Practical Concurrent and Parallel Programming 9

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Plan for today

- More synchronization primitives
  - Semaphore – resource control, bounded buffer
  - CyclicBarrier – thread coordination
- Testing concurrent programs
  - BoundedBuffer example
- Coverage and interleaving
- Mutation and fault injection
- Java Pathfinder
- Concurrent correctness concepts

java.util.concurrent.Semaphore

- A semaphore holds zero or more *permits*
- **`void acquire()`**
  - Blocks till a permit is available, then decrements the permit count and returns
- **`void release()`**
  - Increments the permit count and returns; may cause another blocked thread to proceed
  - NB: a thread may call **`release()`** without preceding acquire, so a semaphore is not like a lock!
- A semaphore is used for resource control
  - Locking may be needed for data consistency
- Writes before **`release`** are *visible* after **`acquire`**

A bounded buffer using semaphores

TestBoundedQueueTest.java

```
class SemaphoreBoundedQueue <T> implements BoundedQueue<T> {
  private final Semaphore availableItems, availableSpaces;
  private final T[] items;
  private int tail = 0, head = 0;
  public SemaphoreBoundedQueue(int capacity) {
    this.availableItems = new Semaphore(0);
    this.availableSpaces = new Semaphore(capacity);
    this.items = makeArray(capacity);
  }
  public void put(T item) throws InterruptedException { // tail
    availableSpaces.acquire();
    doInsert(item);
    availableItems.release();
  }
  public T take() throws InterruptedException {          // head
    availableItems.acquire();
    T item = doExtract();
    availableSpaces.release();
    return item;
  }
}
```

Wait for space

Signal new item

Wait for item

Signal new space

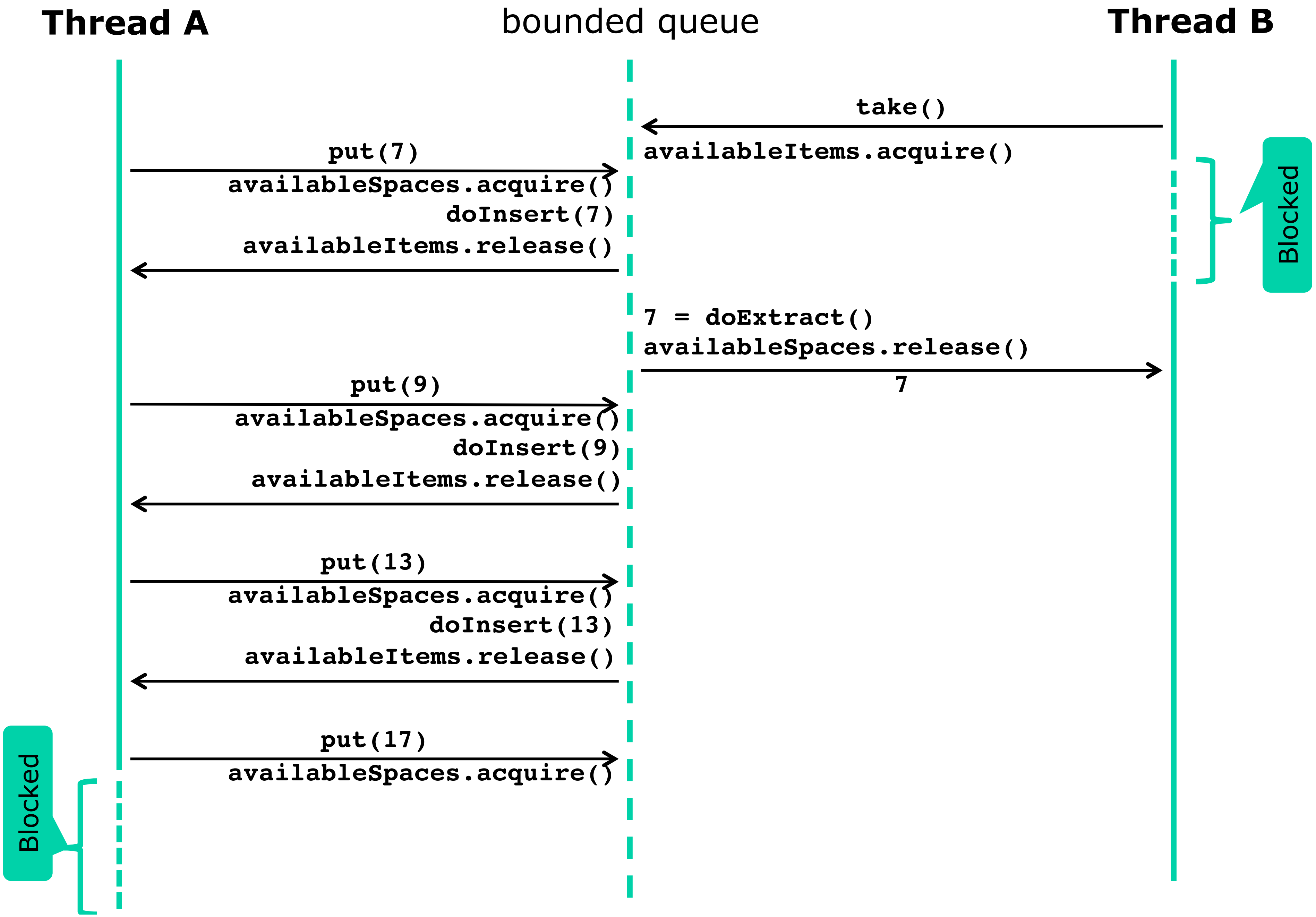
The doInsert and doExtract methods

TestBoundedQueueTest.java

```
class SemaphoreBoundedQueue <T> implements BoundedQueue<T> {
  private final Semaphore availableItems, availableSpaces;
  private final T[] items;
  private int tail = 0, head = 0;
  public void put(T item) throws InterruptedException { ... }
  public T take() throws InterruptedException { ... }
  private synchronized void doInsert(T item) {
    items[tail] = item;
    tail = (tail + 1) % items.length;
  }
  private synchronized T doExtract() {
    T item = items[head];
    items[head] = null;
    head = (head + 1) % items.length;
    return item;
  }
}
```

- *Semaphores* to block waiting for “resources”
- *Locks* (synchronized) for atomic state mutation

Bounded queue with capacity 2



Thread A

bounded queue

Thread B

`take()`

`availableItems.acquire()`

Blocked

`put(7)`

`availableSpaces.acquire()`

`doInsert(7)`

`availableItems.release()`

`7 = doExtract()`

`availableSpaces.release()`

`7`

`put(9)`

`availableSpaces.acquire()`

`doInsert(9)`

`availableItems.release()`

`put(13)`

`availableSpaces.acquire()`

`doInsert(13)`

`availableItems.release()`

`put(17)`

`availableSpaces.acquire()`

Blocked

Testing BoundedQueue

- Divide into
  - Sequential 1-thread test with precise results
  - Concurrent n-thread test with aggregate results
  - … that make it plausible that invariants hold
- Sequential test for queue **`bq`** with capacity 3:

```
assertTrue(bq.isEmpty());
assertTrue(!bq.isFull());
bq.put(7); bq.put(9); bq.put(13);
assertTrue(!bq.isEmpty());
assertTrue(bq.isFull());
assertEquals(bq.take(), 7);
assertEquals(bq.take(), 9);
assertEquals(bq.take(), 13);
assertTrue(bq.isEmpty());
assertTrue(!bq.isFull());
```

