Practical Concurrent and Parallel Programming I

Intro to Concurrency and Mutual Exclusion

Raúl Pardo and Jørgen Staunstrup

Agenda

- Course General Info
- Introduction to Concurrency
- Java Threads
- Mutual Exclusion
- Java Locks
- Happens-before

Teachers

- Course manager: Raúl Pardo
  - PhD from Chalmers University (Sweden) 2017
  - Postdoc at Inria (France) 2017 & ITU (Denmark) 2019
  - Assistant Professor at ITU since Feb 2022
    - Teaching PCPP since 2021 (and concurrency since 2013)
  - Research interest: Privacy & Security, Formal Verification, Probabilistic Reasoning, Concurrency

- Co-teacher: Jørgen Staunstrup
  - PhD from University of Southern California (USA) 1978
  - Joined ITU in 2001, retired in 2014
  - Teaching MSc course Mobile App Development at ITU since 2016

- Teaching Assistants
  - Amund Ranheim Lome
  - Frederik Madsen
  - You will meet them after the lecture

Standard weekly plan

- Lectures
  - Mondays 8-10
  - We publish the readings for the lecture a week before the lecture (approx.)
  - Auditorium 1
- Exercise sessions
  - Mondays 10-12
  - Every week we publish a set of exercises covering the material of the lecture
  - 2A12-14, 2A52 (these two preferred) and 4A58 (if no space in others)

Course Info Online

- The learnIT website (https://learnit.itu.dk/course/view.php?id=3021303) contains information about the course and submission links for the assignments

- The material of the course is hosted in our github repository (https://github.itu.dk/jst/PCPP2022-public)
  - Lecture slides
  - Readings
  - Example code
  - Exercises
  - Accompanying code for the exercises

You may want to “watch” the repository to be notified every time there are updates

Exercises

- You are expected to work on **groups of 2/3 people**
  - Today in the exercise session we will start by forming groups with the help of TAs
- Assignments submissions are **on Fridays before the lecture**
  - We made sure to minimize clashing with other courses in the CS programme
  - In total there are 11 exercise sets, distributed in 6 assignments
- **Oral Feedback and Assessment**
  - Feedback and assessment of assignments is provided in oral sessions
  - You must **book an oral feedback slot with a TA/teacher using the scheduler in learnIT**
  - Today in the exercise session you can already book a slot (https://learnit.itu.dk/mod/scheduler/view.php?id=161438)
- **You must pass 5 assignments to be entitled to take the exam**
  - We encourage you to not skip assignments, as they are one of the best activities to prepare for the exam
- Exercises are divided into *mandatory* and *challenging*
  - Challenging exercises are meant for students aiming at high grades in the exam
  - Challenging exercises are not required to pass the assignments

Questions and Answers Forum

- The main channel of communication is the Questions and Answers Forum in LearnIT
  - https://learnit.itu.dk/mod/hsuforum/view.php?id=160124
  - **We strongly encourage you to use the forum!**
  - We will check the forum regularly
  - But, we also encourage you to answers questions yourself!
    - The forum is meant to be a discussion platform to boost learning and share knowledge

- The only constraint: *do not directly post solutions to exercises*

Questions and Answers Forum

- The main channel of communication is the Questions and Answers Forum in LearnIT
  - https://learnit.itu.dk/mod/hsuforum/view.php?id=160124
  - **We strongly encourage you to use the forum!**
  - We will check the forum regularly
  - But, we also encourage you to answers questions yourself!
    - The forum is meant to be a discussion platform to boost learning and share knowledge

WARNING: You can post anonymously, but teachers and TAs can internally check your identity. Post are effectively anonymous only for your classmates.

- The only constraint: *do not directly post solutions to exercises*

Additional help for exercises

- CS Study lab (Thursdays, 8-10, room 3A50)
  - Jakob Uttenthal Israelsen <jais@itu.dk>
  - Emil Bak-Møller <ebak@itu.dk>

Exam

- 24h take-home written exam
  - Similar to the weekly exercises

Concurrency

It takes one person 2 hours to dig 2 meters of ditch.
How long will it take 2 people to dig 4 meters of ditch?

Concurrency

It takes one person 2 hours to dig 2 meters of ditch.
How long will it take 2 people to dig 4 meters of ditch?

What if they only have one shovel?

Concurrency

It takes one person 2 hours to dig 2 meters of ditch.
How long will it take 2 people to dig 4 meters of ditch?

