Practical Concurrent and Parallel Programming XIV
End of course / Exam

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Agenda

- Examination
- Important concepts you need to know well (no matter the question)
- Race conditions vs data races, and thread-safety
- Monitors
- Fairness
- Happens-before

Examination

Examination – Dates & guidelines (UPDATED)

- Exam hand-out: Dec 19th at 8.00
- Exam hand-in deadline: Dec 20th at 14.00
- There will be ***<u>no</u>*** fraud control
  - Please ignore the info in the slides for week 13 regarding this issue

Collaboration during the exam

- Collaboration is not allowed
- The exam must be solved individually
- You can think of this exam as regular on-premises exam at ITU
  - But with more time and access to the course literature
- The objective of the exam is to measure your individual knowledge on the subject
  - Not the collective knowledge of a group

References in the exam

- No need to provide references to mandatory readings or lecture slides (although it is not forbidden)
- There is no specific format for providing references
- For instance,
  - Lecture slides: title and course week for the slide deck
  - Book: Authors, title (and chapter) of specific material
  - Research Paper: Authors, title (may be year)
  - Internet resource: URL

Course Code

- You can find the course code in the course description page in learnIT
  - https://learnit.itu.dk/local/coursebase/view.php?ciid=1006
  - KSPRCPP2KU

COURSE INFO

Language:
English
ECTS Points:
7.5
Course Code:
KSPRCPP2KU
Participants Max:
160
Offered To Guest Students:
Yes
Offered To Exchange Students:
Yes
Offered As A Single Subject:
Yes
Price For EU/EEA Citizens (Single Subject):
10625 DKK

On clear answers

- There is no *a* way to provide clear/acceptable answers
- The main reason for insisting on explaining answers was the increase in answers of the type: See file XXX.java
  - Answers of this kind will likely result in no points
- We are simply advising to be as clear as possible in your written answers
  - Specially we insist on avoiding simply referring to the code
- This is not the “PCPP answer style” or anything like that

No-examples or anti-examples and their risks

- When a being asked about thread-safety
  - *Answer*: XXX is thread-safe because I use an AtomicInteger/lock/semaphore/…
  - *Risk*: This implies that any program using AtomicInteger/lock/semaphore/… is thread-safe

Is this the case? Why?

- When being asked to implement something:
  - *Answer*: See file XXX.java
  - *Risk*: Here you are relying on the ability of the examiner to understand your code
- When begin asked to explain the output of a performance measurement
  - *Answer*: When I run the program I observe that X is faster than Y
  - *Risk*: This only describes the output, but does not explain it. An explanation should include the reason why X is faster than Y

Executable code in the exam

- Recall that code must be executable using the steps in the [mini guide on using Gradle]
  - This also requires your code to be compatible with JDK 8
- We will provide a Gradle project with all the dependences we used in the course (and skeleton code related to the exam questions)
  - You only need to focus on writing Java code related to the questions

Important concepts you need to know well (no matter the question)

Threads in Java – Example II

- What was is the problem in the previous program?

- To answer this question we need to understand
  - Atomicity
  - States of a thread
  - Non-determinism
  - Interleavings