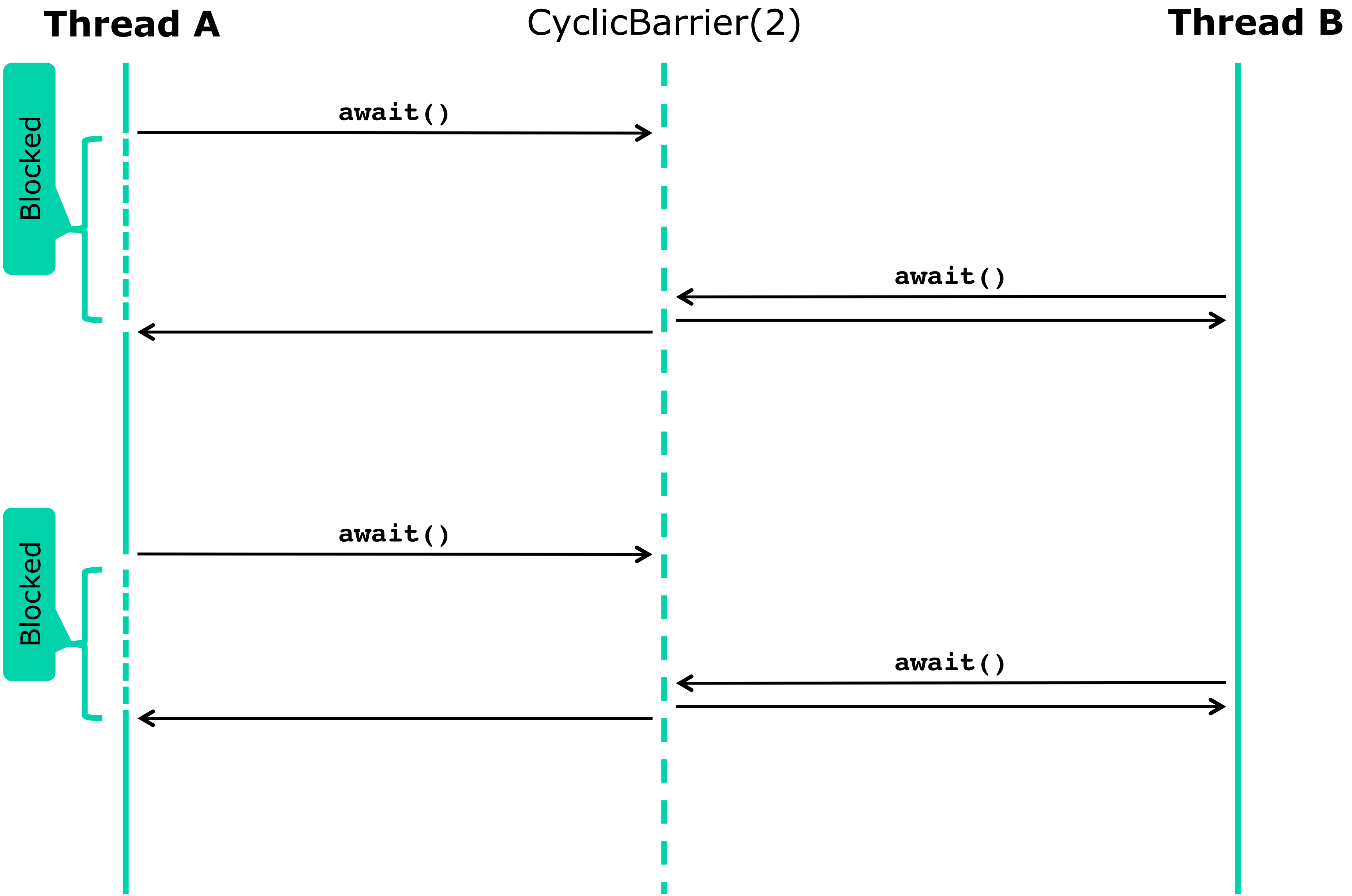
TestBoundedQueueTest.java

java.util.concurrent.CyclicBarrier

- A CyclicBarrier(N) allows N threads
  - to wait for each other, and
  - proceed at the same time when all are ready
- **`int await()`**
  - blocks until all N threads have called await
  - may throw InterruptedException
- Useful to start n test threads + 1 main thread at the same time, N = n + 1

- Writes before **`await`** is called are *visible* after it returns, in all threads passing the barrier

Cyclic barrier with count 2



Concurrent test of BoundedQueue

- Run 10 producer and 10 consumer threads
- A producer inserts 100,000 random numbers
  - Using a *thread-local* random number generator
- A consumer extracts 100,000 numbers
- Afterwards, check that
  - The bounded queue is again empty
  - The sum of consumed numbers equals the sum of produced numbers
- Producers and consumers must sum numbers
  - Using a thread-local sum variable, and afterwards adding to a common AtomicInteger

The PutTakeTest class

```
class PutTakeTest extends Tests {
  protected CyclicBarrier barrier;
  protected final BoundedQueue<Integer> bq;
  protected final int nTrials, nPairs;
  protected final AtomicInteger putSum = new AtomicInteger(0);
  protected final AtomicInteger takeSum = new AtomicInteger(0);

  void test(ExecutorService pool) {
    try {
      for (int i = 0; i < nPairs; i++) {
        pool.execute(new Producer());
        pool.execute(new Consumer());
      }
      barrier.await(); // wait for all threads to be ready
      barrier.await(); // wait for all threads to finish
      assertTrue(bq.isEmpty());
      assertEquals(putSum.get(), takeSum.get());
    } catch (Exception e) {
      throw new RuntimeException(e);
    }
  }
```

Initialize to 2*npairs+1

Make npairs Producers and npairs Consumers

Main: start, finish threads

Check that total effect is plausible

Goetz p. 255

TestBoundedQueueTest.java

A Producer test thread

```
class Producer implements Runnable {
  public void run() {
    try {
      Random random = new Random();
      int sum = 0;
      barrier.await();
      for (int i = nTrials; i > 0; --i) {
        int item = random.nextInt();
        bq.put(item);
        sum += item;
      }
      putSum.getAndAdd(sum);
      barrier.await();
    } catch (Exception e) {
      throw new RuntimeException(e);
    }
  }
}
```

Thread-local Random

Wait till all are ready

Put 100,000 numbers

Add to global putSum

Signal I’m finished

A la Goetz p. 256

TestBoundedQueueTest.java

A Consumer test thread

```
class Consumer implements Runnable {
 public void run() {
  try {
   barrier.await();
   int sum = 0;
   for (int i = nTrials; i > 0; --i) {
    sum += bq.take();
   }
   takeSum.getAndAdd(sum);
   barrier.await();
  } catch (Exception e) {
   throw new RuntimeException(e);
  }
 }
}
```