What if they only have one shovel?

What if they have to dig a hole (and not a ditch)?

Concurrency

It takes one person 2 hours to dig 2 meters of ditch.
How long will it take 2 people to dig 4 meters of ditch?

What if they only have one shovel?

What if they have to dig a hole (and not a ditch)?

How fast can a 100 persons dig 1 meter of ditch?

Concurrency

It takes one person 2 hours to dig 2 meters of ditch.
How long will it take 2 people to dig 4 meters of ditch?

What if they only have one shovel?

What if they have to dig a hole (and not a ditch)?

How fast can a 100 persons dig 1 meter of ditch?

…

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

It is important to distinguish between the abstract concept concurrency and the language/hardware details used to implement concurrency!

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

It is important to distinguish between the abstract concept concurrency and the language/hardware details used to implement concurrency!

Abstract: **streams:** s1;s2;s3; ….
z1;z2;z3;z4; …
…..

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

It is important to distinguish between the abstract concept concurrency and the language/hardware details used to implement concurrency!

Abstract: **streams:** s1;s2;s3; ….
z1;z2;z3;z4; …
…..

\+ **cordination:** s1;s2;s3; ….
z1;z2;z3;z4; …
…..

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

It is important to distinguish between the abstract concept concurrency and the language/hardware details used to implement concurrency!

Abstract: **streams:** s1;s2;s3; ….
z1;z2;z3;z4; …
…..

+

cordination: s1;s2;s3; ….

z1;z2;z3;z4; …
…..

Concrete: Java threads / callbacks / processes / tasks / coroutines …

Programming for concurrency

In PCPP we will study (in detail) the mechanisms/abstractions to program for concurrency in Java and (in less) detail a few other languages.

It is important to distinguish between the abstract concept concurrency and the language/hardware details used to implement concurrency!

Abstract:	**streams:**	s1;s2;s3; …. z1;z2;z3;z4; … …..	+	**cordination:**	s1;s2;s3; …. z1;z2;z3;z4; … …..
Concrete:	Java threads / callbacks / processes / tasks / coroutines …		+	lock / monitor / semaphore / messages / ...	

The first computers were sequential

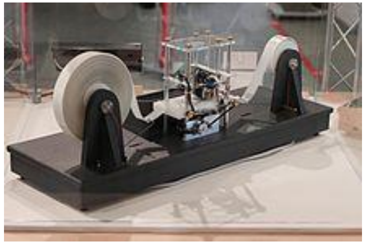
In my first years at university, we used the Danish Gier (1965)

Transistormaskinen GIER, 1961

The first computers were sequential

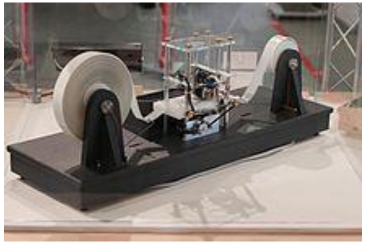
The first computers were sequential

The Turing machine (1936) - a mathematical model

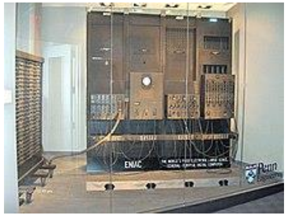


The first computers were sequential

The Turing machine (1936) - a mathematical model

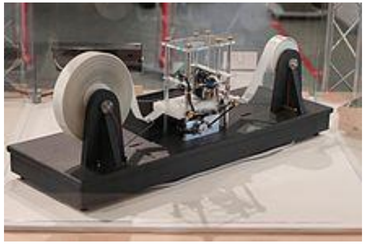


Eniac (1945)

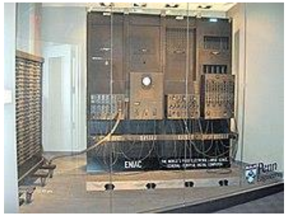


The first computers were sequential

The Turing machine (1936) - a mathematical model



Eniac (1945)



In my first years at university, we used the Danish Gier (1965)

Transistormaskinen GIER, 1961

Timesharing - my first programs (1969)

Via a number of terminals several users shared the computer

Timesharing - my first programs (1969)

Via a number of terminals several users shared the computer

My first (and best) question:

What happens if two users print simultaneously?