Atomicity

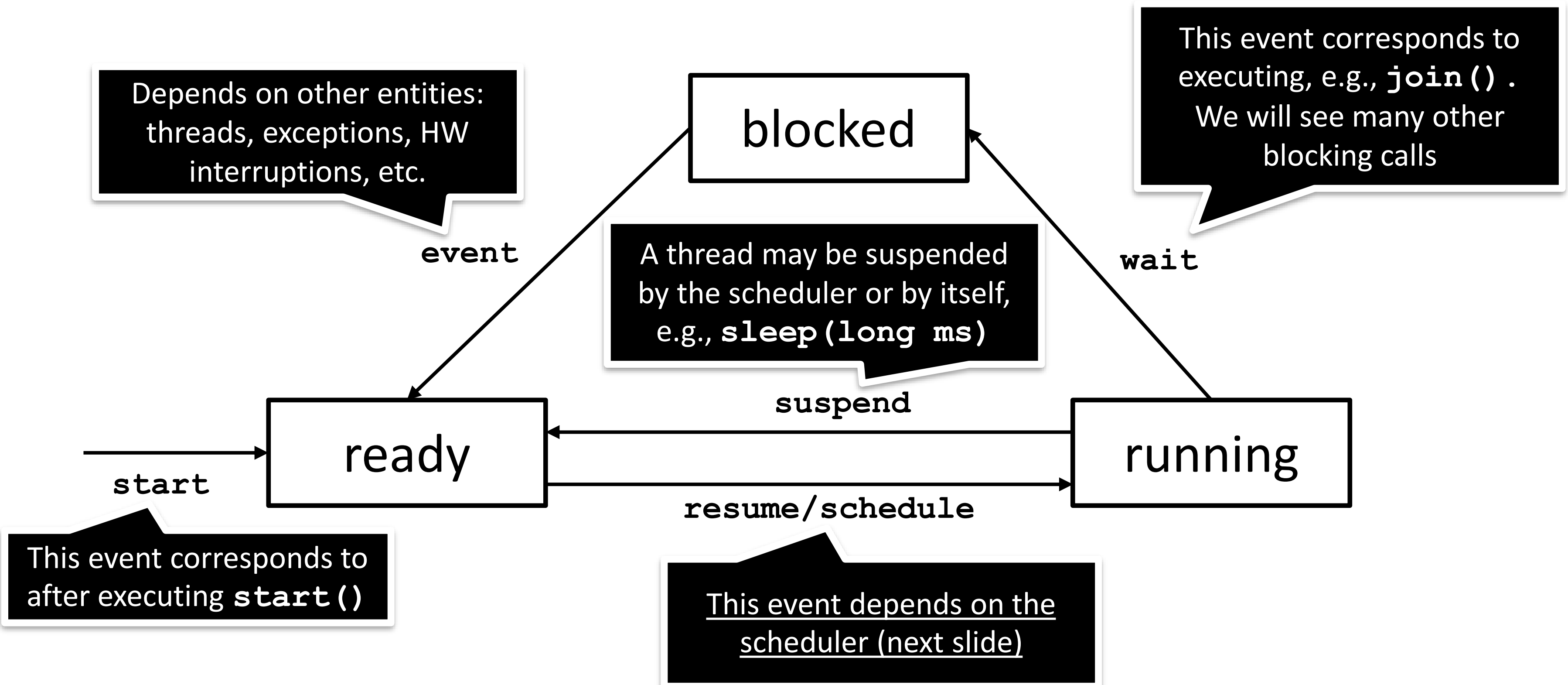
- The program statement **`counter++`** is not *atomic*
- *<u>Atomic statements are executed as a single (indivisible) operation</u>*

```
public class Turnstile extends Thread {
   public void run() {
        for (int i = 0; i < PEOPLE; i++) {
            counter++;
        }
   }
}
```

```
int temp = counter;
counter = temp + 1;
```

<u>Watchout</u>: Just because a program statement is a one-liner, it doesn´t mean that it is atomic

States of a thread (simplified)



Non-determinism | Scheduler

- In all operating systems/executing environments a *scheduler* selects the processes/threads under execution
  - Threads are selected *non-deterministically*, i.e., no assumptions can be made about what thread will be executed next

- Consider two threads t1 and t2 in the ready state; *t1(ready)* and *t2(ready)*
  1. *t1(running) -> t1(ready) -> t1(running) -> t1(ready) -> …*
  2. *t2(running) -> t2(ready) -> t2(running) -> t2(ready) -> …*
  3. *t1(running) -> t1(ready) -> t2(running) -> t2(ready) -> …*
  4. Infinitely many different executions!

Interleaving

- The statements in a thread are executed when the thread is in its “running” state

- An *interleaving* is a possible sequence of operations for a concurrent program
  - Note this: a sequence of operations for a concurrent program, not for a thread. Concurrent programs are composed by 2 or more threads.