Wait till all are ready

Take 100,000 numbers

Add to global takeSum

Signal I’m finished

Goetz p. 256

TestBoundedQueueTest.java

Reflection on the concurrent test

- Checks that *item count* and *item sum* are OK
- The sums say nothing about *item order*
  - Concurrent test would be satisfied by a *stack* also
  - But the sequential test would not
- Could we check better for *item order*?
  - Could use 1 producer, put'ting in increasing order; and 1 consumer take'ing and checking the order
    - But a 1-producer 1-consumer queue may be incorrect for multiple producers or multiple consumers
  - Could make test synchronize between producers and consumers, but
    - Reduces test thread interleaving and thus test efficacy
    - Risk of artificial deadlock because queue synchronizes also

Techniques and hints

- Create a *local random number generator* for each thread, or use ThreadLocalRandom
  - Else may limit concurrency, reduce test efficacy
- Do *no synchronization* between threads
  - May limit concurrency, reduce test efficacy
- Use CyclicBarrier(n+1) to *start* n threads
  - More likely to run at the same time, better testing
- Use it also to wait for the threads to *finish*
  - So main thread can check the results
- Test on a *multicore* machine, 4-16 cores
- Use *more test threads than cores*
  - So some threads occasionally get de-scheduled

Plan for today

- More synchronization primitives
  - Semaphore – resource control, bounded buffer
  - CyclicBarrier – thread coordination
- Testing concurrent programs
  - BoundedBuffer example
- **Coverage and interleaving**
- **Mutation and fault injection**
- Java Pathfinder
- Concurrent correctness concepts

Test coverage

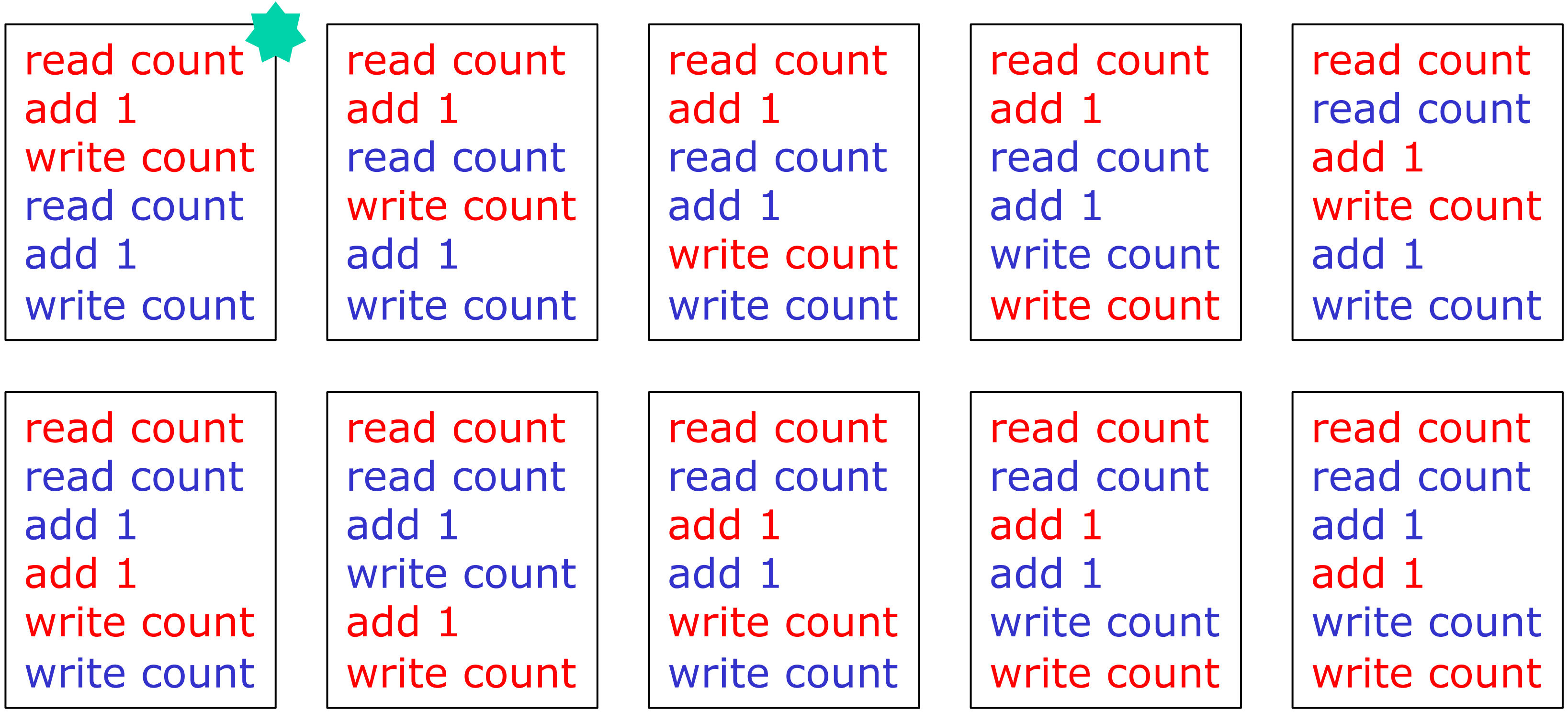
- Sequential
  - *Method coverage*: has each method been called?
  - *Statement coverage*: has each statement been executed?
  - *Branch coverage*: have all branches **`if`**, **`for`**, **`while`**, **`do-while`**, **`switch`**, **`try-catch`** been executed?
  - *Path coverage*: have all paths through the code been executed? (very unlikely)
- Concurrent
  - *Interleaving coverage*: have all interleavings of different methods' execution paths been tried? (extremely unlikely)

Thread interleavings

Two threads both doing `count = count + 1`:

Thread A: read count; add 1; write count

Thread B: read count; add 1; write count



read count add 1 write count read count add 1 write count	read count add 1 read count write count add 1 write count	read count add 1 read count add 1 write count write count	read count add 1 read count add 1 write count write count	read count read count add 1 write count add 1 write count
read count read count add 1 add 1 write count write count	read count read count add 1 write count add 1 write count	read count read count add 1 add 1 write count write count	read count read count add 1 add 1 write count write count	read count read count add 1 add 1 write count write count

Plus 10 symmetric cases, swapping red and blue

Thread interleaving for testing

- To find concurrency bugs, we want to exercise all interesting thread interleavings
- How many: N threads each with M instructions have $(NM)!/(M!)^N$ possible interleavings
  - Zillions of tests needed to cover interleavings
- PutTakeTest explores at most 1m of them
  - And JVM may be too deterministic and explore less
- One can increase interleavings using **`Thread.yield()`** or **`Thread.sleep(1)`**
  - But this requires modification of the tested code
  - Or special tools: Java Pathfinder, Microsoft CHESS

What is $(NM)!/(M!)^N$ in real money?

