Practical Concurrent and Parallel Programming

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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

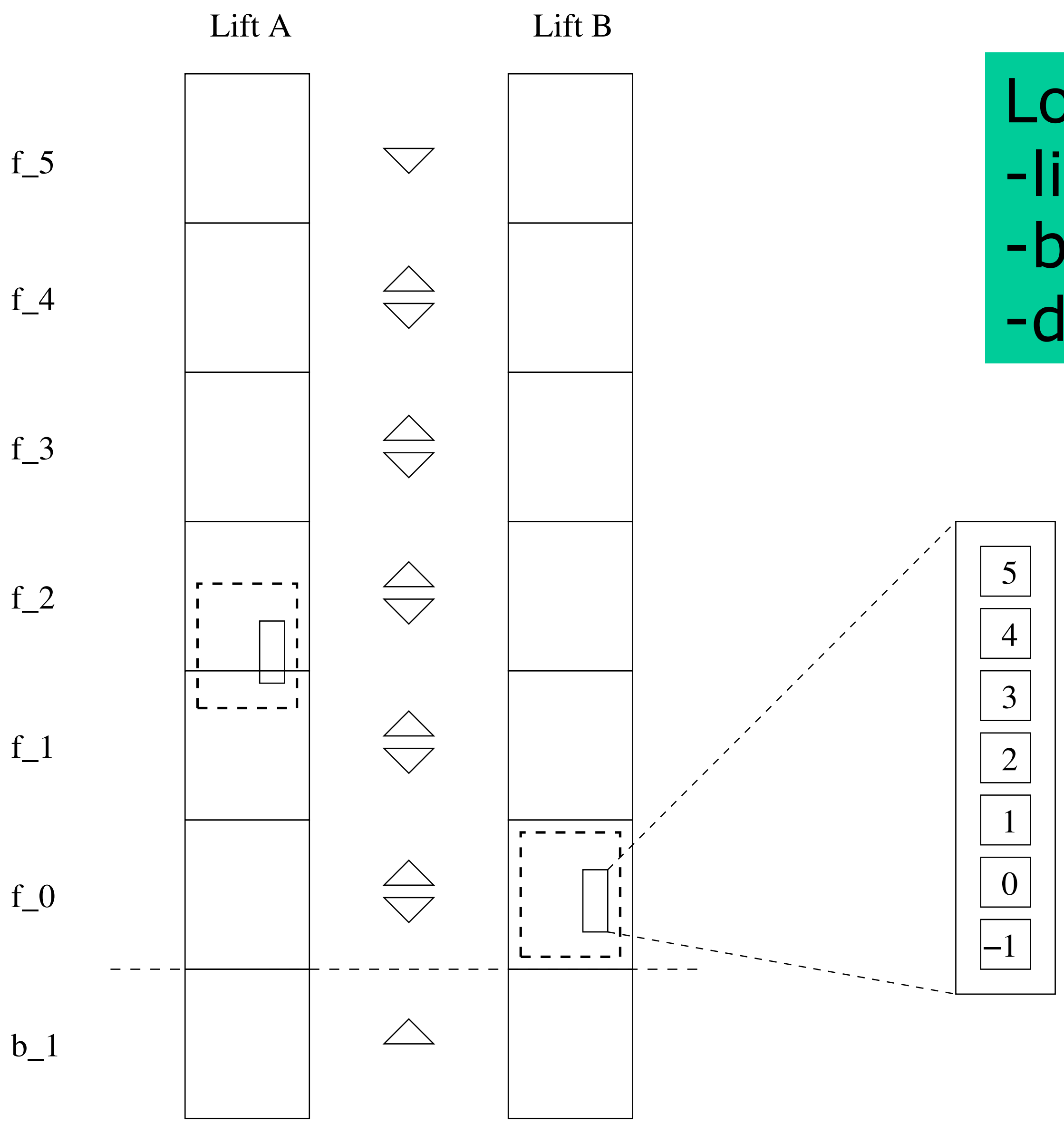
The teachers

- Course responsible: Thomas Dybdahl Ahle
  - BA 2013, University of Oxford
  - PhD 2019, ITU + KU
  - Algorithms & High Dimensional Geometry
  - Chief ML Officer, SupWiz
- Co-teacher: Claus Brabrand
- Material: Peter Sestoft, Riko Jacob
- Teaching Assistants:
  - Jorgel Këci, ITU
  - Jon Voigt Tøttrup, ITU
  - Amund Lome, ITU MSc graduate

Why this course?