Interleaving syntax

- The drawings above are not suitable for thinking about possible interleavings

- When asked to provide an interleaving, use the following syntax

```
<thread>(<step>), <thread>(<step>), …
```

Interleaving – Example II (textual)

*Given the initial memory state on the right, provide an interleaving such that after two threads t1, t2 execute the program on the right the value of **counter==1***

Memory

counter=0	
i=0	i=0

Program

```
public void run() {
  int temp = counter;   // (1)
  counter = temp + 1;   // (2)
}
```

counter=0	
temp=0	temp=0

t1(1),

counter=0	
temp=0	**temp=0**

t2(1),

counter=1	
temp=0	temp=0

t1(2),

counter=1	
temp=0	temp=0

t2(2)

Race conditions, data races & Thread-safety (also very important no matter the question)

Race Conditions

- *A **race condition** occurs when the result of the computation depends on the interleavings of the operations*

Data Races

- *A **data race** occurs when two concurrent threads:*
  - *Access a shared memory location*
  - *At least one access is a write*

Race Conditions vs Data Races

Not all <u>race conditions</u> are <u>data races</u>

- Threads may not access shared memory
- Threads may not write on shared memory

```
public void p() {
  print("P") //P1
}
```

```
public void q() {
  print("Q") //Q1
}
```

```
Interleaving 1: T1(P1)T2(Q1)
Output: P Q
Interleaving 2: T1(Q1)T2(P1)
Output: Q P
```

Not all <u>data races</u> result in <u>race conditions</u>

- The result of the program may not change based on the writes of threads

```
public void p() {
  x=1;   //P1
}
```

```
public void q() {
  x=1;   //Q1
}
```

```
Interleaving 1: T1(P1)T2(Q1)
Final state: x==1
Interleaving 2: T1(Q1)T2(P1)
Final state: x==1
```

Thread-safe program

*A concurrent **program** is said to be **thread-safe** if and only if it is race condition free*

Do not confuse thread-safe classes with thread-safe programs. Thread-safe programs are not defined in Goetz. But it is aligned with the definition of correctly synchronized programs in JLS

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Thread-safe classes

WARNING: Note that, in this course, *thread-safety* is not an umbrella term for code that seem to behave correctly in concurrent environments.

*A **class** is said to be **thread-safe** if and only if*
no concurrent execution of
method calls or field accesses (read/write)
result in race conditions

Note that this definition is independent of class invariants as opposed to Goetz Chapter 4. This definition is more similar to Goetz Chapter 2, page 18.

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Thread-safe classes

- To analyse whether a class is thread-safe, we must identify/consider:
  - Class state
  - Escaping
  - (Safe) publication
  - Immutability
  - **Mutual exclusion**

Very important slide

Use as a reference when answering questions about thread-safety

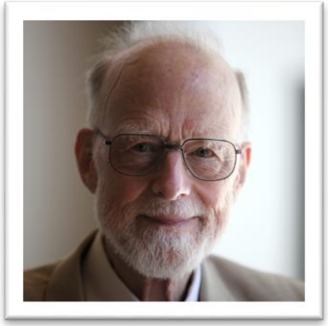
Mutual Exclusion

- An ideal solution to the mutual exclusion problem must ensure the following properties:
  - Mutual exclusion: at most one thread executing the critical section at the same time
  - Absence of *deadlock*: threads eventually exit the critical section allowing other threads to enter
  - Absence of *starvation*: if a thread is ready to enter the critical section, it must eventually do so

Monitors

Monitors

- A *monitor* is a structured way of encapsulating data, methods and synchronization in a single modular package
  - First introduced by Tony Hoare (right photo, see optional readings) and the Danish computer scientist Per Brinch Hansen (left photo)



- *A monitor consists of:*
  - Internal state (data)
  - Methods (procedures)
    - All methods in a monitor are mutually exclusive (ensured via locks)
    - Methods can only access internal state
  - Condition variables (or simply conditions)
    - Queues where the monitor can put threads to wait
- In Java (and generally in OO), monitors are conveniently implemented as classes

Conditions

- Conditions are used when a thread must wait for something to happen, e.g.,
  - A writer thread waiting for all readers and/or writer to finish
  - A reader waiting for the writer to finish

- Queues in condition variables provide the following interface:
  - **`await()`** – releases the lock, and blocks the thread (on the queue)
  - **`signal()`** – wakes up a threads blocked on the queue, if any
  - **`signalAll()`** – wakes up all threads blocked on the queue, if any

- When threads wake up the acquire the lock immediately (before the execute anything else)

Monitors | Readers-Writers Problem

- We define four methods to lock and unlock read and write access to the shared resource

