Java and Android Concurrency

Building Blocks

fausto.spoto@univr.it

git@bitbucket.org:spoto/java-and-android-concurrency.git

git@bitbucket.org:spoto/java-and-android-concurrency-examples.git

Synchronized Collections in `java.util`.

- `Vector`
- `Hashtable`
- `Collections.synchronizedCollection(collection)`
- `Collections.synchronizedSet(set)`
- `Collections.synchronizedSortedSet(sortedSet)`
- `Collections.synchronizedList(list)`
- `Collections.synchronizedMap(map)`

They encapsulate their state and synchronize every method. They commit to explicit support for client-side locking through their own intrinsic lock

Compound Actions are not Atomic

```
@NotThreadSafe
public class UnsafeVectorHelpers {
  public static <T> T getLast(Vector<T> list) {
    int lastIndex = list.size() - 1;  // read-modify
    return list.get(lastIndex);       // write
  }

  public static <T> void deleteLast(Vector<T> list) {
    int lastIndex = list.size() - 1;  // read-modify
    list.remove(lastIndex);           // write
  }
}
```

In a concurrent setting, this might throw an `ArrayIndexOutOfBoundsException`

Make Compound Actions Atomic with Client-Side Locking

```
@ThreadSafe
public class SafeVectorHelpers {
  public static <T> T getLast(Vector<T> list) {
    synchronized (list) {
      int lastIndex = list.size() - 1;
      return list.get(lastIndex);
    }
  }

  public static <T> void deleteLast(Vector<T> list) {
    synchronized (list) {
      int lastIndex = list.size() - 1;
      list.remove(lastIndex);
    }
  }
}
```

Hidden Compound Actions in Iteration

In a concurrent setting, the subsequent code might throw an `ArrayIndexOutOfBoundsException`:

```
@NotThreadSafe
for (int i = 0; i < vector.size(); i++)  // check
  doSomething(vector.get(i));            // then-act
```

How to fix it:

```
@ThreadSafe
synchronized (vector) {
  for (int i = 0; i < vector.size(); i++)
    doSomething(vector.get(i));
}
```

However, this solution prevents other threads from accessing the vector for the whole duration of the iteration, which is undesirable

ConcurrentModificationException

This exception is thrown by iterators on collections, if the original collection gets modified before the iteration ends. It occurs in a sequential setting as well:

```
for (E element: list)
  if (isBad(element))
    list.remove(element);   // ConcurrentModificationException
```

In a concurrent setting, the exception might be thrown in much more surprising situations:

```
@NotThreadSafe
for (E element: vector) // may throw ConcurrentModificationExceptio
  System.out.println(element);
```

Hidden Compound Actions in Iteration

The problem with iteration is that it is a hidden check-then-act operation:

```
@NotThreadSafe
for (E element: vector)              // check
  System.out.println(element);       // then-act
```

A way to fix it:

```
@ThreadSafe
synchronized (vector) {
  for (E element: vector)
    System.out.println(element);
}
```

However, this solution prevents other threads from accessing the vector for the whole duration of the iteration, which is undesirable

Beware of Implicit Iteration

```
@NotThreadSafe
public class HiddenIterator {

  @GuardedBy("this")
  private final Set<Integer> set = new HashSet<Integer>();

  public synchronized void add(Integer i) { set.add(i); }
  public synchronized void remove(Integer i) { set.remove(i); }

  public void addTenThings() {
    Random r = new Random();
    for (int i = 0; i < 10; i++)
      add(r.nextInt());
    // missing synchronization below:
    // this may throw a ConcurrentModificationException
    System.out.println("DEBUG: added ten elements to " + set);
  }
}
```

Other Implicit Uses of Iteration on Collections

- `hashCode()` and `equals()`, possibly called if a collection is used as an element of another collection
- `containsAll()`, `removeAll()`, `retainAll()`
- constructors that take a collection as parameter and build a copy

Always synchronize on the shared mutable collection before such operations

Concurrent Collections

Synchronized collections: `Vector`, `Hashtable`, `synchronizedXXX`

Thread-safety achieved by serializing all access: poor concurrency

Concurrent collections: `ConcurrentHashMap`, `CopyOnWriteArrayList`

Multiple threads can concurrently access the collection in a thread-safe way: high concurrency, slightly increased memory footprint