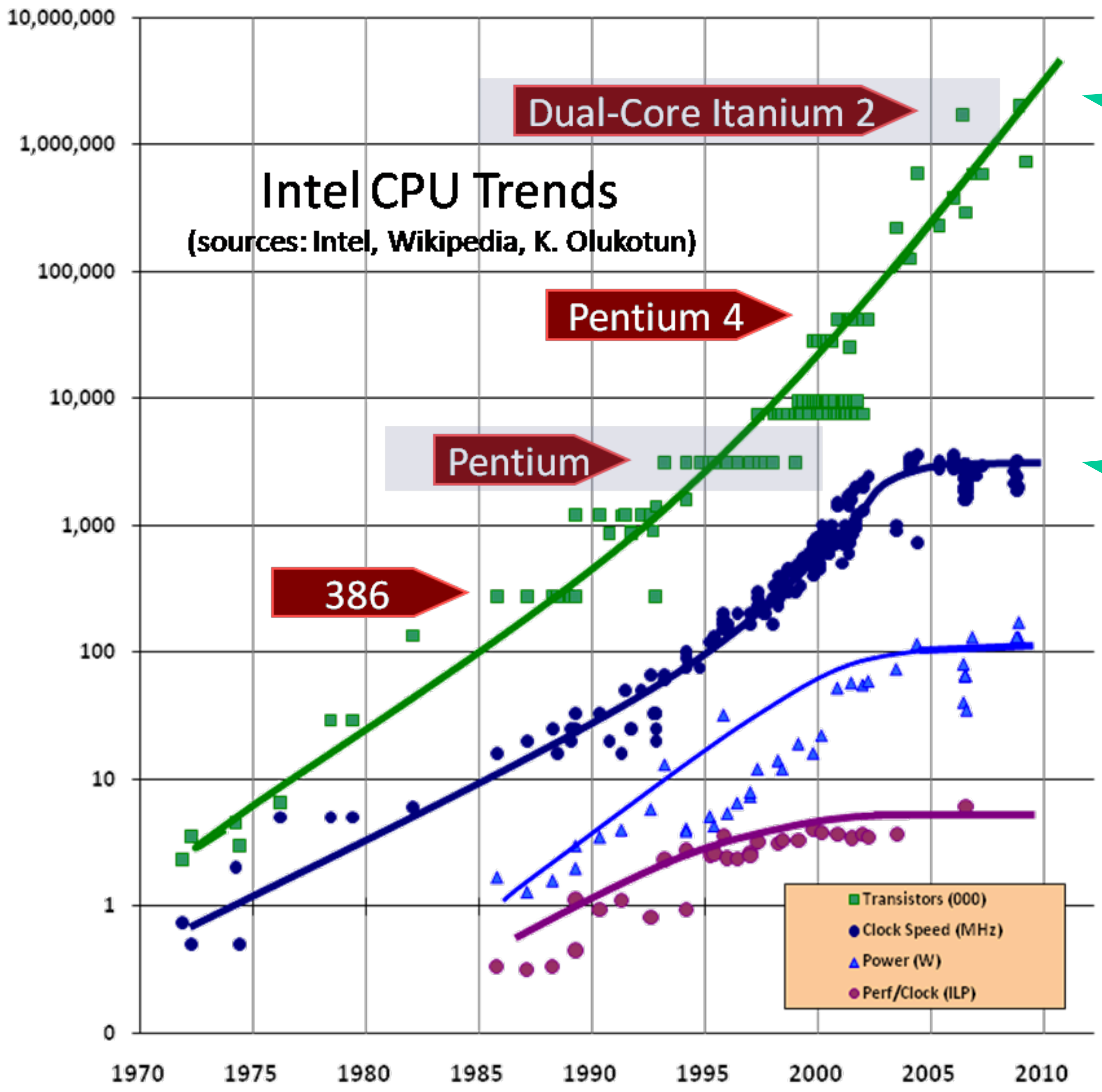
- Parallel programming is necessary
  - For responsiveness in user interfaces etc.
  - The real world is parallel
    - Think of the atrium lifts: lifts move, buttons are pressed
    - Think of handling a million online banking customers
  - For performance: *The free lunch is over*
- It is easy, and 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

Example: 2 lifts, 7 floors, 26 buttons



Lots of concurrency:
-lifts move
-buttons are pressed
-doors open & close

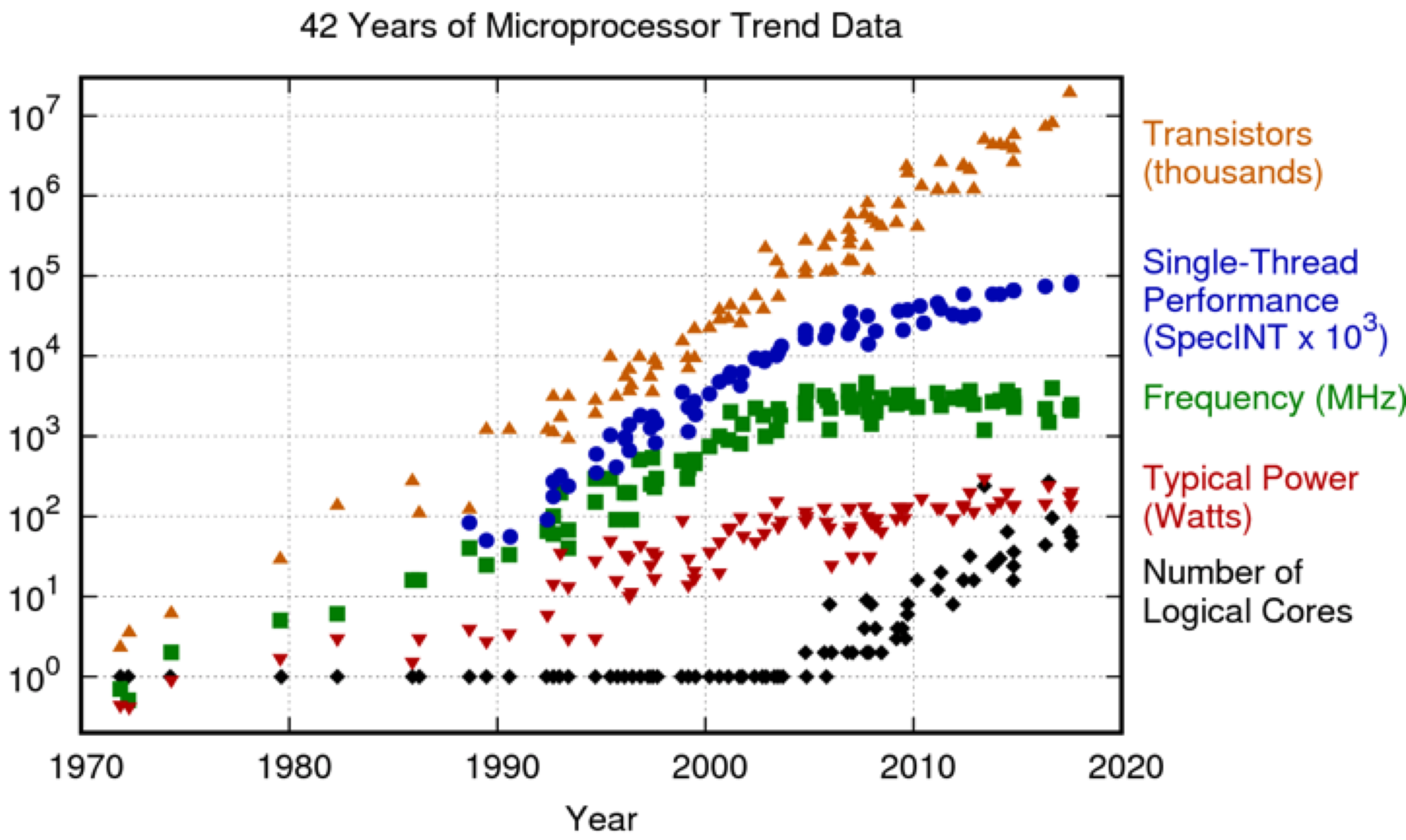
The free lunch is over: No more growth in single-core speed



