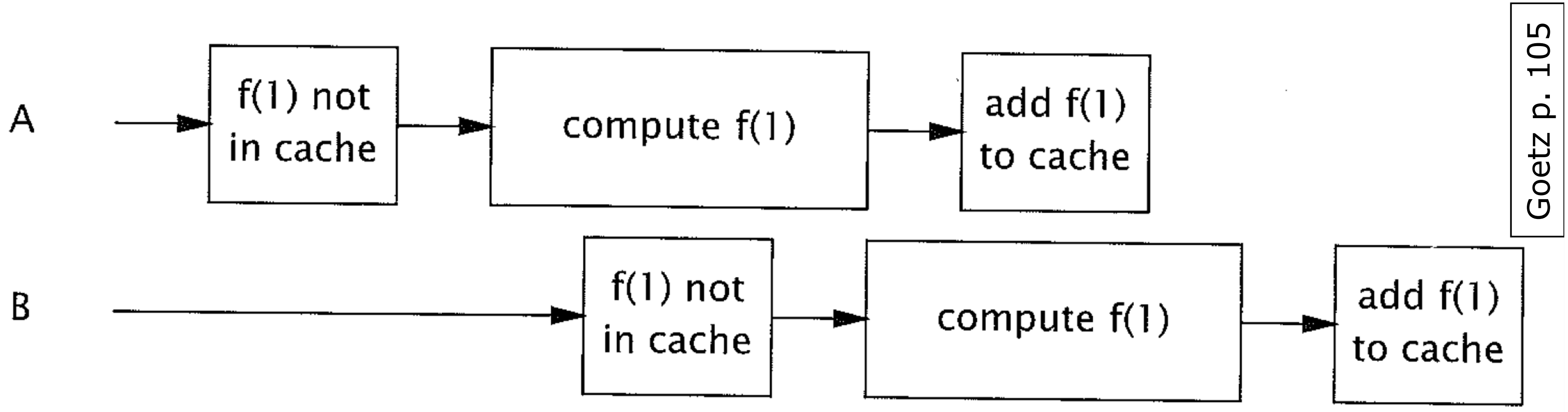

FIGURE 5.3. Two threads computing the same value when using `Memoizer2`.

- 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

C3

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

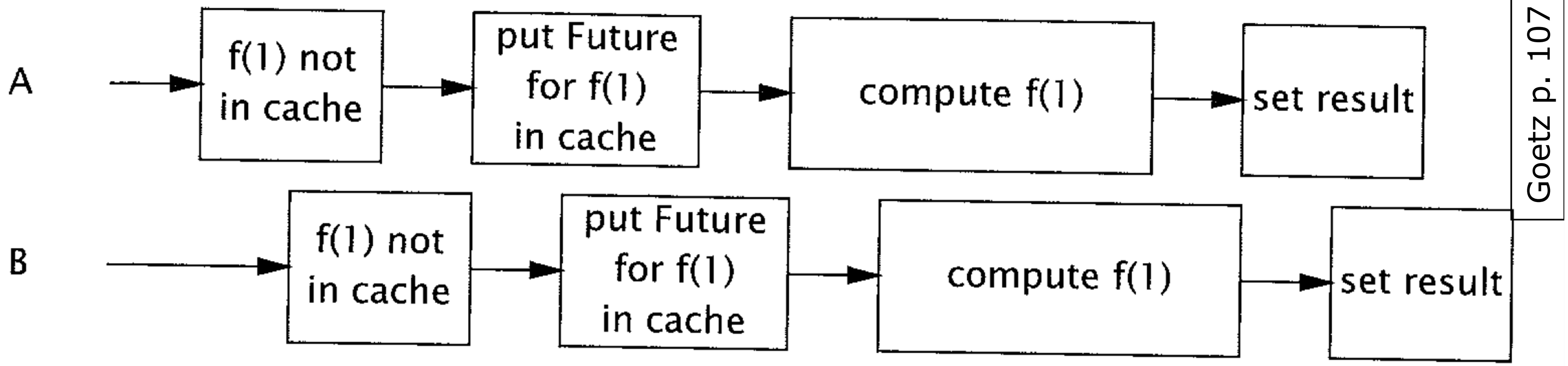

FIGURE 5.4. Unlucky timing that could cause `Memoizer3` to calculate the same value twice.

- 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

C4

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

- (Before Java 8) one cannot atomically test-then-create-future-and-add-it
- Hence, suggested by Bloch item 69:
  - Make a fast (non-atomic) test for arg in cache
  - If not there, create 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, but looks complicated

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

C5

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, new Function<...>(){
      public Future<V> apply(final A arg) {
        Callable<V> eval = new Callable<V>() {
            public V call() throws InterruptedException {
              return c.compute(arg);
            }};
        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

Parts of Java are 20 years old, have some design mistakes

- Never use these Thread methods (API):
  - **`destroy()`**
  - **`countStackFrames()`**
  - **`resume()`**
  - **`stop()`**
  - **`suspend()`**
- Avoid thread groups (Bloch item 73)
- Prefer non-synchronized
  - StringBuilder over StringBuffer
  - ArrayList or CopyOnWriteArrayList over Vector
  - HashMap or ConcurrentHashMap over HashTable

This week

- Reading
  - Goetz et al chapters 4 and 5
- Exercises
  - Build a threadsafe class, use built-in collection classes, use the future concept
- Read before next week's lecture
  - Sestoft: Microbenchmarks in Java and C#
  - Optional: McKenney chapter 3