ConcurrentHashMap implements ConcurrentMap

Synchronized collections synchronize for the full duration of a simple `map.get(key)` operation, which might take longer than expected. `ConcurrentHashMap` instead uses lock striping:

- readers can access the map concurrently
- readers and writers can access the map concurrently
- a limited number of writers can modify the map concurrently
- iterators are not fail-fast: they yield a snapshot of the map at the time of their creation and never throw a `ConcurrentModificationException`
- there is no need to synchronize during iteration
- there is no support for client-side locking
- there are extra atomic check-then-act operations
  - `V putIfAbsent(K key, V value)`
  - `boolean remove(K key, V value)`
  - `boolean replace(K key, V oldValue, V newValue)`
  - `V replace(K key, V newValue)`

CopyOnWriteArrayList and CopyOnWriteArraySet

They hold a backing collection that is recreated every time the collection gets modified:

- iterators refer to the backing collection at the time of creation, hence they reflect a snapshot of the collection at their creation time, are not fail-safe and never throw a `ConcurrentModificationException`
- there is no need to synchronize during iteration
- mutative methods are slow

They are the perfect concurrent data structure when modification is rare, while iteration is the predominant operation

- such as for implementing a list of listeners, that must be iterated at each notification

Implementing a List of Listeners

```
@ThreadSafe
public class VisualComponent {
  private final List<KeyListener> keyListeners = new CopyOnWriteArrayList<>();

  public void addKeyListener(KeyListener listener) {
    keyListeners.add(listener);
  }

  public void removeKeyListener(KeyListener listener) {
    keyListeners.remove(listener);
  }

  public void fireKeyListeners(KeyEvent event) {
    // no need to synchronize here
    for (KeyListener listener: keyListeners)
      listener.keyPressed(event);
  }
}
```