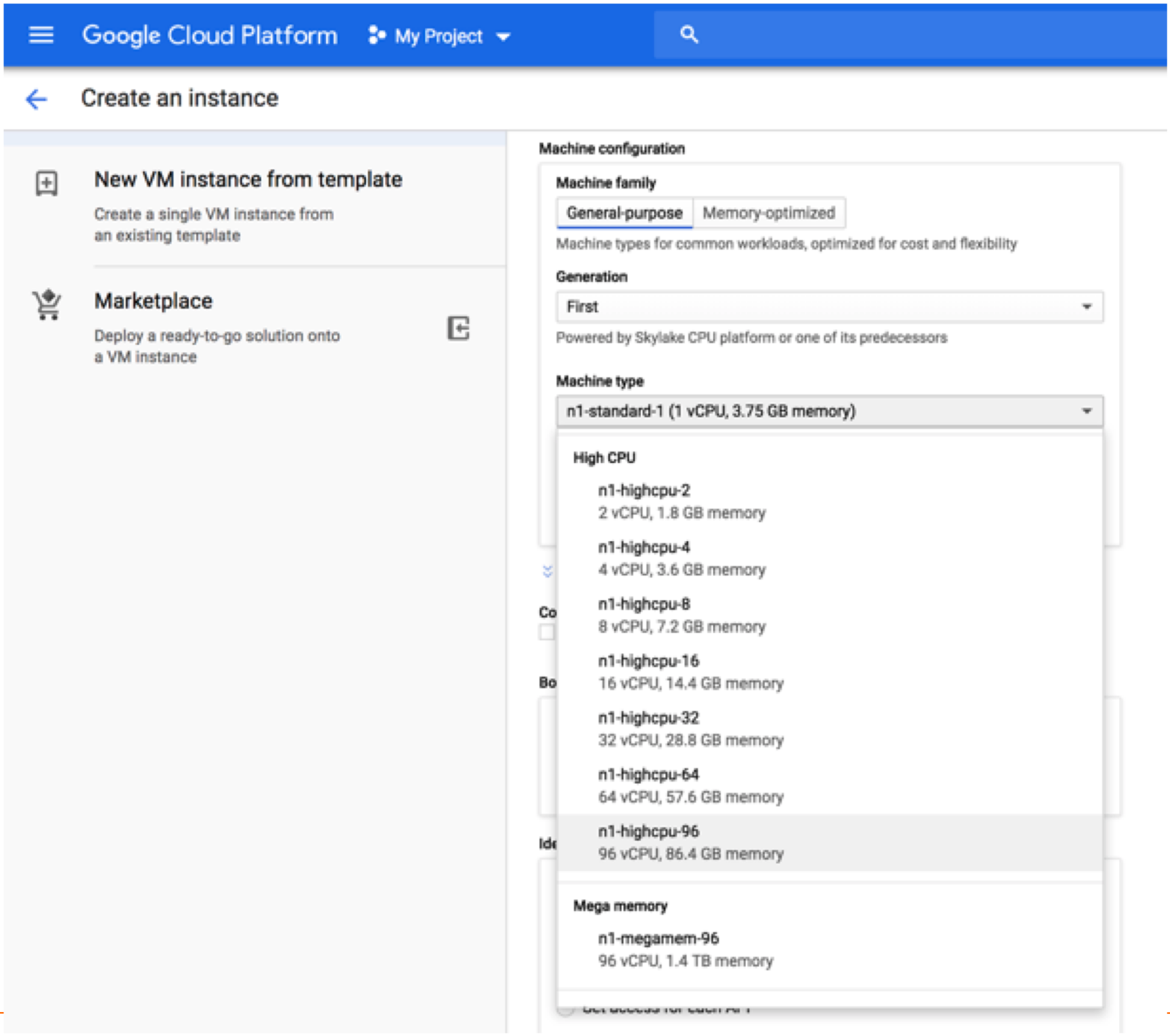
Moore's law

Clock speed

Herb Sutter: The free lunch is over, Dr Dobbs, 2005.
Figure updated August 2009.
http://www.gotw.ca/publications/concurrency-ddj.htm



