Practical Concurrent and Parallel Programming

Kasper Østerbye
IT University of Copenhagen

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Plan for today

- Why this course?
- Course contents, learning goals
- Practical information
- Mandatory exercises, examination

- Java threads
- Java locking, the **`synchronized`** keyword
  - Use **`synchronized`** on blocks, not on methods
- Visibility of memory writes
- Threads for performance

Based on slides by
Peter Sestoft

The teachers

- Course responsible: Kasper Østerbye
  - PhD 1989, Aalborg University
  - Programming languages and software understanding
  - Joined ITU in 2000 (but has been away for 5 years)
- Co-teacher: Jørgen Staunstrup
- Material/Course: Peter Sestoft, ’14, ’15, ’16
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Why this course?

- Parallel programming is necessary
  - The real world is parallel
    - Think of the atrium lifts: lifts move, buttons are pressed
    - Think of handling a million online banking customers
  - For performance
  - To share ressources (think virtual machines)
- It is easy, and disastrous, to get it wrong
  - Testing is even harder than for sequential code
  - You should learn how to make correct parallel code
    - in a real language, used in practice
  - You should learn how to make fast parallel code
    - and measure whether one solution is faster than another
    - and understand why

Course contents

- Threads, locks, mutual exclusion, scalability
- **Java 8** streams, functional programming
- Performance measurements
- Tasks, the Java executor framework
- Safety, liveness, deadlocks
- Testing concurrent programs
- Some more advanced concepts from Java and other languages

Learning objectives

See formal page in LearnIT

Expected prerequisites

- From the ITU course base:
  “Students must know the Java programming language very well, including inner classes and a first exposure to threads and locks, and event-based GUIs as in Swing or AWT.”

- Today we will briefly review the basics of
  - Java threads
  - Java synchronized methods and statements
  - Java’s `final` keyword
  - Java inner classes and lambdas

Standard weekly plan

- Lectures Fridays in zoom
  - Oral feedback on Thursdays (zoom)
- Exercise hand-in: Thursday morning by 7
  - On LearnIT, as a link to your itu github with solutions

Course information online

- Course LearnIT page, restricted access:
  https://learnit.itu.dk/course/view.php?id=3017108

- Course gitrepo, public access:
  https://github.itu.dk/kasper/PCPP-Public
  - Overview of lectures and exercises
  - Lecture slides and exercise sheets
  - Example code
  - List of all mandatory reading materials

Exercises

- There are 13 sets of weekly exercises
- You are expected to work in groups of 2-3 students, and in teams of two groups.
- Hand in the solutions through LearnIT
- Each team will be given oral feedback for upto 45 minutes on Thursday - a schedule is available.
- 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**

Ambition levels

- We (teachers) acknowledge that you might have different ambition levels for this class and your education.
- Exercises are in three ambition levels.
  - Green: “I want a 4, but can live with a 2”.
  - Yellow: “I want a 7, but hope for a 10”.
  - Red: “I will be disappointed if less than 10”.
- Red must do all exercises, Yellow those marked Yellow and Green, and Green only need to do the Green.
- Groups and teams must be same ambition level.
- Oral feedback according to ambition.

The exam

- A 30 hour take-home written exam/project
  - Electronic submission in LearnIT
  - Followed by random sample “cheat check”
- Expected exam workload is 16 hours
  - Individual exam, no collaboration
  - All materials, including Internet, allowed
  - Always credit the sources you use
  - Plagiarism is **forbidden** – as always
- The old exams are on the public homepage

Stuff you need

- Buy Goetz et al: *Java Concurrency in Practice*
  - From 2006, still the best on Java concurrency
  - Most contents is relevant for C#/.NET too
- Free lecture notes and papers, see homepage
- A few other book chapters, see LearnIT

- **Java 8** SDK installed on your computer
  - Java 7 or earlier will **not** work

What about other languages?

- .NET and C# are very similar to Java
  – We will point out differences on the way
- Kotlin, Scala, F#, ... build on JVM or .NET
- C and C++ have some differences (ignore)
- GO, Rust, Python, …
  - The list is long, but we will only touch upon other languages as background material.