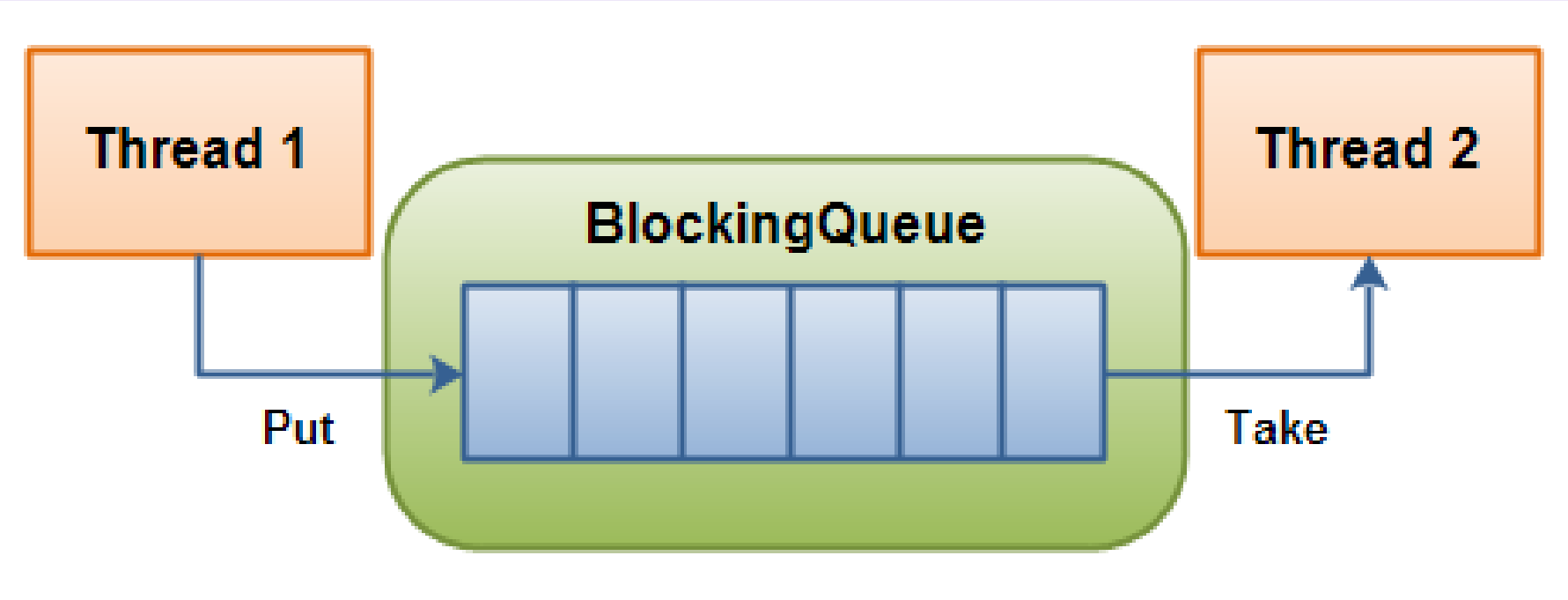
Blocking Queues

Blocking queues implement a FIFO or priority buffer with methods:

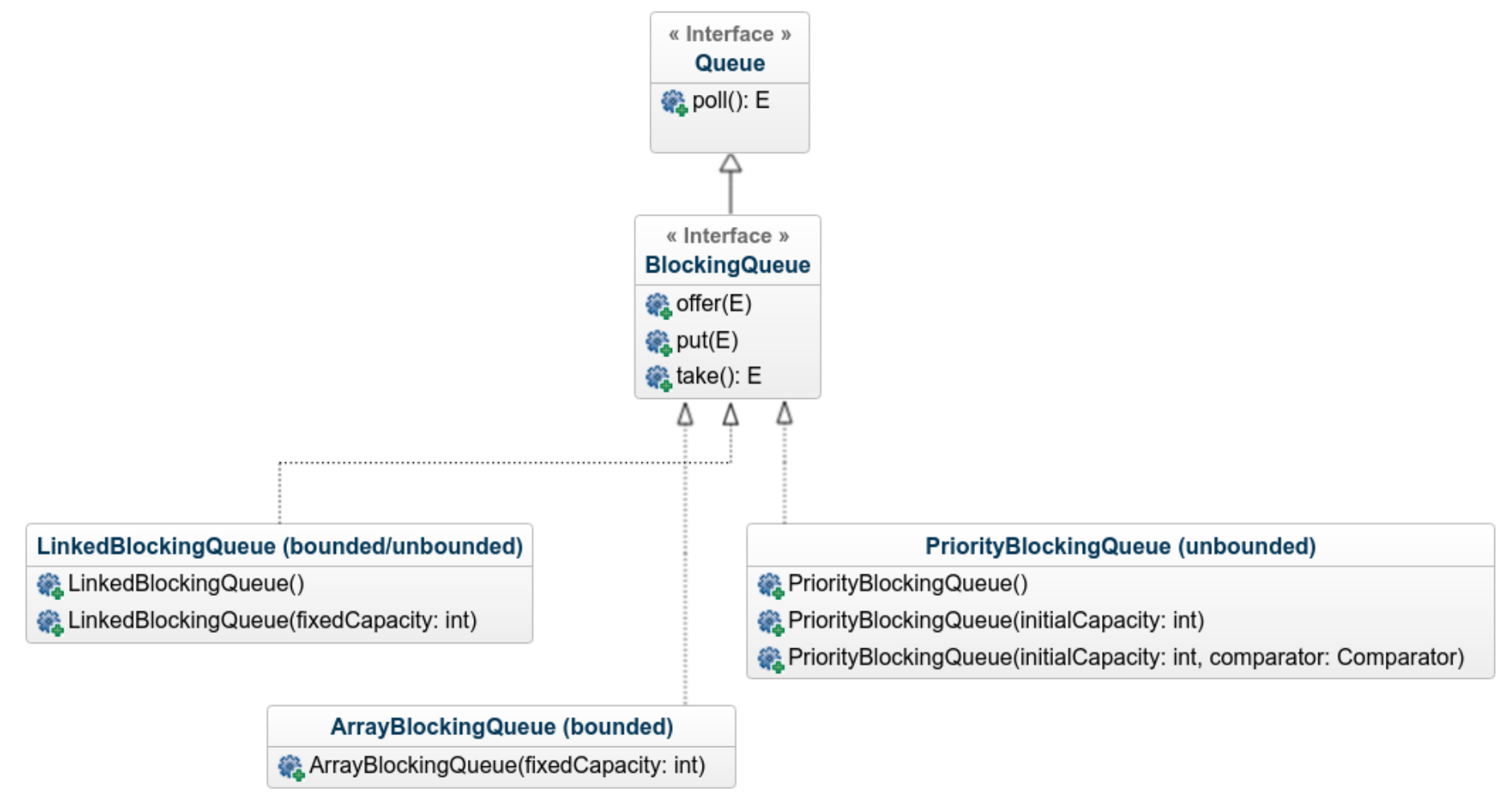
- `put(element)` that adds an element to the queue
  - bounded queues: blocks if full
  - unbounded queues: never blocks
- `take()` that extracts the first element from the queue
  - if the queue is empty, it blocks
- `offer(element)` that adds an element to the queue
  - bounded queues: returns `false` if full
  - unbounded queues: equivalent to `put`
- `poll()` that extracts the first element from the queue
  - if the queue is empty, yields `null`
- timed versions of `offer` and `poll`