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp



Google Cloud Platform · My Project

Create an instance

New VM instance from template
Create a single VM instance from an existing template

Marketplace
Deploy a ready-to-go solution onto a VM instance

Machine configuration

Machine family
General-purpose | Memory-optimized
Machine types for common workloads, optimized for cost and flexibility

Generation
First
Powered by Skylake CPU platform or one of its predecessors

Machine type
n1-standard-1 (1 vCPU, 3.75 GB memory)

High CPU
- n1-highcpu-2 — 2 vCPU, 1.8 GB memory
- n1-highcpu-4 — 4 vCPU, 3.6 GB memory
- n1-highcpu-8 — 8 vCPU, 7.2 GB memory
- n1-highcpu-16 — 16 vCPU, 14.4 GB memory
- n1-highcpu-32 — 32 vCPU, 28.8 GB memory
- n1-highcpu-64 — 64 vCPU, 57.6 GB memory
- n1-highcpu-96 — 96 vCPU, 86.4 GB memory

Mega memory
- n1-megamem-96 — 96 vCPU, 1.4 TB memory

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
- Transactional memory, Multiverse
- Lock-free data structures, Java mem. model
- Message passing, Akka

Learning objectives

After the course, the successful student can:

- ANALYSE the correctness of concurrent Java software, and RELATE it to the Java memory model
- ANALYSE the performance of concurrent Java software
- APPLY Java threads and related language features (locks, final and volatile fields) and libraries (concurrent collections) to CONSTRUCT correct and well-performing concurrent Java software
- USE software tools for accelerated testing and analysis of concurrency problems in Java software
- CONTRAST different communication mechanisms (shared mutable memory, transactional memory, message passing)

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 Auditorium 1
  Corresponding exercise assignment is ready
- Exercise Lab: Mondays, 2A54, 5A60, 3A12-14
  - Two slots: 8-10 (3A12-14)
  - and 10-12 (5A60, 3A12-14)
- Exercise hand-in: 6.5 days after lecture
  - That is, the following Wednesday at 23:55
  - Feedback by 7 days after handin

Course information online

- Course LearnIT page, restricted access: https://learnit.itu.dk/
  -
  -
  -
  -

- Course homepage, public access:
  - Overview of lectures and exercises
  - Lecture slides and exercise sheets
  - Example code
  - List of all mandatory reading materials

Course information online

- Course LearnIT page, restricted access: https://learnit.itu.dk/
  - Exercises and hand-ins, deadlines, feedback
  - Mandatory exercises and hand-ins, deadlines, feedback
  - Discussion forum
  - Non-public reading materials
- Course homepage, public access: http://thomasahle.com/teaching/pcpp2019
  - 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
- Point system: 1 point for “hard work”, 2 for accepted.
- No resubmissions.
- 15 points to qualify for exam!
- You can work in teams of 1,2 or 3 students
- The teaching assistants provide quality feedback
- What is important is that **you learn**
  - No limit on number of exercises that can be handed in. Get your money's worth!

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** – obviously
- The old (2014 - 2018) exams are on the public homepage.
- Exam is very similar to weekly exercises.

Expected Time Usage

This course is 7.5 ECTS = 210 hours of work
For average student to get an average grade

Total hours	Weekly hours	
96	8	Solving / submitting exercise (12x)
42		Exam prep (2 old exams)
28	2	Reading
28	2	Lecture
16		Exam
Total: 210		

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
  - Java 9 or later should work

- Various optional materials, see homepage:
  - Bloch: *Effective Java*, 2008, **highly recommended**
  - Sestoft: *Java Precisely*, 3rd edition 2016
  - more ...

What about other languages?

- .NET and C# are very similar to Java
  - We will point out differences on the way
- Clojure, Scala, F#, ... build on JVM or .NET
  - So thread concepts are very similar too
- C and C++ have some differences (ignore)
- Haskell has transactional memory
  - We will see this in Java too (Multiverse)
- Erlang, Scala, F# have message passing
  - We will see this in Java too (Akka)
- Dataflow, CSP, CCS, Pi-calculus, Join, Cω, ...
  - Zillions of other concurrency mechanisms

Other concurrency models

- Java threads interact via shared mutable fields
  - Shared: Visible to multiple threads
  - Mutable: The fields can be updated, assigned to
- This is a source of many problems
- **Alternatives** exist:
- No sharing: interact via message passing
  - Erlang, Scala, MPI, F#, Go ... and Java Akka library
- No mutability: use functional programming
  - Haskell, F#, ML, Google MapReduce, ...
- Allow shared mutable mem., but avoid locks
  - Transactional memory, optimistic concurrency
  - In Haskell, Clojure, ... and Java Multiverse library

Other parallel hardware

- We focus on multicore (standard) hardware
  - Typically 2-32 general cores on a CPU chip
  - (Instruction-level parallelism, invisible to software)
- Other types of parallel hardware exist
- Vector instructions (SIMD, SSE, AVX) on core
  - Typically 2-8 floating-point operations/CPU cycle
  - Soon available through .NET JIT and hence C#
- General purpose graphics processors GPGPU
  - Such as Nvidia CUDA, up to 2500 cores on a chip
  - We're using those in a research project
- Clusters, cloud: servers connected by network