Scala

```
def fac(n: Int): BigInt = if (n==0) 1 else n*fac(n-1)
def power(M: BigInt, P: Int): BigInt = if (P == 0) 1 else M*power(M, P-1)
def interleaving(N : Int, M : Int) = fac(N*M) / power(fac(M), N)
```

```
interleaving(1, 15) is 1

interleaving(5, 1) is 120

interleaving(5, 2) is 113400

interleaving(2,3) is 20

interleaving(5, 3) is 168168000

interleaving(5, 100) is
1723416559477700853414837928472199681495283861586428952219489469740322151844673449823990180491172965116996270064140072158794074346
```

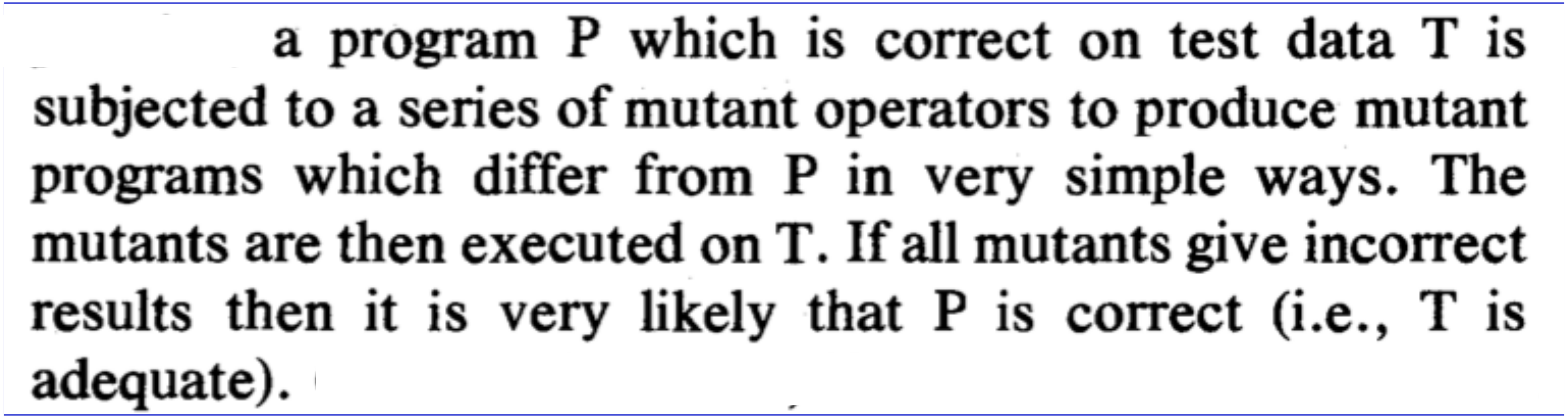
```
interleaving(5, 100) is
172341655947770085341483792847219968149528386158642895221948946974
```

How good is that test?
Mutation testing and fault injection

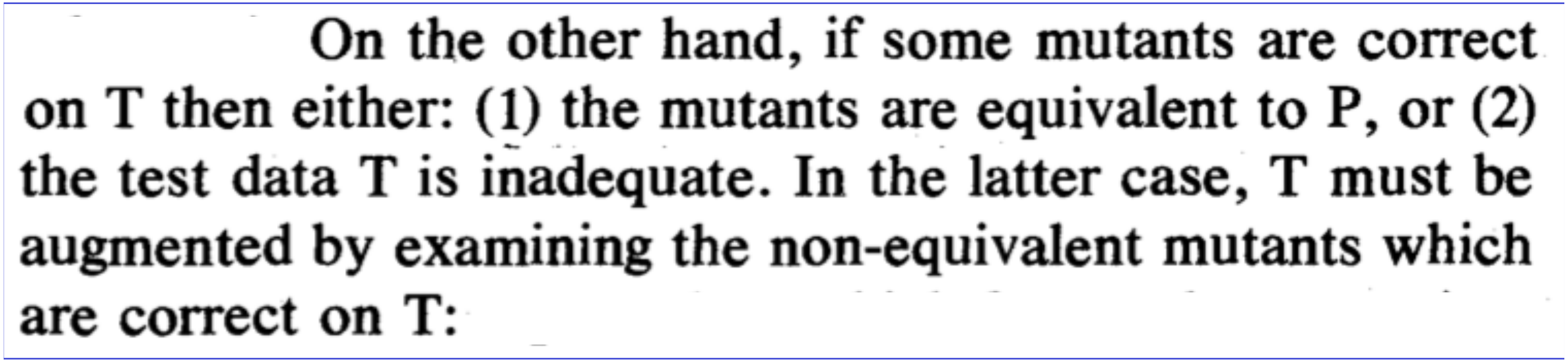
- If some code passes a test,
  - is that because the code is correct?
  - or because the test is too weak, bad coverage?
- To find out, *mutate* the **program**, *inject faults*
  - eg. remove synchronization
  - eg. lock on the wrong object
  - do anything that should make the code not work

- If it still passes the test, the **test** is too weak
  - Improve the test so it finds the code fault

Mutation testing quotes



a program P which is correct on test data T is subjected to a series of mutant operators to produce mutant programs which differ from P in very simple ways. The mutants are then executed on T. If all mutants give incorrect results then it is very likely that P is correct (i.e., T is adequate).



On the other hand, if some mutants are correct on T then either: (1) the mutants are equivalent to P, or (2) the test data T is inadequate. In the latter case, T must be augmented by examining the non-equivalent mutants which are correct on T:

Budd, Lipton, Sayward, DeMillo: The design of a prototype mutation system for software testing, 1978

Some mutations to BoundedQueue

```
public void put(T item) throws InterruptedException { // tail
  availableSpaces.acquire();
  doInsert(item);
  availableItems.release();
}
```

Delete

Insert

```
availableSpaces.release()
```

Delete

```
private synchronized void doInsert(T item) {
  items[tail] = item;
  tail = (tail + 1) % items.length;
}
```

Delete

```
private synchronized T doExtract() {
    T item = items[head];
    items[head] = null;
    head = (head + 1) % items.length;
    return item;
  }
```