Beware of unbounded queues that might fill up the memory

Producer/Consumer Pattern



Concurrent Queue Classes from the Java Library



Example: File Crawling as Consumer/Producer

```
private static final int BOUND = 10;
private static final int N_CONSUMERS
    = Runtime.getRuntime().availableProcessors();

public static void startIndexing(File[] roots) {
  BlockingQueue<File> queue = new LinkedBlockingQueue<>(BOUND);

  // start producers
  for (File root: roots)
    new Thread(new FileCrawler(queue, root)).start();

  // start consumers
  for (int i = 0; i < N_CONSUMERS; i++)
    new Thread(new Indexer(queue)).start();
}
```

The Producer

```
@ThreadSafe
class FileCrawler implements Runnable {
  private final BlockingQueue<File> fileQueue;
  private final File root;

  public FileCrawler(BlockingQueue<File> fileQueue, File root) {
    this.fileQueue = fileQueue;
    this.root = root;
  }
  ...
  public void run() {
    crawl(root);
  }

  private void crawl(File root) {
    File[] entries = root.listFiles();
    if (entries != null)
      for (File entry : entries)
        if (entry.isDirectory())
          crawl(entry);
        else if (!alreadyIndexed(entry))
          fileQueue.put(entry);
  }
}
```

The Consumer

```
@ThreadSafe
class Indexer implements Runnable {
  private final BlockingQueue<File> queue;

  public Indexer(BlockingQueue<File> queue) {
    this.queue = queue;
  }

  public void run() {
    while (true)
      indexFile(queue.take());
  }

  public void indexFile(File file) {
    // index the file...
  }
}
```

Blocking and Interruptible Methods

Cooperative interruption

A thread cannot be stopped. It is only possible to send an interruption request to a thread by calling its `interrupt()` method. This will result in

- a checked `InterruptedException`, if the thread is blocked at a blocking method (such as `queue.take()`)
- its interruption flag being set, otherwise. This can be checked through the `isInterrupted()` method of the thread

Dealing with InterruptedException

The simplified code of two slides ago:

```
class Indexer implements Runnable {
  ...
  public void run() {
    while (true)
      indexFile(queue.take());
  }
}
```

The real code:

```
class Indexer implements Runnable {
  ...
  public void run() {
    try {
      while (true)
        indexFile(queue.take());
    }
    catch (InterruptedException e) {
      // propagate back the interruption to the thread running this Runnable
      Thread.currentThread().interrupt();
    }
  }
}
```

Never Swallow an Interruption

Interruptions should not be eaten

```
class Indexer implements Runnable {
  ...
  public void run() {
    try {
      while (true)
        indexFile(queue.take());
    }
    catch (InterruptedException e) {} // don't do this at home
  }
}
```

This means that the request has been ignored. Instead

- either propagate back the exception
- or propagate back the interruption request

Interruptions could be swallowed only if you are extending `Thread`!

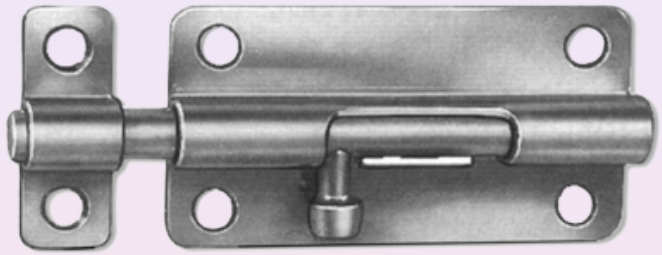
Synchronizers

A synchronizer is any object that coordinates the control flow of threads based on its state:

- blocking queues
- latches
- semaphores
- barriers
- futures

Latches

A latch is a synchronizer that can delay the progress of threads until it reaches its terminal state



Class `CountDownLatch` allows threads to wait for a set of events to occur. It is initialized to a positive number, representing the number of events to wait for

- method `countDown()` decrements the counter
- method `await()` blocks until the counter reaches zero

Example: Use Latches to Profile a Runnable

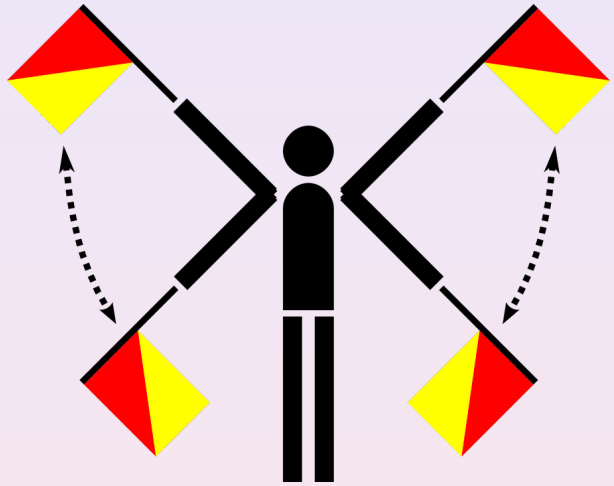
```
public class TestHarness {
  public long timeTasks(int nThreads, final Runnable task) throws InterruptedExcept
    final CountDownLatch startGate = new CountDownLatch(1);
    final CountDownLatch endGate = new CountDownLatch(nThreads);

    for (int i = 0; i < nThreads; i++)
      new Thread() {
       public void run() {
          try {
            startGate.await(); // wait for the GO!
            try {
              task.run();
            } finally {
              endGate.countDown(); // finished!
            }
          } catch (InterruptedException ignored) {}
        }
      }.start();

    long start = System.nanoTime();
    startGate.countDown();      // let all thread start now
    endGate.await();            // wait for the last thread to finish
    return System.nanoTime() - start;
  }
}
```

Semaphores

A semaphore is a synchronizer that controls the number of agents that can access a certain resource



Class `Semaphore` is initialized to a positive number, representing the number of available access permits

- method `acquire()` grabs a permit and blocks if no permit is available
- method `release()` pushes back a permit

A Bounded Set with Blocking Addition

```
@ThreadSafe
public class BoundedHashSet<T> {
  private final Set<T> set;
  private final Semaphore sem;

  public BoundedHashSet(int bound) {
    this.set = Collections.synchronizedSet(new HashSet<>());
    this.sem = new Semaphore(bound);
  }
```

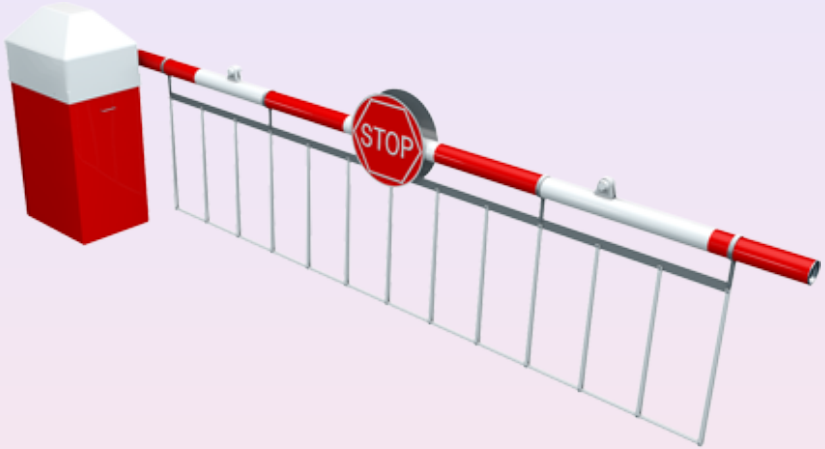
A Bounded Set with Blocking Addition

```
  public boolean add(T o) throws InterruptedException {
    sem.acquire();
    boolean wasAdded = false;
    try {
      wasAdded = set.add(o);
      return wasAdded;
    } finally {
      if (!wasAdded)
        sem.release();
    }
  }

  public boolean remove(Object o) {
    boolean wasRemoved = set.remove(o);
    if (wasRemoved)
      sem.release();
    return wasRemoved;
  }
}
```