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

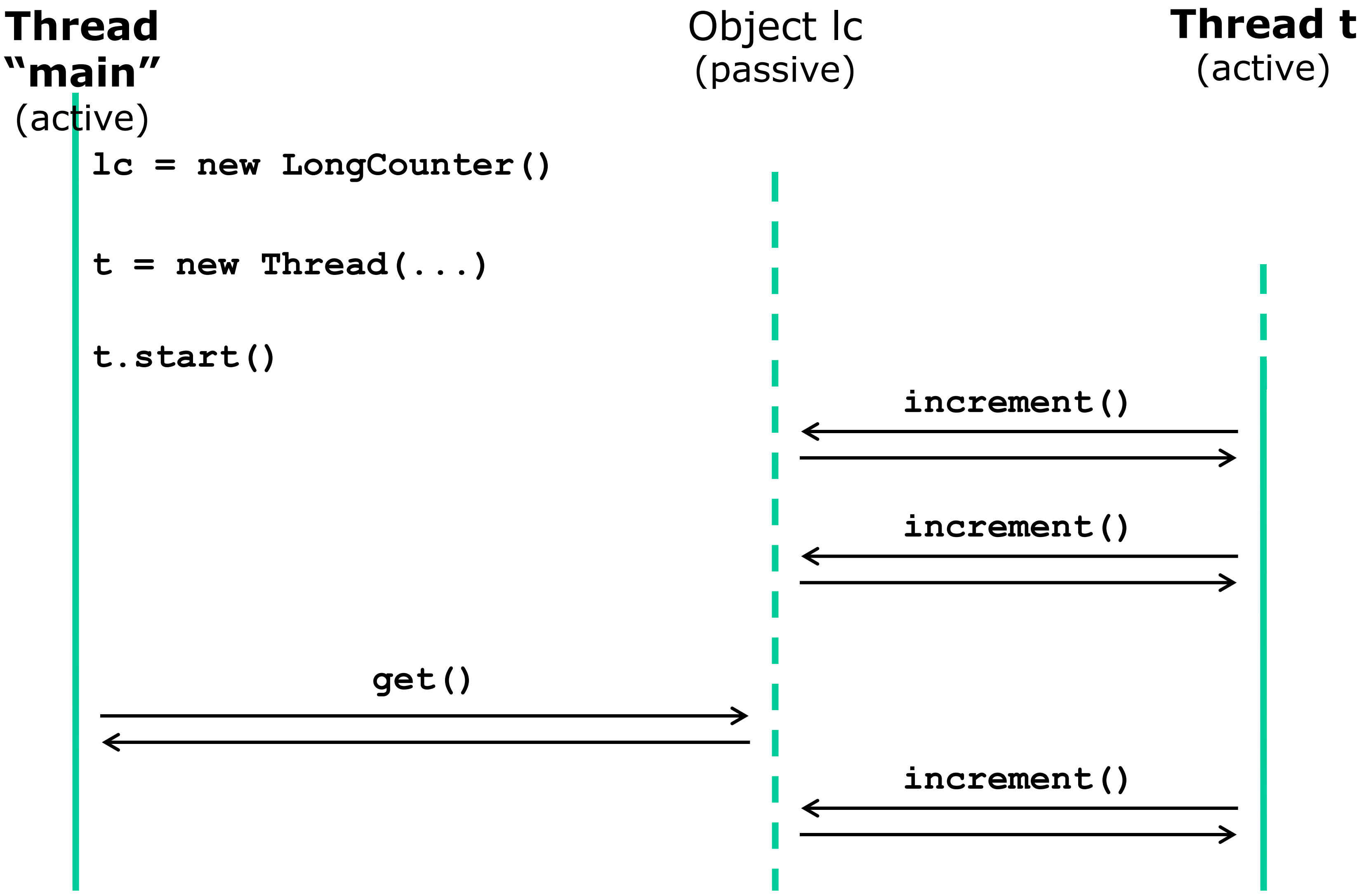
TestLongCounter7.java

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?

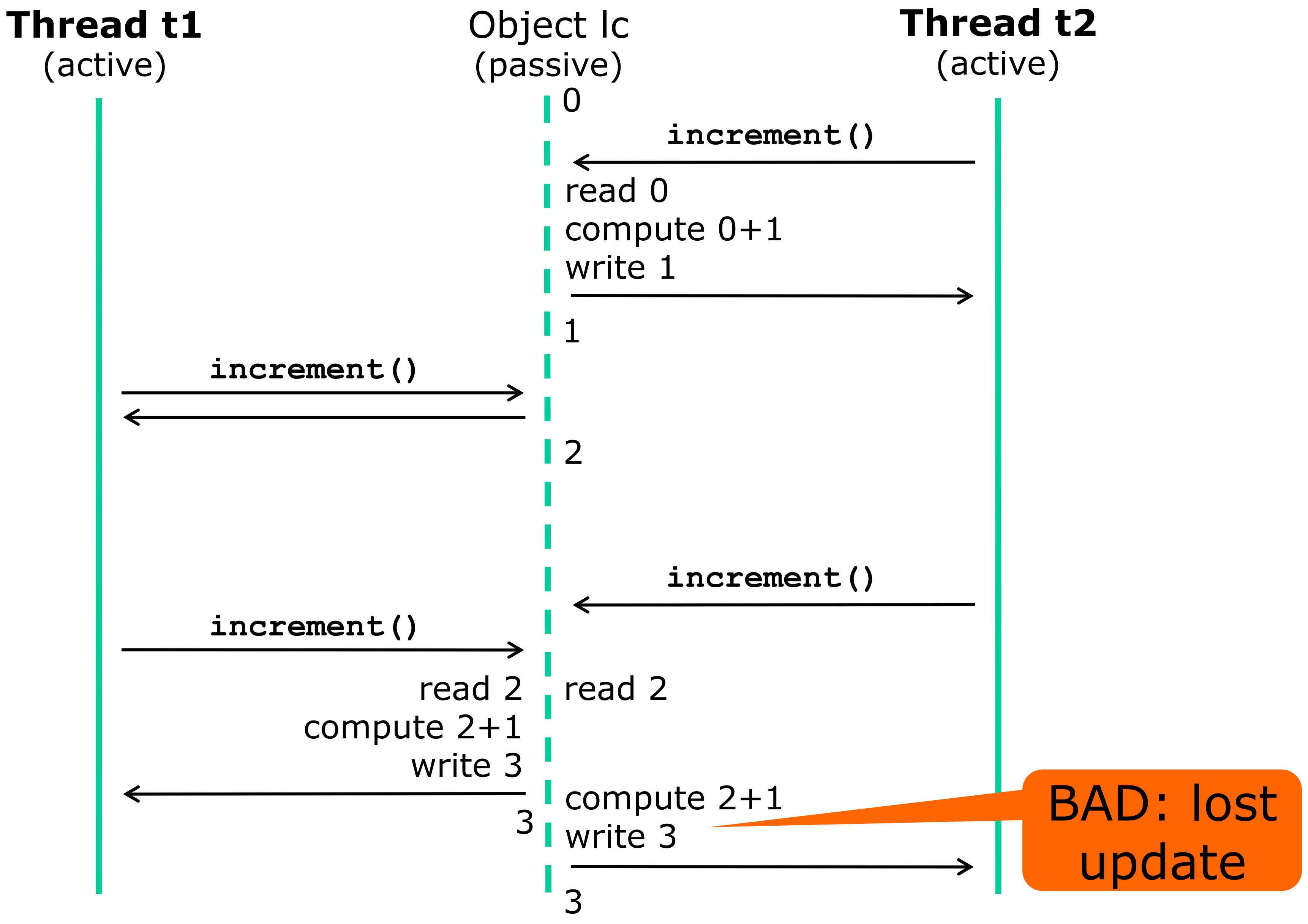
The operation `count = count + 1` is not atomic