Single vs multiple streams

Single vs multiple streams

```
public class RemoveDuplicateInArrayExample{
  public static int removeDuplicateElements(int arr[], int n){
    if (n==0 || n==1){  return n; }
    int[] temp = new int[n];
    int j = 0;
    for (int i=0; i<n-1; i++){
      if (arr[i] != arr[i+1]){
        temp[j++] = arr[i];
      }
     }
    temp[j++] = arr[n-1];
    // Changing original array
    for (int i=0; i<j; i++){
      arr[i] = temp[i];
    }
    return j;
  }

  public static void main (String[] args) {
    int arr[] = {10,20,20,30,30,40,50,50};
    int length = arr.length;
    length = removeDuplicateElements(arr, length);
    //printing array elements
    for (int i=0; i<length; i++)   System.out.print(arr[i]+" ");
  }
}
```

Single stream

Single vs multiple streams

```
public class RemoveDuplicateInArrayExample{
  public static int removeDuplicateElements(int arr[], int n){
    if (n==0 || n==1){  return n; }
    int[] temp = new int[n];
    int j = 0;
    for (int i=0; i<n-1; i++){
      if (arr[i] != arr[i+1]){
        temp[j++] = arr[i];
      }
    }
    temp[j++] = arr[n-1];
    // Changing original array
    for (int i=0; i<j; i++){
      arr[i] = temp[i];
    }
    return j;
  }

  public static void main (String[] args) {
    int arr[] = {10,20,20,30,30,40,50,50};
    int length = arr.length;
    length = removeDuplicateElements(arr, length);
    //printing array elements
    for (int i=0; i<length; i++)    System.out.print(arr[i]+" ");
  }
}
```

Single stream

Single vs multiple streams

```
public class RemoveDuplicateInArrayExample{
  public static int removeDuplicateElements(int arr[], int n){
    if (n==0 || n==1){  return n; }
    int[] temp = new int[n];
    int j = 0;
    for (int i=0; i<n-1; i++){
      if (arr[i] != arr[i+1]){
        temp[j++] = arr[i];
      }
    }
    temp[j++] = arr[n-1];
    // Changing original array
    for (int i=0; i<j; i++){
      arr[i] = temp[i];
    }
    return j;
  }

  public static void main (String[] args) {
    int arr[] = {10,20,20,30,30,40,50,50};
    int length = arr.length;
    length = removeDuplicateElements(arr, length);
    //printing array elements
    for (int i=0; i<length; i++)   System.out.print(arr[i]+" ");
  }
}
```

Single stream

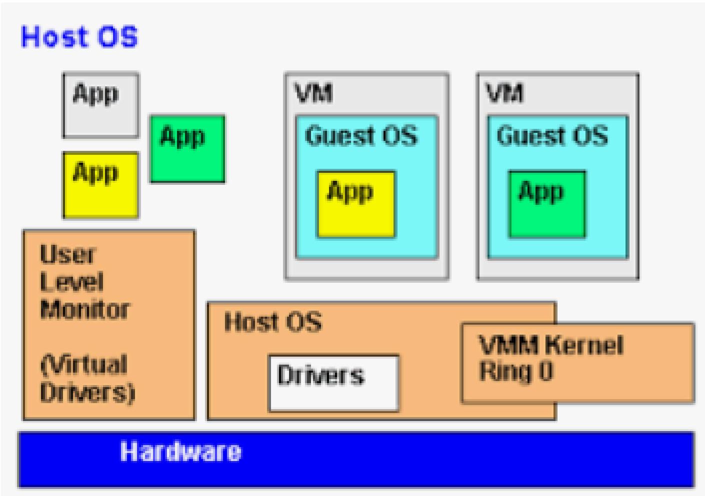
```
------------
----
--------
-----
---
-------
```

Concurrent (multiple streams)

```
----------   ----        ------------
----         ---------   ----
--------     -----       --------
-----        --------    -----
---          ---------   ---
-------      --------    -------
             ---------
             -----
```

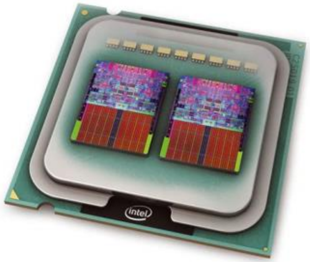
Motivations for Concurrency

Hidden (virtual)