Barriers

A barrier is a synchronizer that blocks a group of threads until they have all reached a barrier point, then they proceed



Class `CyclicalBarrier` is initialized to a positive number n, representing the number of threads that should be awaited at the barrier

- method `await()` blocks until the remaining $n - 1$ have called `await()` as well, at which moment all n threads are allowed to proceed

The Backbone of a Cyclical Game

```
@ThreadSafe
public class CellularAutomata {
  private final Board mainBoard;
  private final CyclicBarrier barrier;
  private final Worker[] workers;

  public CellularAutomata(Board board) {
    int count = Runtime.getRuntime().availableProcessors();
    this.mainBoard = board;
    this.barrier = new CyclicBarrier(count, () -> mainBoard.commitNewValues());
    this.workers = new Worker[count];
    for (int i = 0; i < count; i++) // split work between workers
      workers[i] = new Worker(mainBoard.getSubBoard(count, i));
  }

  public void start() {
    // start all workers
    for (Worker worker: workers)
      new Thread(worker).start();

    mainBoard.waitForConvergence();
  }
```

The Backbone of a Cyclical Game

```
// inner class
private class Worker implements Runnable {
  private final Board board;

  public Worker(Board board) { this.board = board; }

  public void run() {
    while (!board.hasConverged()) {
      // compute the next generation of the values
      for (int x = 0; x < board.getMaxX(); x++)
        for (int y = 0; y < board.getMaxY(); y++)
          board.setNewValue(x, y, computeValue(x, y));

      try {
        // wait until all other workers have finished
        barrier.await();
      }
      catch (InterruptedException | BrokenBarrierException ex) {
        return; // nobody can interrupt this
      }
    }
  }
}
```

Latches, Semaphores and Barriers at a Glance

Latch
`new CountDownLatch(counter >= 0)`
`countDown()` decrements the counter
`await()` blocks until the counter reaches 0
Semaphore
`new Semaphore(counter >= 0)`
`acquire()` decrements the counter and blocks if it is 0
`release()` increments the counter
Barrier
`new CyclicBarrier(counter >= 0)`
`await()` decrements the counter and blocks if it is not 0. If it reaches 0, reset the counter to its initial value and wakes up all blocked threads

Back to the Future

`Runnable`

The specification of a task that does not return any value nor throws any exception

`Callable<V>`

The specification of a task that can return a value of type `V` or throw an exception

`Future<V>`

A pointer to the future result of a computation, not necessarily terminated yet, that eventually will return a value of type `V` or throw an exception

A Pointer to a Future Result

```
// specify the task to compute a V as a Callable<V> c
FutureTask<V> future = new FutureTask<>(c);

// build and start your worker
Thread thread = new Thread(future);
thread.start();

// do other things here
// and others things as well
// do more things

// eventually, ask for the result, when you need it
V result = future.get();
```

Getting the Result of a FutureTask<V>

The statement `V result = future.get()` might have many outcomes:

- the worker has already terminated and computed value $r \Rightarrow$ assign r immediately to variable `result` and continue
- the worker has already terminated by throwing an exception $e \Rightarrow$ throw immediately a new `ExecutionException` with cause e
- the worker has been cancelled $\Rightarrow$ throws a new `CancellationException`
- the worker is still working $\Rightarrow$ block until:
  - either the worker terminates by computing a value $r \Rightarrow$ wake up, assign r to `result` and continue
  - or the worker terminates by throwing an exception $e \Rightarrow$ wake up and throw a new `ExecutionException` with cause e
  - or the blocked thread gets interrupted $\Rightarrow$ throw a new `InterruptedException`

An Example of the Use of FutureTask

```
public class Preloader {
  private final FutureTask<ProductInfo> future =
    new FutureTask<>(new Callable<ProductInfo>() {
      public ProductInfo call() throws DataLoadException {
        return loadProductInfo();
      }
    });
  private final Thread thread = new Thread(future);

  public void start() { thread.start(); }

  public ProductInfo get() throws DataLoadException, InterruptedException {
    try {
      return future.get();
    } catch (ExecutionException e) {
      Throwable cause = e.getCause();
      if (cause instanceof DataLoadException)
        throw (DataLoadException) cause;
      else
        throw launderThrowable(cause); // cast cause into unchecked
    }
  }
}
```