- 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++`

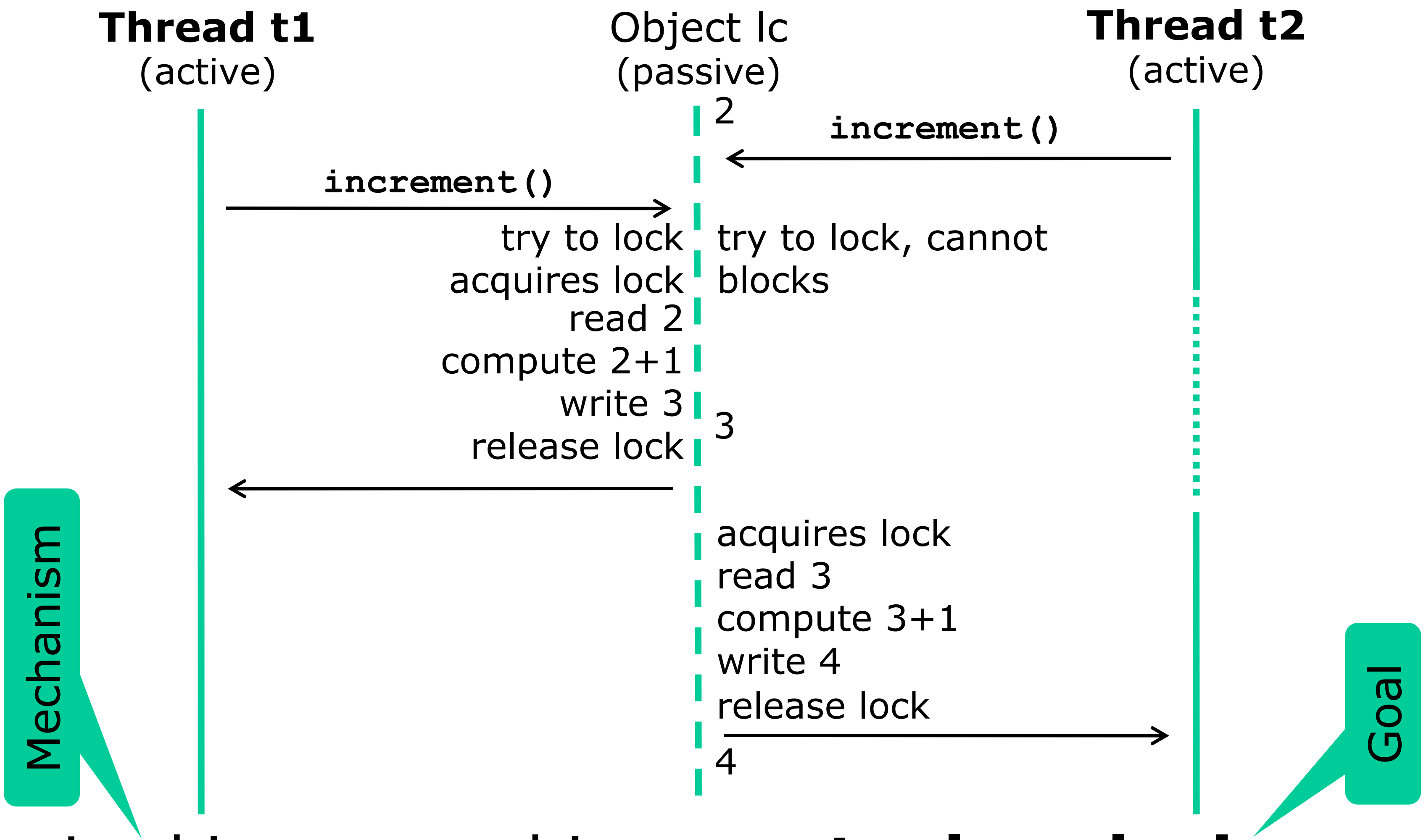
Without locking

No locking: lost update



With locking

How does locking help?