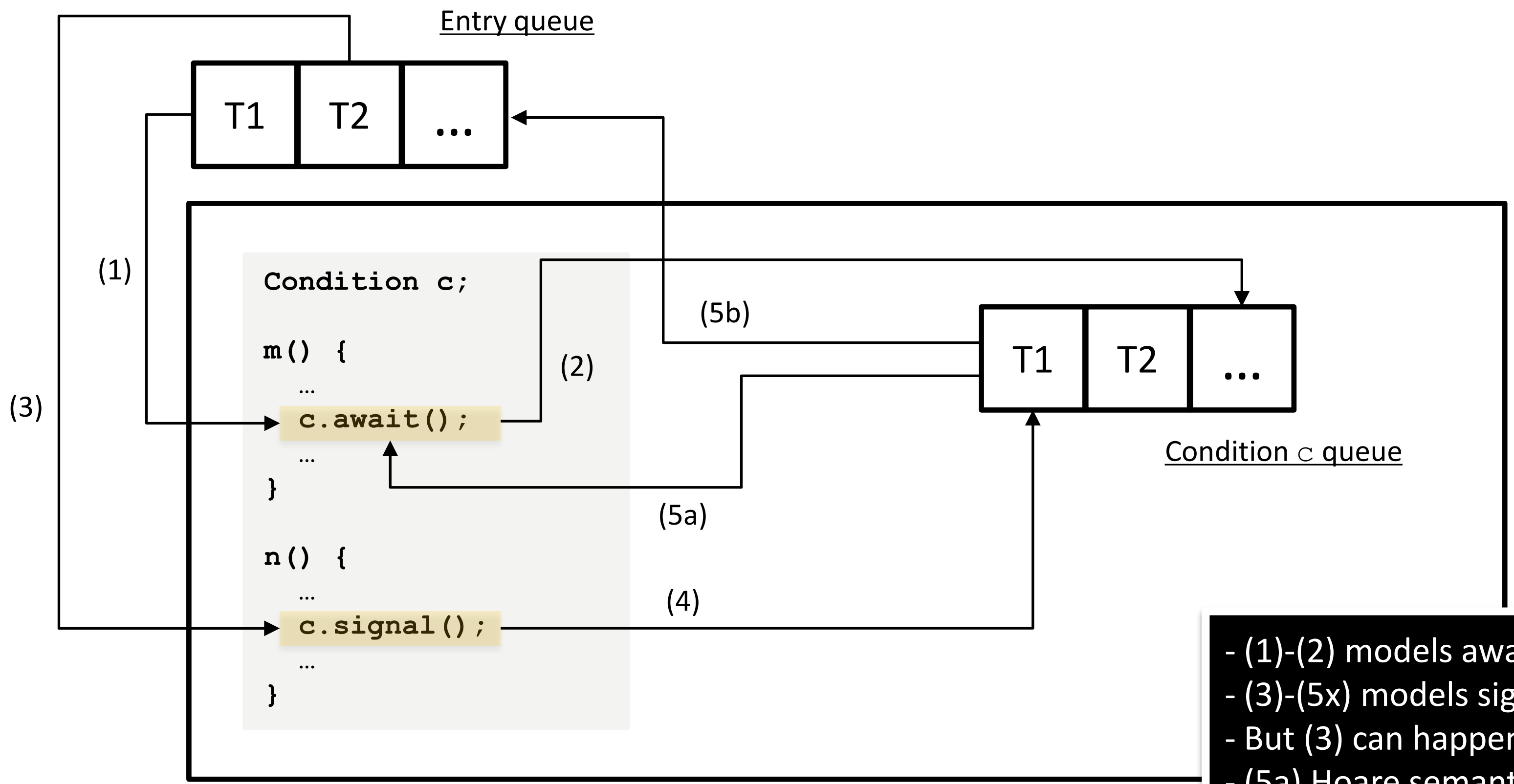
```
public void readLock() {
      lock.lock();
      try {
          while(writer)
            condition.await();
          readers++;
      }
      catch (InterruptedException e) {…}
      finally {lock.unlock();}
}

public void readUnlock() {
      lock.lock();
      try {
          readers--;
          if(readers==0)
            condition.signalAll();
      }
      finally {lock.unlock();}
}
```

```
public void writeLock() {
      lock.lock();
      try {
          while(readers > 0 || writer)
            condition.await();
          writer=true;
      }
      catch (InterruptedException e) {…}
      finally {lock.unlock();}
}

public void writeUnlock() {
      lock.lock();
      try {
          writer=false;
          condition.signalAll();
      }
      finally {lock.unlock();}
}
```