Delete

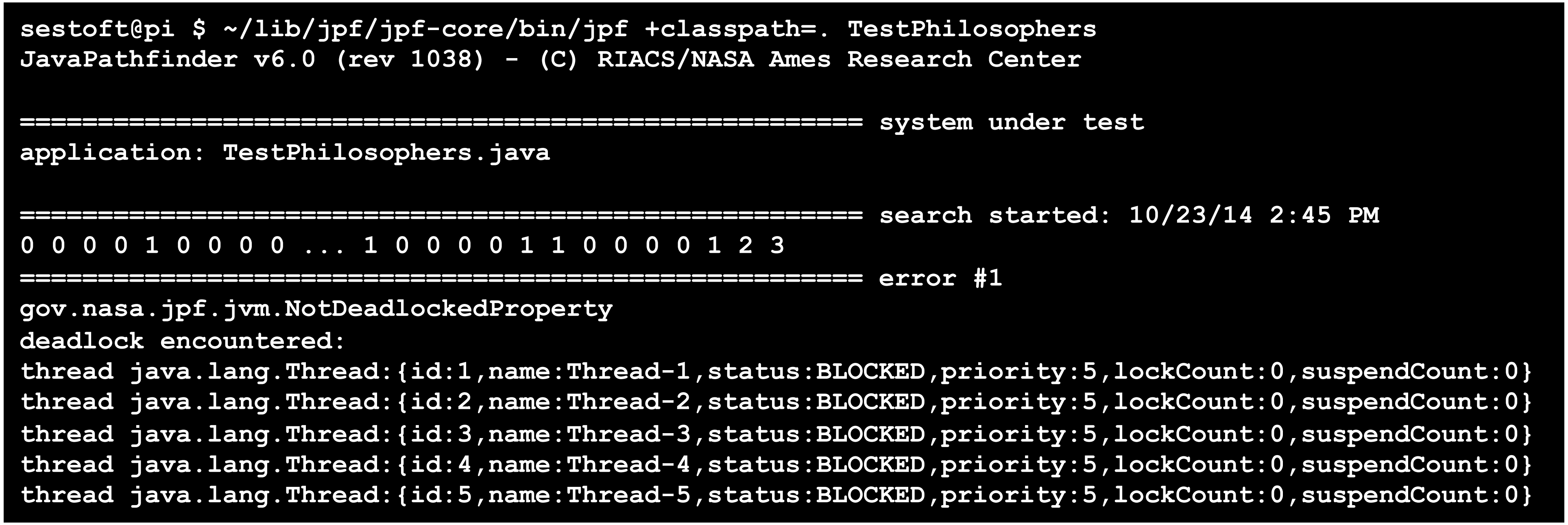
Delete

The Java Pathfinder tool

- NASA project at http://babelfish.arc.nasa.gov/trac/jpf
- A Java Virtual Machine that
  - can explore all computation paths
  - supervise the execution with “listeners”
  - generate test cases
- Properties of Java Pathfinder
  - a multifaceted research project
  - slow execution of code
  - much better test coverage, eg deadlock detection

Java Pathfinder example

- TestPhilosophers on 1 core never deadlocks
  - at least not within the bounds of my patience ...
- But Java Pathfinder discovers a deadlock
  - because it explores many thread interleavings



```
sestoft@pi $ ~/lib/jpf/jpf-core/bin/jpf +classpath=. TestPhilosophers
JavaPathfinder v6.0 (rev 1038) - (C) RIACS/NASA Ames Research Center

====================================================== system under test
application: TestPhilosophers.java

====================================================== search started: 10/23/14 2:45 PM
0 0 0 0 1 0 0 0 0 ... 1 0 0 0 0 1 1 0 0 0 0 1 2 3
====================================================== error #1
gov.nasa.jpf.jvm.NotDeadlockedProperty
deadlock encountered:
thread java.lang.Thread:{id:1,name:Thread-1,status:BLOCKED,priority:5,lockCount:0,suspendCount:0}
thread java.lang.Thread:{id:2,name:Thread-2,status:BLOCKED,priority:5,lockCount:0,suspendCount:0}
thread java.lang.Thread:{id:3,name:Thread-3,status:BLOCKED,priority:5,lockCount:0,suspendCount:0}
thread java.lang.Thread:{id:4,name:Thread-4,status:BLOCKED,priority:5,lockCount:0,suspendCount:0}
thread java.lang.Thread:{id:5,name:Thread-5,status:BLOCKED,priority:5,lockCount:0,suspendCount:0}
```

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- Testing concurrent programs
  - BoundedBuffer example
- Coverage and interleaving
- Mutation and fault injection
- Java Pathfinder
- **Concurrent correctness concepts**

Correctness concepts

- Quiescent consistency
  - *Method calls separated by a period of quiescence should appear to take effect in their real-time order*
  - Says nothing about overlapping method calls
- Sequential consistency

Not very useful

  - *Method calls should appear to take effect in program order* – seen from each thread
- Linearizability
  - *A method call should appear to take effect at some point between its invocation and return*
  - This is called its *linearization point*

Non-blocking queue example code

A la Herlihy & Shavit p. 46, 48

TestHSQueues.java

```
class WaitFreeQueue <T> {
  private final T[] items;
  private          int tail = 0, head = 0;
  public              boolean enq(T item) {
    if (tail - head == items.length)
      return false;
    else {
      items[tail % items.length] = item;
      tail++;
      return true;
  } }
  public              T deq() {
    if (tail == head)
      return null;
    else {
      T item = items[head % items.length];
      head++;
      return item;
} } }
```

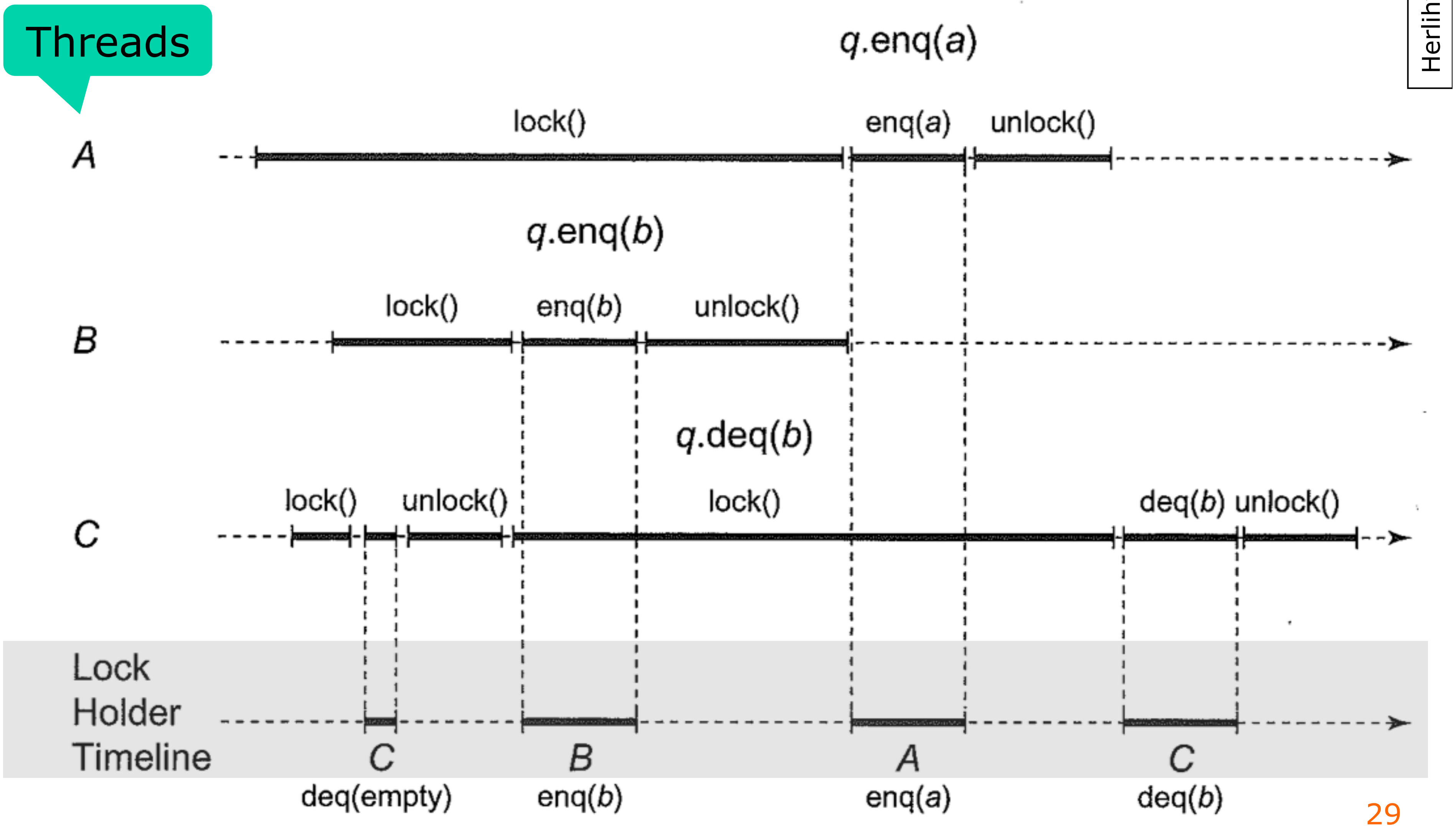
- With only one enqueuer and one dequeuer, the queue needs no locking!