- 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)

Visibility is really important

WARNING: Useless

```
class MutableInteger {
  private int value = 0;
  public void set(int value) { this.value = value; }
  public int get() { return value; }
}
```

TestMutableInteger.java

- Looks OK, no need for synchronization?
- But thread t may loop forever in this scenario:

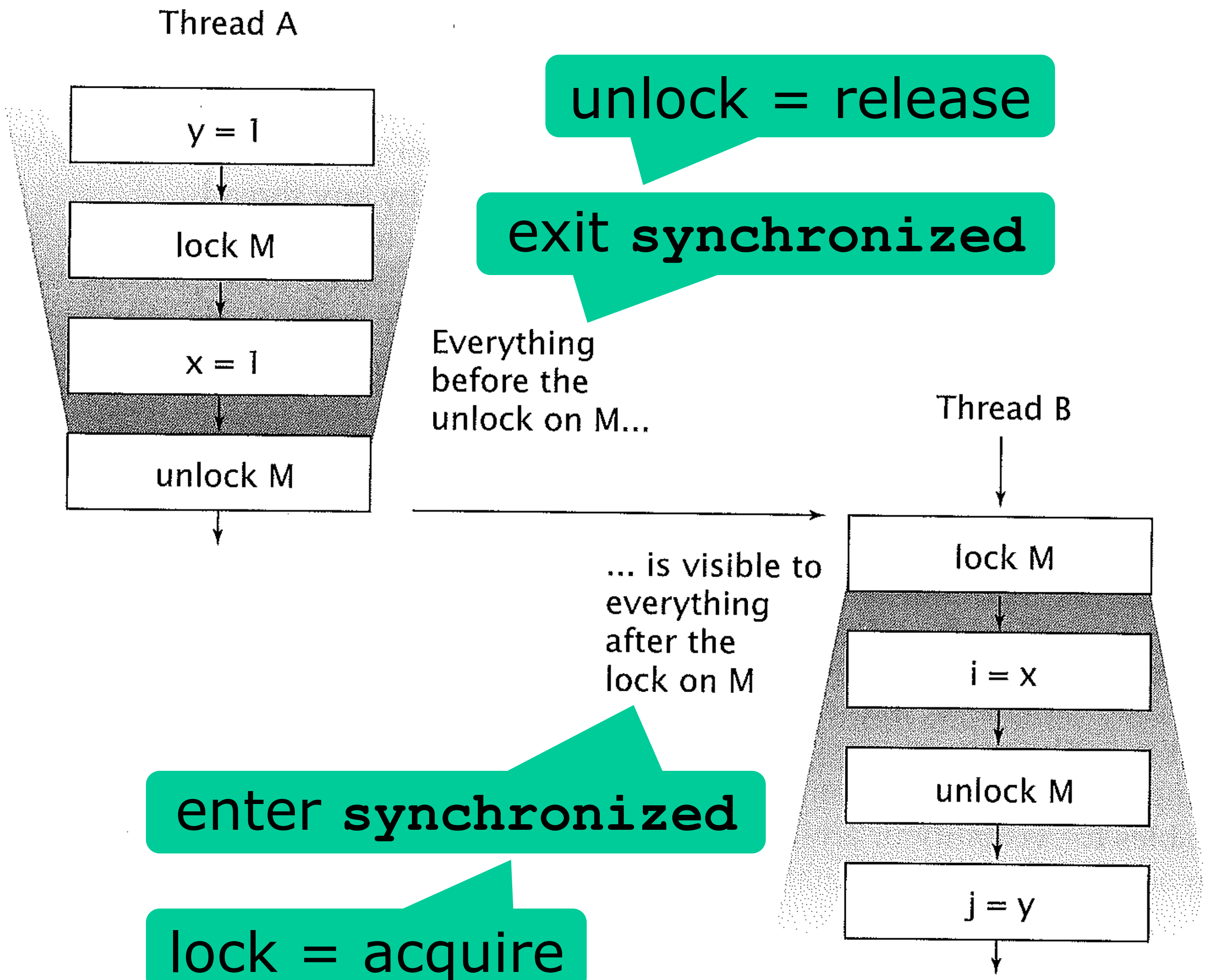
```
final MutableInteger mi = new MutableInteger();
Thread t = new Thread(() -> {
  while (mi.get() == 0) { }
});
t.start();
mi.set(42);
```

Loop while zero

This write by thread "main" may be forever invisible to thread t

- Two possible fixes:
  - Add **synchronized** to methods **get** and **set**, OR
  - Add **volatile** to field **value**

Visibility by synchronization



Thread A
y = 1
lock M
x = 1
unlock M
Everything before the unlock on M...
Thread B
lock M
i = x
unlock M
j = y
... is visible to everything after the lock on M