Monitor behaviour - schematic representation



- (1)-(2) models await scenario
- (3)-(5x) models signal scenario
- But (3) can happen before (1)
- (5a) Hoare semantics
- (5b) MESA semantics (and Java)

Fairness

Fairness

- There exist two notions of fairness
  - Weak fairness: A thread that is continuously active will eventually make progress
  - Strong fairness: A thread that is infinitely often active will eventually make progress
- Note that fairness is not always achievable programmatically
  - The scheduler must ensure it
  - This is specially important for strong fairness

Fairness (a bit more formally)

Weak fairness

```
m(Semaphore s) {
  while(true) {
    s.acquire();   // (1)
    // c.s.        // (2)
    s.release();   // (3)
  }
}
```

```
main() {
  Semaphore s = new Semaphore(2)
  Thread t1 = new Thread(() -> m(s));
  Thread t2 = new Thread(() -> m(s));
  t1.start();t2.start();
  …
}
```

- Let *I* denote the set of all possible interleavings of this program
- If [T1(1)T1(2)T1(3)]* is in *I*, then *weak fairness* is not enforced
  - In other words, if there is an interleaving where T2 never executes, then weak fairness is violated
  - This is because the semaphore has enough capacity for two threads, so T2 is *continuously active*
  - Is the interleaving above possible (i.e., included in the set of all interleavings)?

Fairness (a bit more formally)

Strong fairness

```
m(Semaphore s) {
  while(true) {
    s.acquire();  // (1)
    // c.s.        // (2)
    s.release();  // (3)
  }
}
```

```
main() {
  Semaphore s = new Semaphore(1)
  Thread t1 = new Thread(() -> m(s));
  Thread t2 = new Thread(() -> m(s));
  t1.start();t2.start();
  …
}
```

- If there exists an interleaving *i* in *I* such that [*T1(2)*T2(2)*]* is not in *i*, then strong fairness is not ensured
  - In other words, there must be an interleaving where T1(2) and T2(2) are executed infinitely often

Fairness (a bit more formally)

Strong fairness

```
m(Semaphore s) {
  while(true) {
    s.acquire();   // (1)
    // c.s.        // (2)
    s.release();   // (3)
  }
}
```

```
main() {
  Semaphore s = new Semaphore(1)
  Thread t1 = new Thread(() -> m(s));
  Thread t2 = new Thread(() -> m(s));
  t1.start();t2.start();
  …
}
```

- If there exists an interleaving *i* in *I* such that [*T1(2)*T2(2)*]* is not in *i*, then strong fairness is not ensured
  - In other words, there must be an interleaving where T1(2) and T2(2) are executed infinitely often
- The condition above is sufficient because after T1(3) the operation T2(1) is enabled (and vice versa), and this happens infinitely often

Fairness (a bit more formally)

Strong fairness

```
m(Semaphore s) {
  while(true) {
    s.acquire();  // (1)
    // c.s.       // (2)
    s.release();  // (3)
  }
}
```

```
main() {
  Semaphore s = new Semaphore(1)
  Thread t1 = new Thread(() -> m(s));
  Thread t2 = new Thread(() -> m(s));
  t1.start();t2.start();
  …
}
```

- If there exists an interleaving *i* in *I* such that [*T1(2)*T2(2)*]* is not in *i*, then strong fairness is not ensured
  - In other words, there must be an interleaving where T1(2) and T2(2) are executed infinitely often
- The condition above is sufficient because after T1(3) the operation T2(1) is enabled (and vice versa), and this happens infinitely often
- Because in this case T2 is not continuously active (only initially and after T1(3)), the property above is not enough to show that weak fairness is not enforced

Fairness

- In the exam we will not go into details regarding weak vs strong fairness
- For the exam it is more important to consider fairness as absence of starvation
  - Is it possible that a thread that is ready to enter the critical section never makes progress?
- Absence of starvation can be achieved programmatically in some cases
  - Recall the fair readers-writers program
  - Fair flags for Semaphores, see above