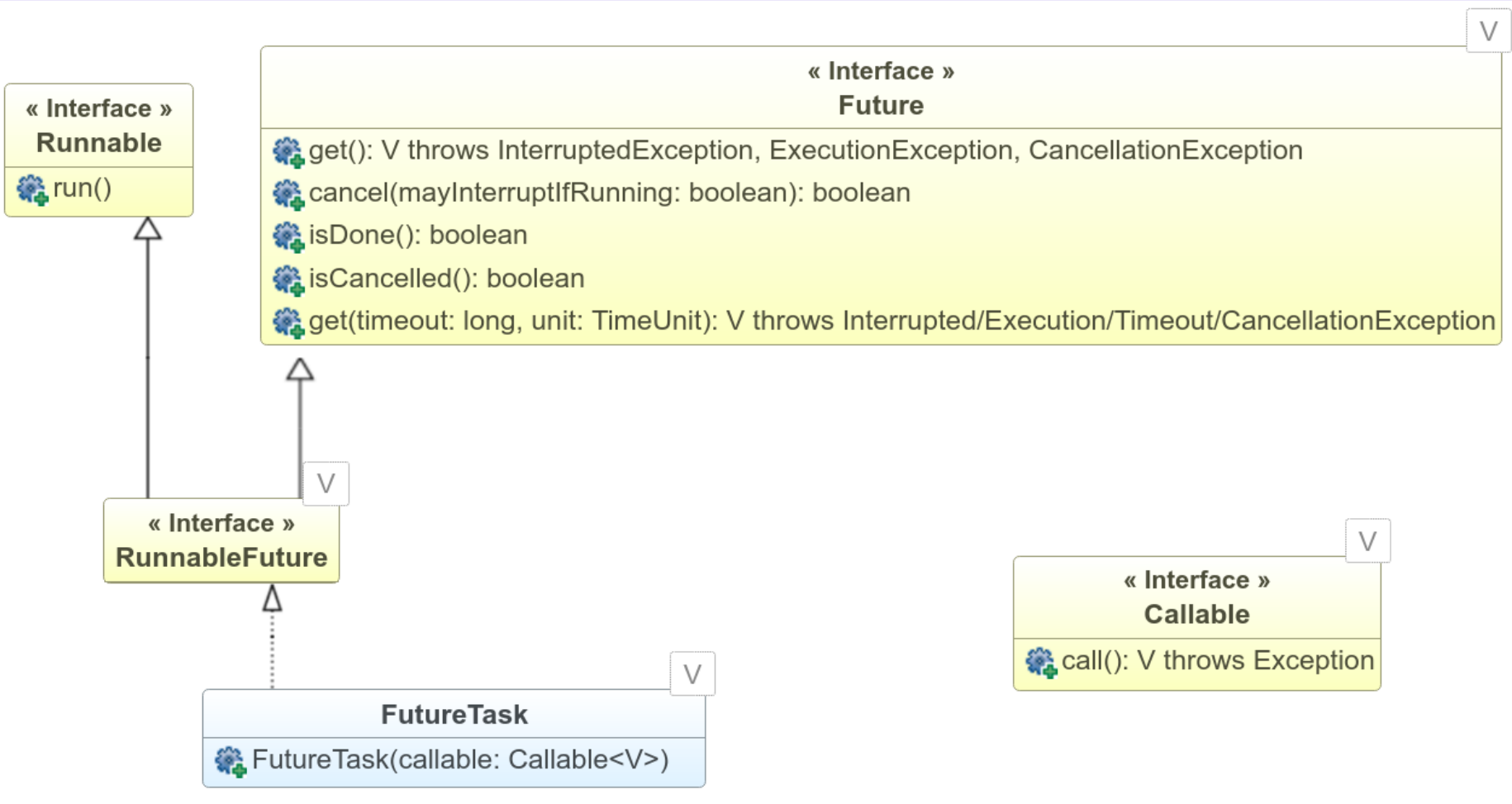
Cast an Exception into an Unchecked Exception

- unchecked exceptions: instances of `RuntimeException` and `Error`. No need to declare them with `throws`
- checked exceptions: all other exceptions. Must be declared with `throws`