unlock = release

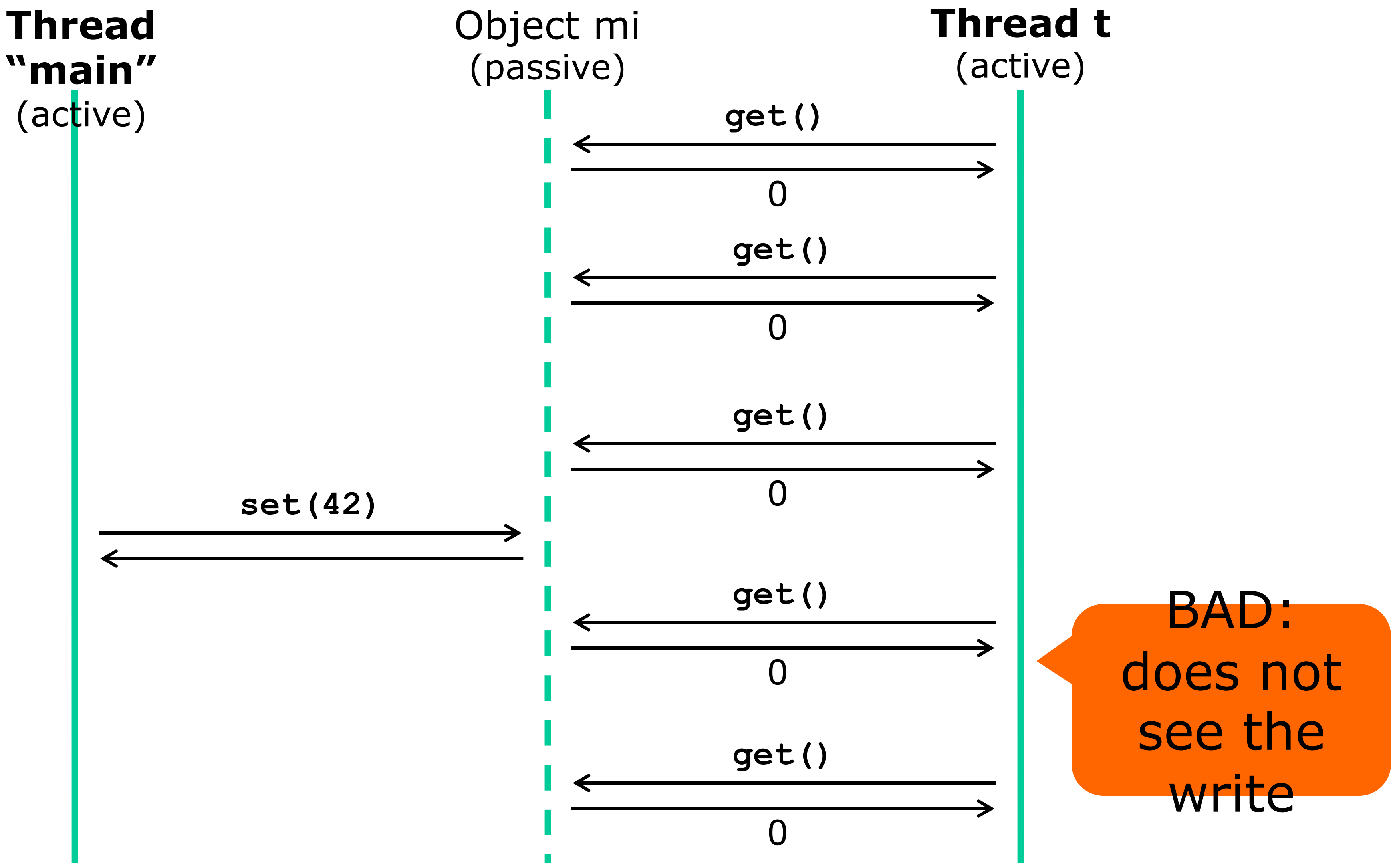
exit `synchronized`

enter `synchronized`

lock = acquire

Goetz p. 37

Communication through mutable shared state fails if no visibility



The volatile field modifier

- The **`volatile`** field modifier can be used to ensure visibility (but not mutual exclusion)

```
class MutableInteger {
  private volatile int value = 0;
  public void set(int value) { this.value = value; }
  public int get() { return value; }
}
```

OK

- All writes by thread A before writing a **`volatile`** field are visible to thread B when, and after, reading the **`volatile`** field
- Note: A single **`volatile`** write+read makes writes to all other fields visible also!
  - A bit mysterious, but a consequence of the implementation
  - This is Java semantics; C#, C, C++ volatile are different

Goetz advice on volatile

Use volatile variables only when they simplify your synchronization policy; avoid it when verifying correctness would require subtle reasoning about visibility.

Locking can guarantee both visibility and atomicity; volatile variables can only guarantee visibility.

Goetz p. 38, 39

- Rule 1: Use locks (**`synchronized`**)
- Rule 2: If circumstances are right, and you are an expert, maybe use **`volatile`** instead
- Rule 3: There are few experts

That was Java. What about C# and .NET?

- C# Language Spec. § 17.3.4 *Volatile Fields*
- CLI Ecma-335 standard section § I.12.6.7:
  - "A volatile write has *release* semantics ... the write is guaranteed to happen *after* any memory references *prior* to the write instruction in the CIL instruction sequence"
  - "volatile read has *acquire* semantics ... the read is guaranteed to occur *prior* to any references to memory that occur *after* the read instruction in the CIL instruction sequence"

- C#'s **`volatile`** is weaker than Java's
  - And very unclearly described
  - Maybe use C# **`lock`** or MemoryBarrier() instead

Ways to ensure visibility

- Unlocking followed by locking the same lock
- Writing a volatile field and then reading it
- Calling one method on a concurrent collection and another method on same collection
  - java.util.concurrent.*
- Calling one method on an atomic variable and then another method on same variable
  - java.util.concurrent.atomic.*
- Finishing a constructor that initializes final or volatile fields
- Calling **`t.start()`** before anything in thread **`t`**
- Anything in thread **`t`** before **`t.join()`** returns

(Java Language Specification 8 § 17.4, and the Javadoc for concurrent collection classes etc, give the full and rather complicated details)

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

```
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**

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