Threads and concurrency in Java

- A **thread** is
  - a sequential activity executing Java code
  - running at the same time as other activities
- Concurrent = at the same time = in parallel
- Threads communicate via fields
  - That is, by updating **shared mutable state**

A thread-safe class for counting

- A thread-safe long counter:

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

TestLongCounter.java

- The state (field **`count`**) is **`private`**
- Only **`synchronized`** methods read and write it

A thread that increments the counter

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

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

An anonymous inner class, and an instance of it

When started, the thread will do this: increment forever

- This only *creates* the thread, does not *start* it

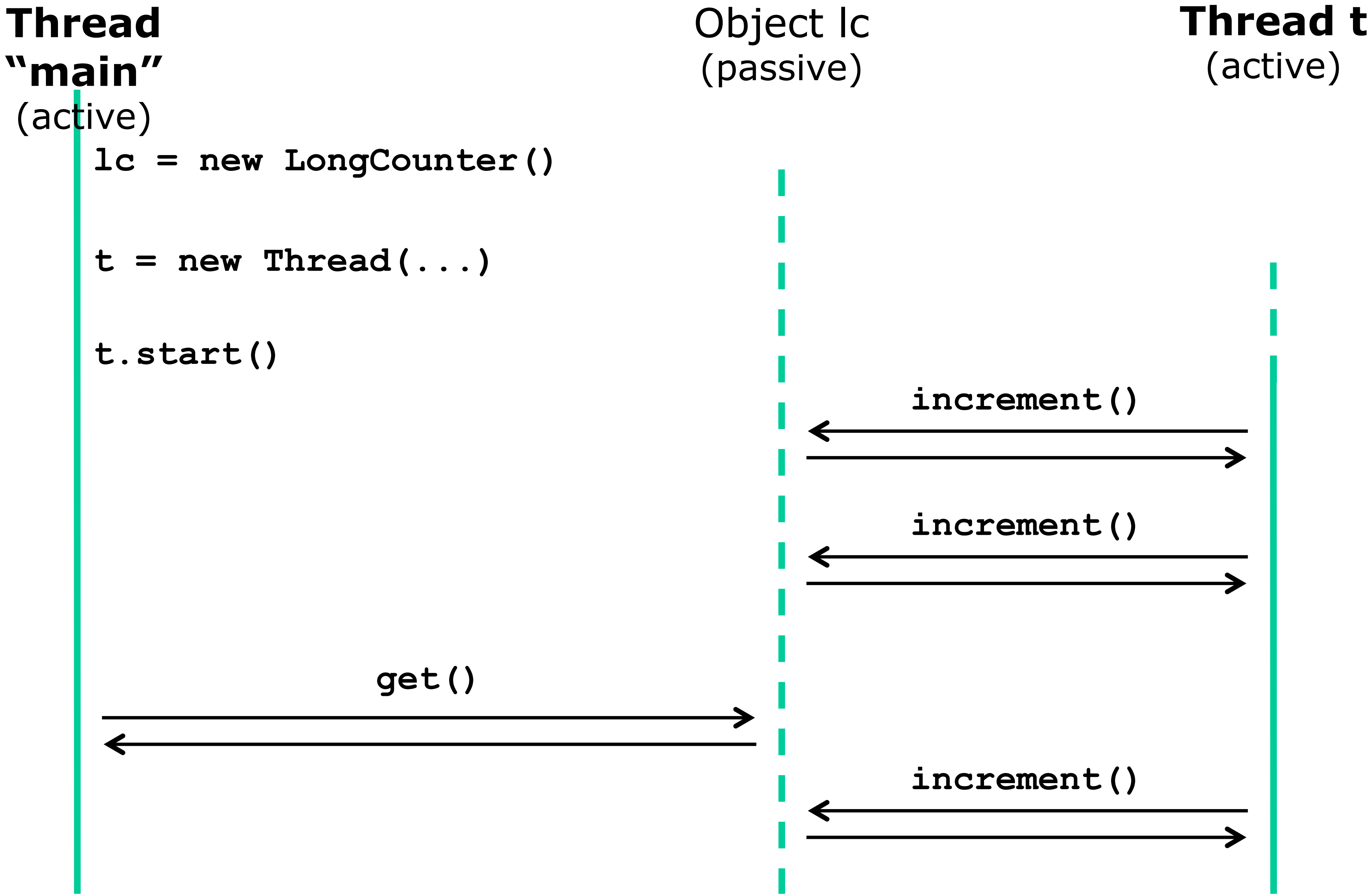
TestLongCounter7.java

Starting the thread in parallel with the main thread

```
public static void main(String[] args) ... {
  final LongCounter lc = new LongCounter();
  Thread t = new Thread(new Runnable() { ... });
  t.start();
  System.out.println("Press Enter ... ");
  while (true) {
    System.in.read();
    System.out.println(lc.get());
  }
}
```

```
Press Enter to get the current value:
60853639
103606384
263682708
...
```

Creating and starting a thread (and communicating via object)



Java 8 lambda expressions

- Instead of old anonymous inner classes:

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

TestLongCounter7.java

- ... we use neat Java 8 lambda expressions:

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

TestLongCounter.java

Locks and the synchronized statement

- Any Java object can be used for *locking*
- The **`synchronized`** statement

```
synchronized (obj) {
   ... body ...
}
```

  - Blocks until the lock on **`obj`** is available
  - Takes (acquires) the lock on **`obj`**
  - Executes the body block
  - Releases the lock, also on **`return`** or exception
- By consistently locking on the same object
  - one can obtain **mutual exclusion**, so
  - at most one thread can execute the code at a time

A synchronized method simply locks the "this" reference around body

- A synchronized instance method

```
class C {
  public synchronized void method() { ... }