Absence of starvation

```
m(Semaphore x, y) {
  while(true) {
    x.acquire();   // (1)
    // c.s.        // (2)
    y.release();   // (3)
  }
}
```

```
main() {
  Semaphore s1 = new Semaphore(1)
  Semaphore s2 = new Semaphore(0)
  Thread t1 = new Thread(() -> m(s1,s2));
  Thread t2 = new Thread(() -> m(s2,s1));
  t1.start();t2.start();
  …
}
```

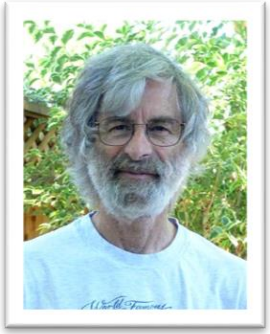
- The program above ensures that both threads run infinitely often
- In fact, allows a single interleaving
  [T1(1)T1(2)T1(3)T2(1)T2(2)T2(3)]*
- Note that this is not always possible; the problem specification may require interleavings which lead to possible starvation problems
  - Recall that for the fair readers-writers, writers may starve (if they keep jumping from the condition queue to the entry queue)
  - This can only be prevented by an scheduler that ensures strong fairness

Happens-before

Happens-before

We will focus on the Java happens-before relation (page 341 Goetz and JLS documentation)

- In fact, we can now characterize an order of execution between some of the operations of a program
- We say that an operation a *happens-before* than operation b, denoted as $a \rightarrow b$, iff
  - a and b belong to the same thread and a appears before b in the thread definition
  - a is an **`unlock()`** and b is a **`lock()`** on the same lock
- In the absence of *happens-before* relation between operations, the JVM is free to choose any execution order
  - In that case we say that operations are executed *concurrently*
  - Sometimes denoted as $a \mid\mid b$
- *Happens-before* is a *partial order* over operations of concurrent programs
  - Reflexive, transitive, antisymmetric
- "Happened-before" was first introduced by Leslie Lamport for distributed systems
  - See optional readings



volatile

In this program the output (0,0) is not possible (explanation based on happens-before)

- Because of volatile we have (the following premises)
  $a \coloneqq 1 \rightarrow x \coloneqq b$ and
  $b \coloneqq 1 \rightarrow y \coloneqq a$
- Assume, by contradiction, that the output of the program is (0,0). This can only happen as a result of any of the following interleavings
  $one(x \coloneqq b), other(y \coloneqq a), one(a \coloneqq 1), other(b \coloneqq 1)$ (1) or
  $one(x \coloneqq b), other(y \coloneqq a), other(b \coloneqq 1), one(a \coloneqq 1)$ (2) or
  $other(y \coloneqq a), one(x \coloneqq b), one(a \coloneqq 1), other(b \coloneqq 1)$ (3) or
  $other(y \coloneqq a), one(x \coloneqq b), other(b \coloneqq 1), one(a \coloneqq 1)$ (4)
- In (1) and (2), it holds $x \coloneqq b \rightarrow a \coloneqq 1$ which contradicts the premise $a \coloneqq 1 \rightarrow x \coloneqq b$
- In (3) and (4), it holds $y \coloneqq a \rightarrow b \coloneqq 1$ which contradicts the premise $b \coloneqq 1 \rightarrow y \coloneqq a$
- Therefore, the output (0,0) is not possible

```
// shared variables
x=0;
y=0;
volatile a=0;
volatile b=0;

// Threads definition
Thread one = new Thread(() -> {
    a=1;
    x=b;
});
Thread other = new Thread(() -> {
    b=1;
    y=a;
});
one.start();other.start();
one.join();other.join();
System.out.println("("+x+","+y+")");
```

volatile

In this program the output (0,0) is not possible (explanation based on happens-before)

- Because of volatile we have (the following premises)
  $a \coloneqq 1 \rightarrow x \coloneqq b$ and
  $b \coloneqq 1 \rightarrow y \coloneqq a$

We also have other premises coming from volatile, depending on the scheduler:
$a \coloneqq 1 \rightarrow y \coloneqq a$ or $y \coloneqq a \rightarrow a \coloneqq 1$ and
$b \coloneqq 1 \rightarrow x \coloneqq b$ or $x \coloneqq b \rightarrow b \coloneqq 1$

These premises come from our earlier definition of happens-before for volatile variables:
A write to a volatile variable happens-before any subsequent read to the volatile variable