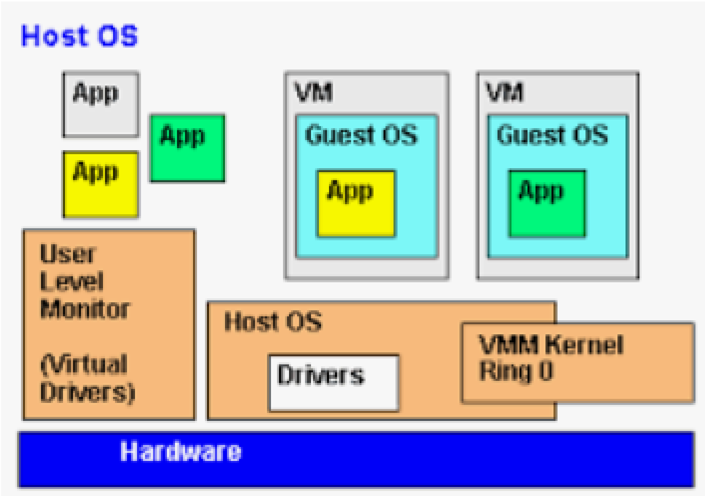


Motivations for Concurrency

Exploitation

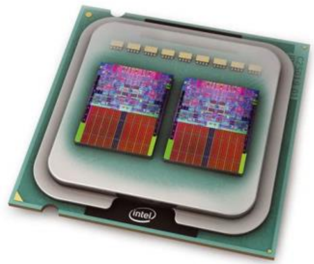


Hidden (virtual)



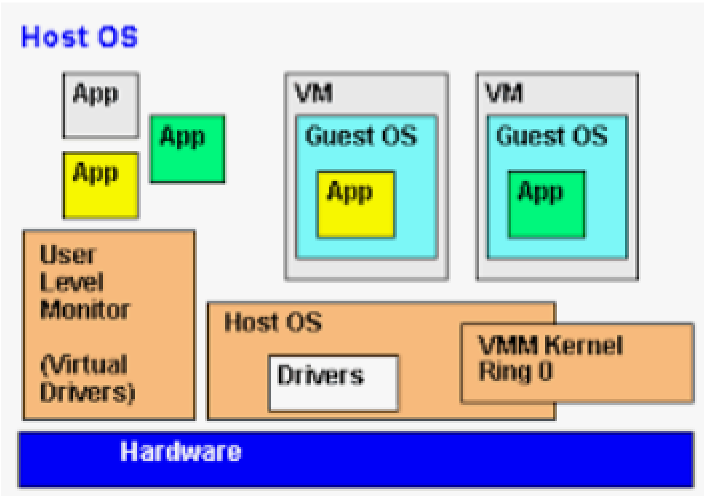
Motivations for Concurrency

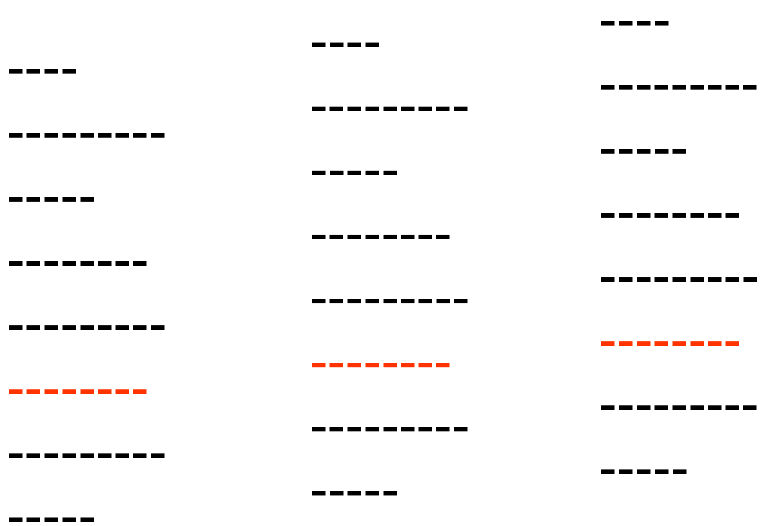
Exploitation



Inherent

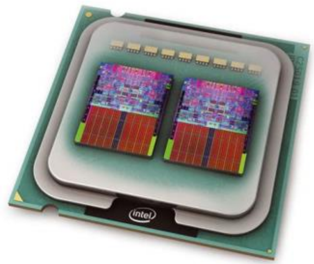
Hidden (virtual)