}
```

really uses a **synchronized** statement:

```
class C {
  public void method() {
    synchronized (this) { ... }
  }
}
```

- Q: What is being locked? (The entire class, the method, the instance, the Java system)?

What about synchronized *static* methods?

- A synchronized static method

```
class C {
  public synchronized static void method()
    { ... }
}
```

locks on the class runtime object C.class:

```
class C {
  public static void method() {
    synchronized (C.class) { ... }
  }
}
```

Use synchronized statements, not synchronized methods

- So it is clear what object is being locked on
- So only your methods lock on the object

```
class LongCounter {
  public synchronized void increment() { ... }
  public synchronized long get() { ... }
}
```

Good

```
class LongCounterBetter {
  private final Object myLock = new Object();
  public void increment() {
    synchronized (myLock) { ... }
  }
  public long get() {
    synchronized (myLock) { ... }
  }
}
```

TestLongCounterBetter.java

Only these methods can lock on myLock

Clear what is locked on

Better

Multiple threads, locking

- Two threads incrementing counter in parallel:

```
final int counts = 10_000_000;
Thread t1 = new Thread(() -> {
  for (int i=0; i<counts; i++)
    lc.increment();
});
Thread t2 = new Thread(() -> {
  for (int i=0; i<counts; i++)
    lc.increment();
});
```

TestLongCounterExperiments.java

- Q: How many threads are running now?

Starting the threads, and waiting for their completion

```
t1.start(); t2.start();
```

- A thread completes when the lambda returns
- To wait for thread **`t`** completing, call **`t.join()`**
- May throw InterruptedException

```
try { t1.join(); t2.join(); }
catch (InterruptedException exn) { ... }
```

```
System.out.println("Count is " + lc.get());
```

- What is **`lc.get()`** after threads complete?
  - Each thread calls **`lc.increment()`** ten million times
  - So it gets called 20 million times

Removing the locking

- Non-thread-safe counter class:

```
class LongCounter2 {
  private long count = 0;
  public void increment() {
    count = count + 1;
  }
  public long get() { return count; }
}
```

- Produces very wrong results, not 20 million:

```
Count is 10041965
Count is 19861602
Count is 18939813
```