Note that
$(a \coloneqq 1 \rightarrow y \coloneqq a$ or $y \coloneqq a \rightarrow a \coloneqq 1) \quad \neq \quad (a \coloneqq 1 \nrightarrow y \coloneqq a$ and $y \coloneqq a \nrightarrow a \coloneqq 1)$

- Therefore, the output (0,0) is not possible

```
// shared variables
x=0;
y=0;
volatile a=0;

inition
ew Thread(() -> {

 new Thread(() -> {

her.start();
er.join();
System.out.println("("+x+","+y+")");
```

volatile

In this program the output (0,0) is not possible (explanation based on happens-before)

- Because of volatile we have (the following premises)
  $a := 1 \rightarrow x := b$ and
  $b := 1 \rightarrow y := a$

We also have other premises coming from volatile, depending on the scheduler:
$a := 1 \rightarrow y := a$ or $y := a \rightarrow a := 1$ and
$b := 1 \rightarrow x := b$ or $x := b \rightarrow b := 1$

These premises come from our earlier definition of happens-before for volatile variables:
A write to a volatile variable happens-before any subsequent read to the volatile variable

Note that
$(a := 1 \rightarrow y := a$ or $y := a \rightarrow a := 1) \quad \neq \quad (a := 1 \nrightarrow y := a$ and $y := a \nrightarrow a := 1)$

```
// shared variables
x=0;
y=0;
volatile a=0;

inition
ew Thread(() -> {

new Thread(() -> {

her.start();
er.join();
x+","+y+")");
```

$a \nrightarrow b$ actually means $a \,||\, b$. In other words, absence of happens before relation between the actions

- Therefore, the output (0,0) is no

Java happens-before rules, Goetz Chp. 16

The rules for *happens-before* are:

Program order rule. Each action in a thread *happens-before* every action in that thread that comes later in the program order.

Monitor lock rule. An unlock on a monitor lock happens-before every subsequent lock on that same monitor lock.[3]

[3]. Locks and unlocks on explicit Lock objects have the same memory semantics as intrinsic locks.

Volatile variable rule. A write to a volatile field happens-before every subsequent read of that same field.[4]

[4]. Reads and writes of atomic variables have the same memory semantics as volatile variables.

Thread start rule. A call to Thread.start on a thread *happens-before* every action in the started thread.

Thread termination rule. Any action in a thread *happens-before* any other thread detects that thread has terminated, either by successfully return from Thread.join or by Thread.isAlive returning false.

Interruption rule. A thread calling interrupt on another thread happens-before the interrupted thread detects the interrupt (either by having InterruptedException thrown, or invoking isInterrupted or interrupted).

Finalizer rule. The end of a constructor for an object *happens-before* the start of the finalizer for that object.

Transitivity. If A *happens-before* B, and B *happens-before* C, then A *happens-before* C.

Mandatory assignments

- To be eligible for the exam, 5 (or more) mandatory assignments must be approved

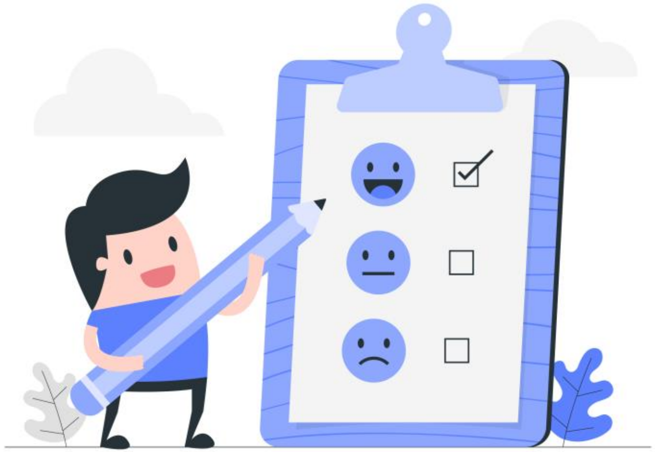
- You will get confirmation in the feedback for assignment 6
  - *"Your assignments have been approved and you may take the exam"*

- *<u>It is your responsibility to let us know if there are any errors in grading</u>*
  - For instance, missing grades, ungraded assignment, etc.

- There will be a final extra deadline in Dec 14^{th} to hand-in assignments that have not yet been approved
  - With no possibility of re-submission and written feedback

Course Evaluation Survey

Please participate in the course evaluation



Questions ?