If we know that `t` is an unchecked exception, the following code will throw it back as such:

```
public RuntimeException launderThrowable(Throwable t) {
  if (t instanceof RuntimeException)
    return (RuntimeException) t;
  else if (t instanceof Error)
    throw (Error) t;
  else
    // this should never happen, since t was assumed unchecked
    throw new IllegalStateException("Not unchecked!", t);
}
```

Runnable, Callable, Future and FutureTask



Example: A Scalable Result Cache

Consider the specification of a function that transforms an `A` into a `V` and that might be arbitrarily expensive:

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

We want to define a decorator that adds a layer of caching to the process:

```
computable2 = new Memoizer(computable1)
```

The function `computable2` is equivalent to `computable1`, but caches repeated applications

Attempt #1: Synchronize on a Hash Map

```
@ThreadSafe
public class Memoizer1<A, V> implements Computable<A, V> {
  @GuardedBy("this") private final Map<A, V> cache = new HashMap<>();
  private final Computable<A, V> c;

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

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

Only a computation can run at a time, in sequence!

Attempt #2: Use a Concurrent Map

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

The same computation might be executed more times!

Attempt #3: Use a Concurrent Map and FutureTask

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

  public Memoizer3(Computable<A, V> c) { this.c = c; }

  public V compute(A arg) throws InterruptedException {
    Future<V> f = cache.get(arg);
    if (f == null) {
      FutureTask<V> ft = new FutureTask<>(() -> c.compute(arg));
      cache.put(arg, f = ft);
      ft.run(); // call to c.compute happens here
    }
    try {
      return f.get();
    }
    catch (ExecutionException e) {
      throw launderThrowable(e.getCause());
    }
  }
}
```

Very rarely, the same computation might be executed more times!

Attempt #4: Exploit putIfAbsent of Concurrent Maps

```
@ThreadSafe
public class Memoizer<A, V> implements Computable<A, V> {
  private final Map<A, Future<V>> cache = new ConcurrentHashMap<>();
  private final Computable<A, V> c;
  public Memoizer(Computable<A, V> c) { this.c = c; }

  public V compute(A arg) throws InterruptedException {
    while (true) {
      Future<V> f = cache.get(arg);
      if (f == null) {
        FutureTask<V> ft = new FutureTask<>(() -> c.compute(arg));
        f = cache.putIfAbsent(arg, ft);
        if (f == null) {
          f = ft; ft.run();
        }
      }
      try {
        return f.get();
      } catch (CancellationException e) {
        cache.remove(arg, f); // cache eviction, while (true) will retry
      } catch (ExecutionException e) {
        throw launderThrowable(e.getCause());
      }
    }
  }
```

Use the Concurrent Cache in the Factorization Servlet

```
@ThreadSafe
@WebServlet("/Factorizer")
public class Factorizer extends StatelessFactorizer {
  private static final long serialVersionUID = 1L;
  private final Computable<BigInteger, BigInteger[]> cache
    = new Memoizer<>(arg -> factor(arg));

  @Override
  protected void doPost(HttpServletRequest request, HttpServletResponse response)
      throws IOException {

    BigInteger number = extractFromRequest(request);

    try {
      encodeIntoResponse(response, cache.compute(number));
    }
    catch (InterruptedException e) {
      encodeErrorIntoResponse(response, "factorization interrupted");
    }
  }
}
```

Exercise 1

Consider class `MD5s`, that implements a producer/consumer algorithm for generating the MD5 digests of files in some directories

1. complete method `index` of the `Indexer`, in order to store in memory and print on standard output the MD5 digest of each file. The digest can be computed through the auxiliary `md5` method
2. complete methods `alreadyIndexed` and `getMD5sOf`
3. complete method `stop` in order to interrupt all `Indexers`. Pending work should be processed, hence implement the handler for `InterruptedException` inside the `run` method of the `Indexer`

If everything works, it should be possible to invoke `MD5s` from the command line and print the MD5s of the specified directories:

```
java -classpath examples/bin it.univr.concurrency.MD5s examples servlets
```

The execution should terminate at the end of the computation of the digests, always with the same printout (but typically in different orders)

Exercise 2

Implement a board for the `CellularAutomata` example, in order to implement the Game of Life. How do you implement the blocking `waitForConvergence()` method?