- With locks, method calls cannot overlap, clear
- Without locks, how understand overlapping calls?
  - One thread calling enq, another calling deq, overlapping

A program run = method calls

- Method call: invocation, return, and duration
- Method calls may overlap in time

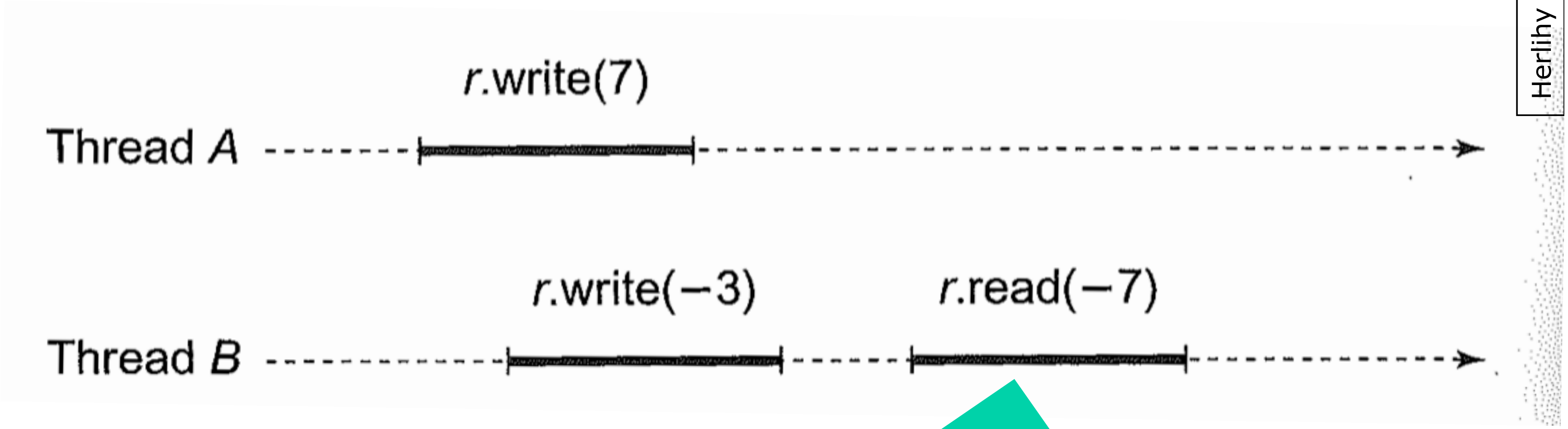
Herlihy & Shavit p. 47



Method call effect seems instantaneous

- Principle 3.3.1: *A method call should appear to take effect instantaneously*
  - Method calls take effect one at a time

Herlihy & Shavit p. 50



Not acceptable, the method calls' effects are not instantaneous

Quiescent consistency

- Principle 3.3.2: *Method calls separated by a period of quiescence should appear to take effect in their real-time order*
  - This says nothing about overlapping method calls
  - This assumes we can observe inter-thread actions
- Java's ConcurrentHashMap:

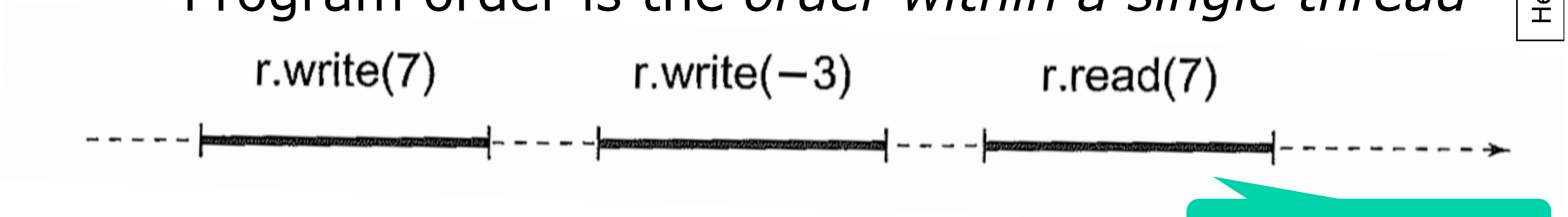
> "Bear in mind that the results of aggregate status methods including **`size`**, **`isEmpty`**, and **`containsValue`** are typically useful only when a map is not undergoing concurrent updates in other threads.
>
> Otherwise the results of these methods reflect transient states that may be adequate for monitoring or estimation purposes, but not for program control.

Class java.util.concurrent.ConcurrentHashMap documentation

Sequential consistency and program order

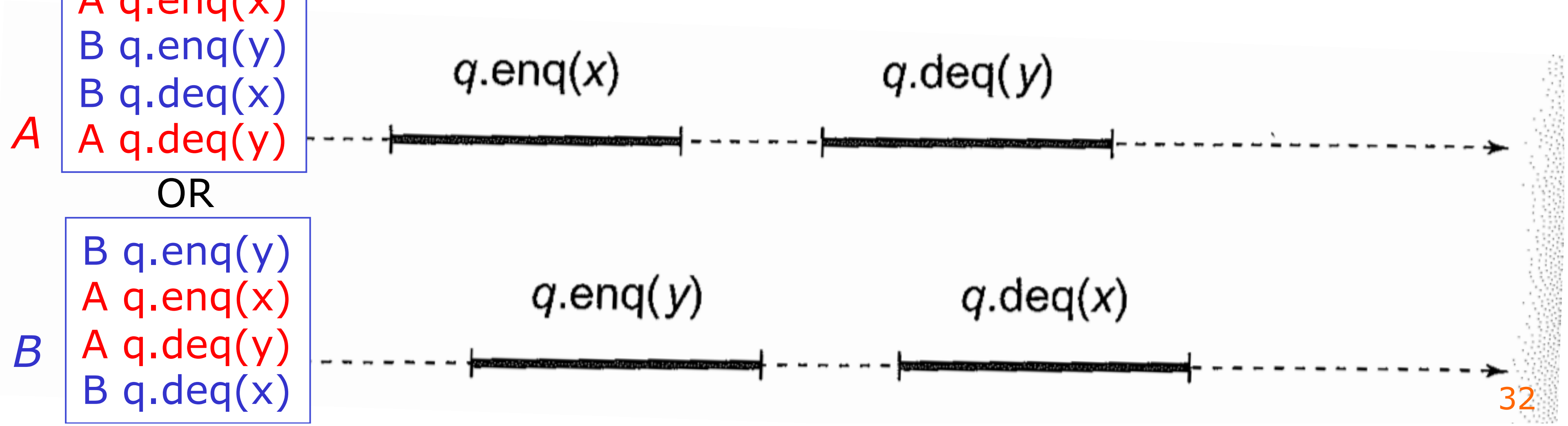
Herlihy & Shavit p. 50

- Principle 3.4.1: *Method calls should appear to take effect in program order*
  - Program order is the *order within a single thread*