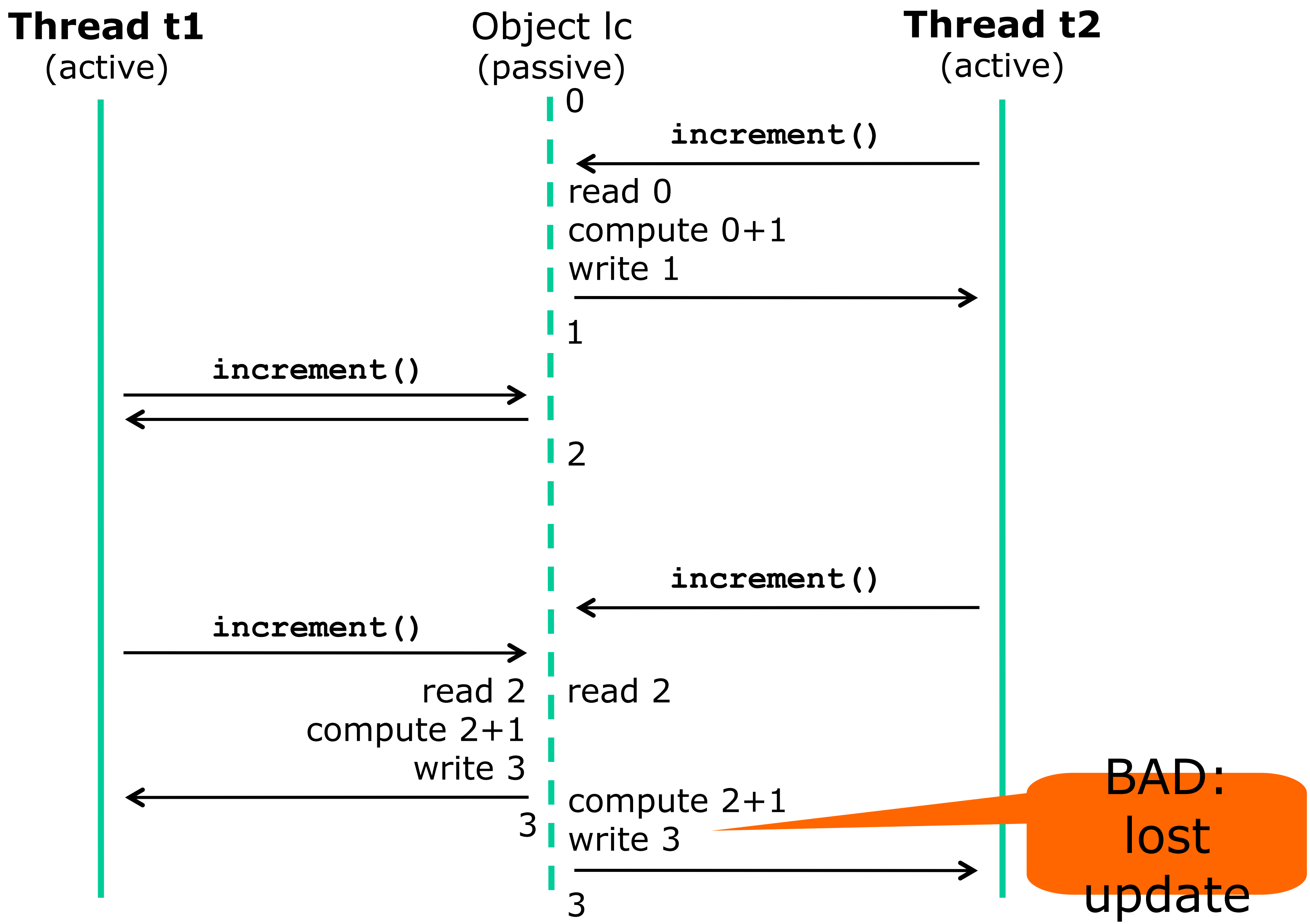
- Q: Why?

The operation `count = count + 1` is not atomic

- What `count = count + 1` means:
  - read `count`
  - add 1
  - write result to `count`
- Hence *not atomic*
- So risk that two `increment()` calls will increase `count` by only 1
- NB: Same for `count += 1` and `count++`