Not acceptable

- This scenario is sequentially consistent:

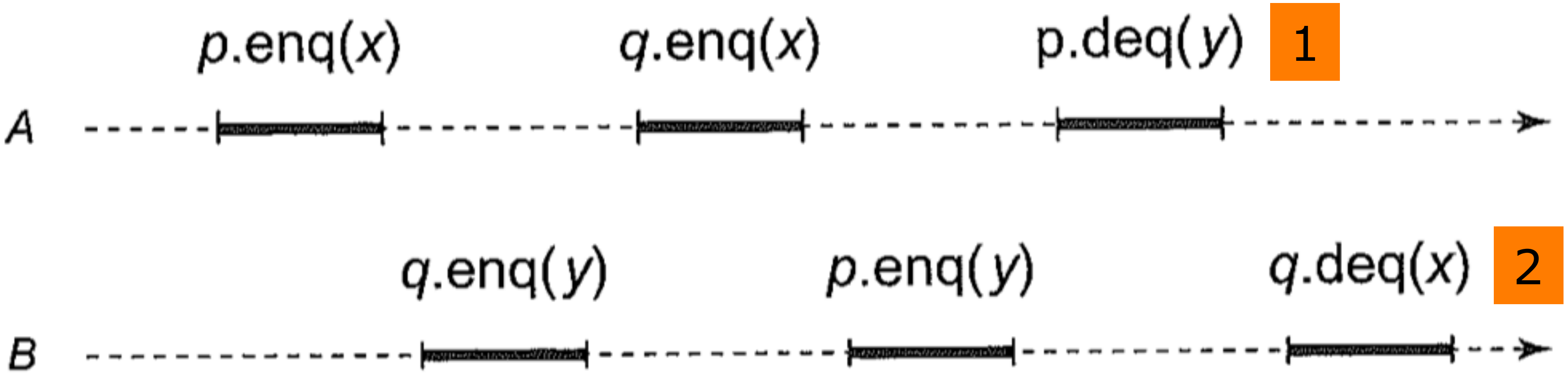


A q.enq(x)
B q.enq(y)
B q.deq(x)
A q.deq(y)

OR

B q.enq(y)
A q.enq(x)
A q.deq(y)
B q.deq(x)

Seq. consistency is not compositional



Herlihy & Shavit p. 54

- Sequentially consistent for each queue p, q:

B p.enq(y)
A p.enq(x)
A p.deq(y)

AND

B q.enq(y)
A q.enq(x)
B q.deq(y)

- Taken together, they are not seq. consistent:
  1 – p.enc(y) must precede p.enc(x)
    - which precedes q.enc(x) in thread A program order
  2 – q.enc(x) must precede q.enc(y)
    - which precedes p.enc(y) in thread B program order
  – So p.enc(y) must precede p.enc(y), impossible

Reflection on sequential consistency

- Seems natural
- It is what synchronization tries to achieve
- If all (unsynchronized) code were to satisfy it, that would preclude optimizations:

Java, or C#, does not guarantee sequential consistency of non-synchronized non-volatile fields (eg. JLS §17.4.3)

- The lack of compositionality makes sequential consistency a poor reasoning tool
  - Using a bunch of sequentially consistent data structures together does not give seq. consistency

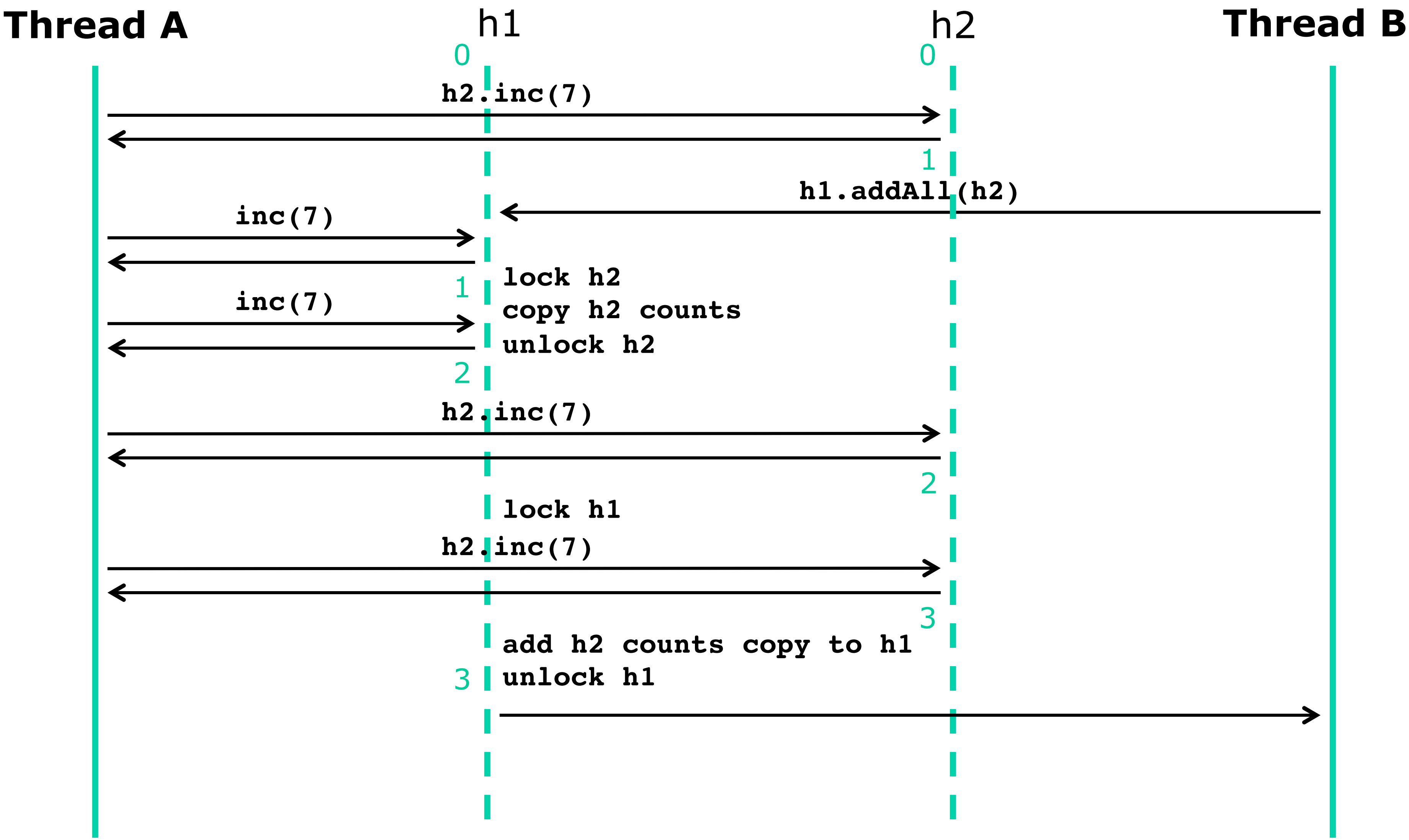
Linearizability

- Principle 3.5.1: *Each method call should appear to take effect instantaneously at some moment between its invocation and response.*
- Usually shown by identifying a *linearization point* for each method.