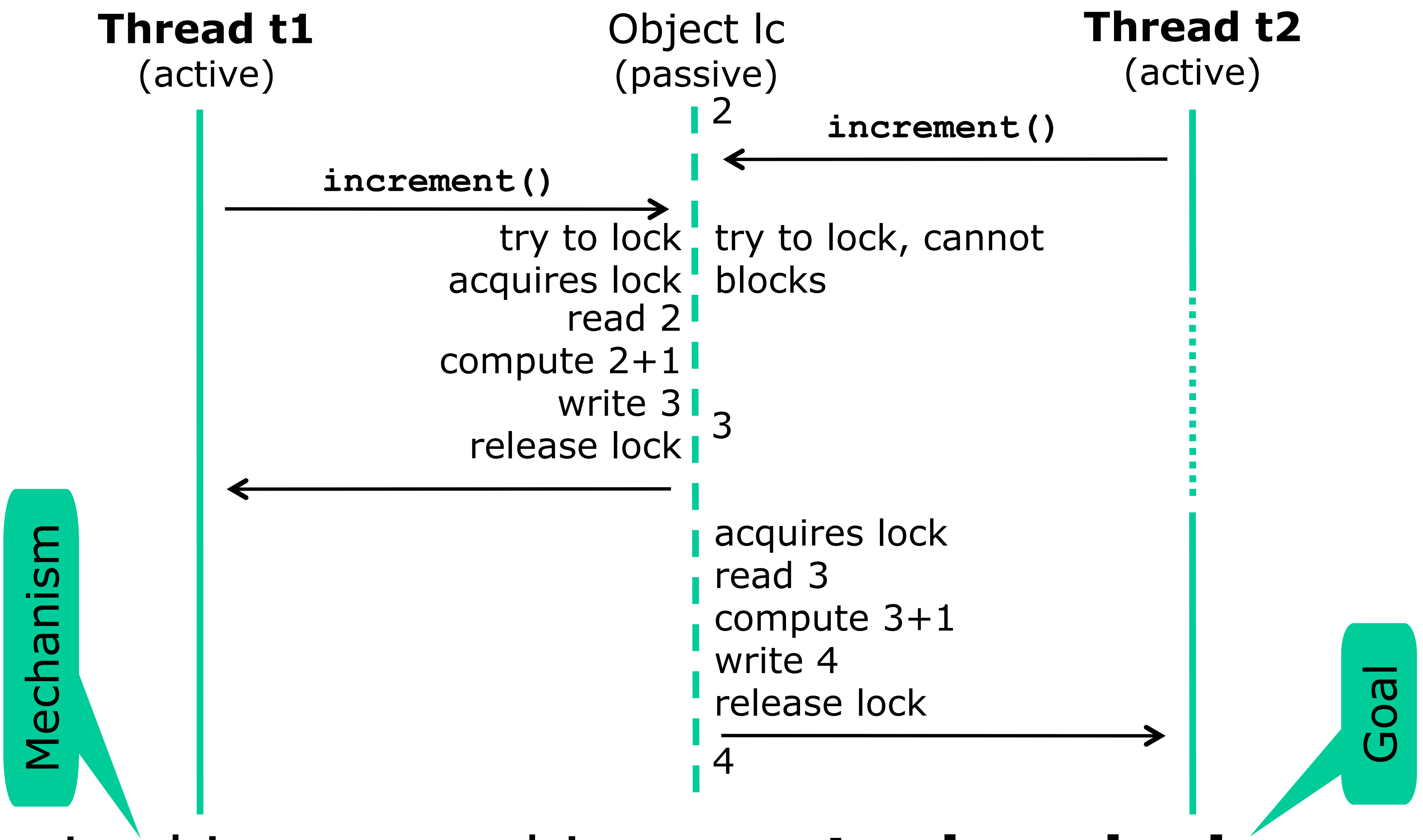
No locking: lost update

Without locking



How does locking help?

With locking



- Locking can achieve **mutual exclusion**
  - Lock on the same object before **all** state accesses
  - Unfortunately, quite easy to get it wrong

Why synchronize just to read data?

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

Why needed?

TestLongCounter.java

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

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;
}
```

TestCountPrimes.java

Result is 664579

- 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

```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

TestCountPrimes.java

- 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
- Use Java 8 parallel streams instead, **week 3**
- Proper performance measurements, **week 4**
- Very bad idea to use many (> 500) threads
  - Each thread takes much memory for the stack
  - Each thread slows down the garbage collector
- Use *tasks* and Java “executors”, **week 5**
- More advice on scalability, **week 7**
- How to avoid locking, **week 10 and 11**