- In a Java monitor pattern methods, the linearization point is typically at lock release
- In non-locking WaitFreeQueue<T>
  - linearization point of **`enc()`** is at **`tail++`** update
  - linearization point of **`dec()`** is at **`head++`** update
- Less clear in lock-free methods, week 11-12

TestHSQueues.java

A Histogram h1.addAll(h2) scenario



Thread A

h1

h2

Thread B

0

0

h2.inc(7)

1

h1.addAll(h2)

inc(7)

lock h2

1

inc(7)

copy h2 counts

unlock h2

2

h2.inc(7)

2

lock h1

h2.inc(7)

3

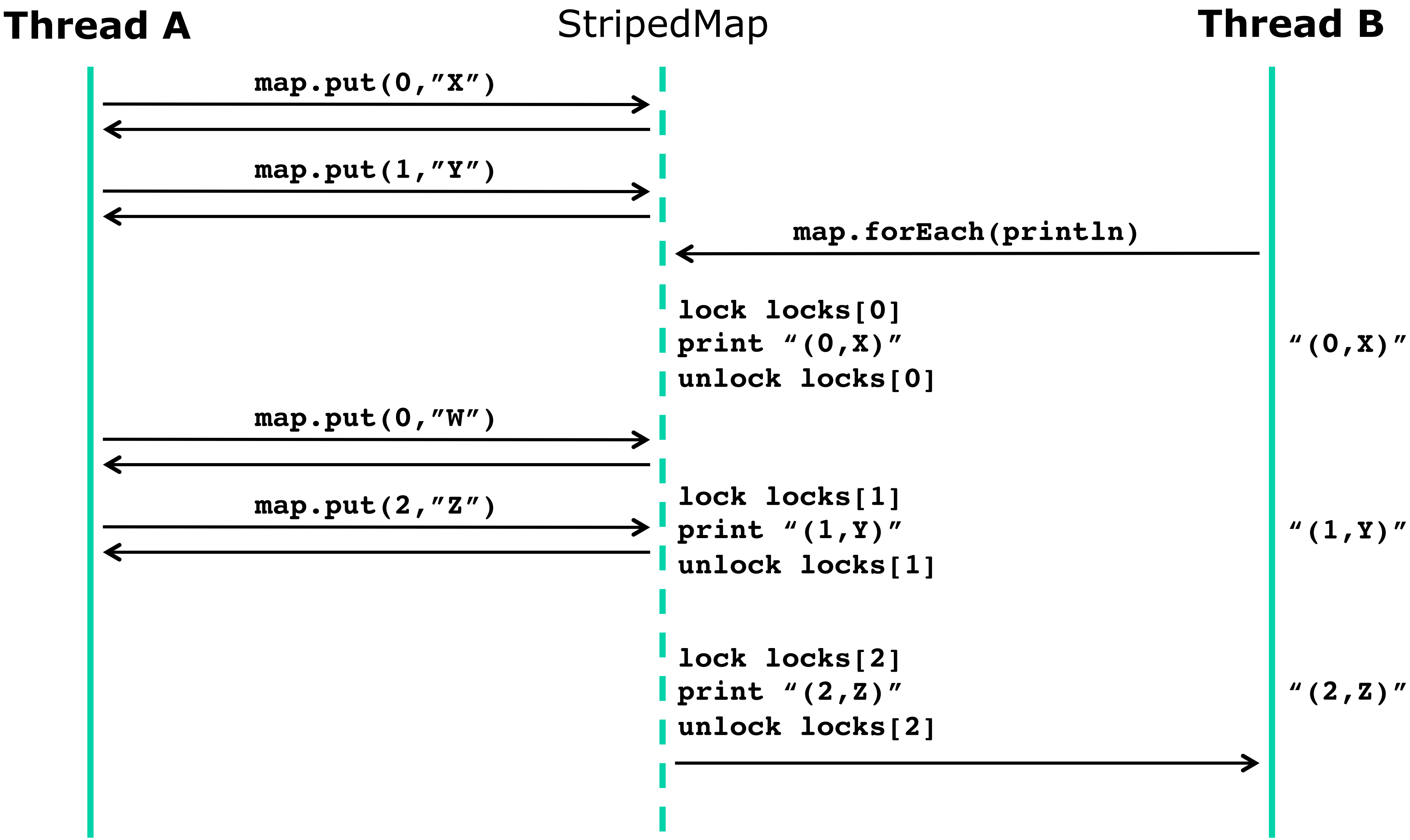
add h2 counts copy to h1

3

unlock h1

The result does not reflect the joint state of h1 and h2 at any point in time.
(Because h1 may be updated while h2 is locked, and vice versa).

A StripedMap.forEach scenario



Thread A

StripedMap

Thread B

`map.put(0,"X")`

`map.put(1,"Y")`

`map.forEach(println)`

```
lock locks[0]
print "(0,X)"
unlock locks[0]
```

"(0,X)"

`map.put(0,"W")`

`map.put(2,"Z")`

```
lock locks[1]
print "(1,Y)"
unlock locks[1]
```

"(1,Y)"

```
lock locks[2]
print "(2,Z)"
unlock locks[2]
```

"(2,Z)"

Seen from Thread A it is strange that (2,Z) is in the map but not (0,W).
(Stripe 0 is enumerated before stripe 2, and stripe 1 updated in between).

Concurrent bulk operations

- These typically have rather vague semantics:

> "Iterators and Spliterators provide *weakly consistent* [...] traversal:
> - 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"

Package java.util.concurrent documentation

- The three bullets hold for StripedMap.forEach
- Precise test only in quiescent conditions
  - But (a) does not skip entries that existed at call time, and (b) does not process an entry twice

This week

- Reading
  - Goetz et al chapter 12
  - Herlihy & Shavit chapter 3

- Exercises
  - Show you can test concurrent software with subtle synchronization mechanisms

- Read before next week's lecture
  - Herlihy and Shavit sections 18.1-18.2
  - Harris et al: *Composable memory transactions*
  - Cascaval et al: *STM, Why is it only a research toy*

Next week's reading: Software transactional memory STM

- Herlihy and Shavit sections 18.1-18.2
  - Brief critique of locking and introduction to STM
- Harris et al: *Composable memory transactions, 2008*
  - Made STM popular again around 2004
  - Using the functional language Haskell
- Cascaval et al: *STM, Why is it only a research toy, 2008*
  - Some people are skeptical, but they use C
  - STM more likely to be useful in mostly-immutable settings than in anarchic imperative/OO settings