Motivations for Concurrency

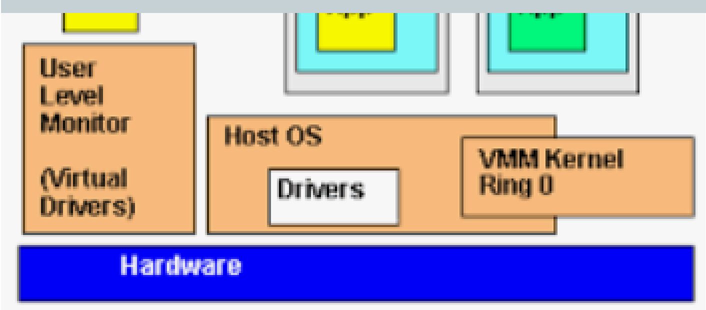
Exploitation

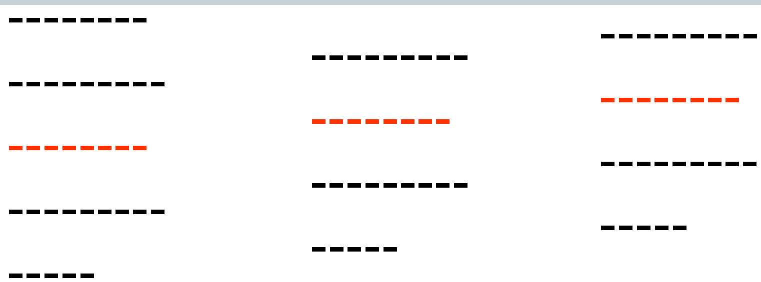


Inherent

Concurrency is an abstraction for all of these

(and more)





Other important abstractions

Animal: general properties of all species

Other important abstractions

Animal: general properties of all species

Car: ignoring the details of a specific brand/model

Other important abstractions

Animal: general properties of all species

Car: ignoring the details of a specific brand/model

Computer: ignore details of hardware/software

Other important abstractions

Animal: general properties of all species

Car: ignoring the details of a specific brand/model

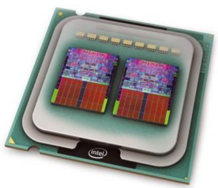
Computer: ignore details of hardware/software

etc:

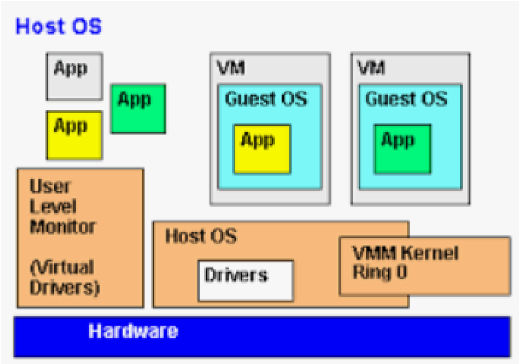
Concurrency

Concepts, challenges, theories that are common to:

Exploitation



Hidden (virtual)

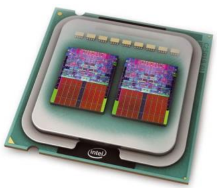


Inherent

Concurrency

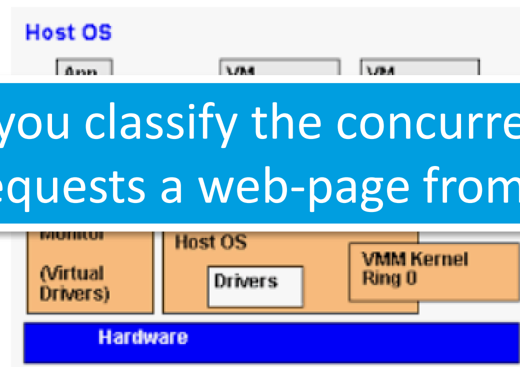
Concepts, challenges, theories that are common to:

Exploitation



Inherent

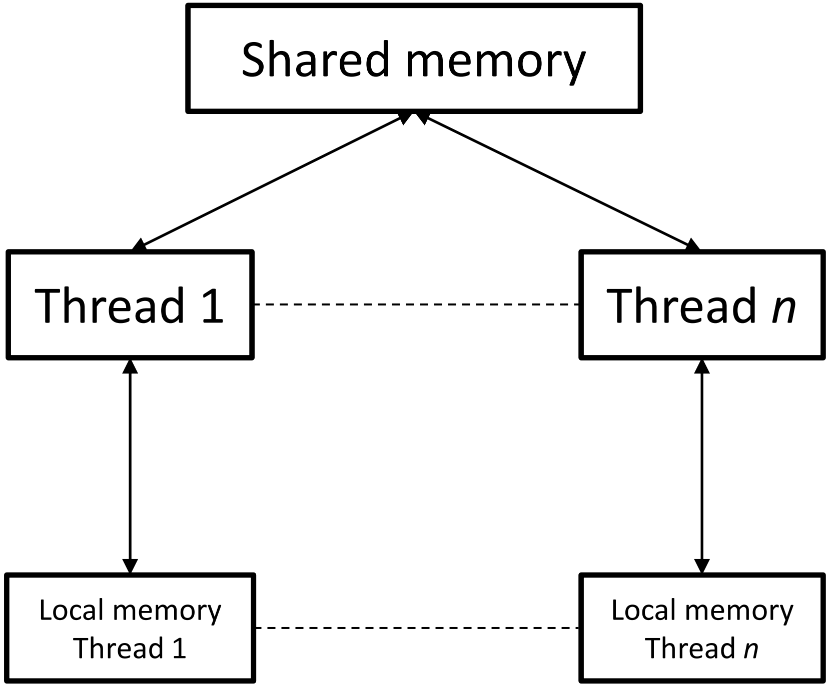
Hidden (virtual)



How would you classify the concurrency when a browser requests a web-page from a server?

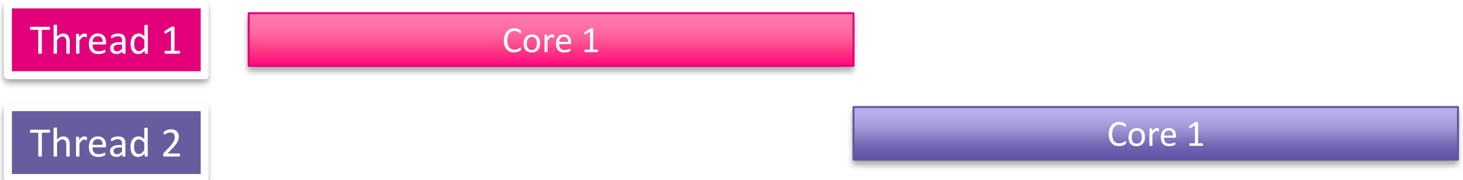
Threads in Java

- A *thread* is a stream of program statements executed sequentially
- Several threads can be executed at the same time, i.e., *concurrently*
- Each threads works at its own speed
- Each thread has its own local memory
- Threads can communicate via shared memory

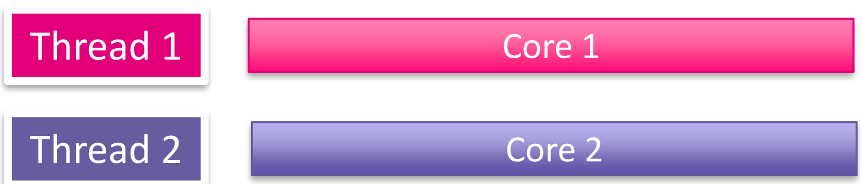


Sequential vs Parallel vs Concurrent

- **Sequential** execution (in 1 processing core)

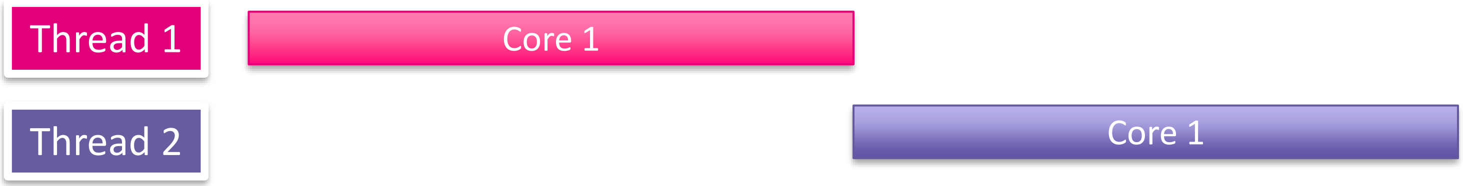


- **Parallel** execution (in 2 processing cores)

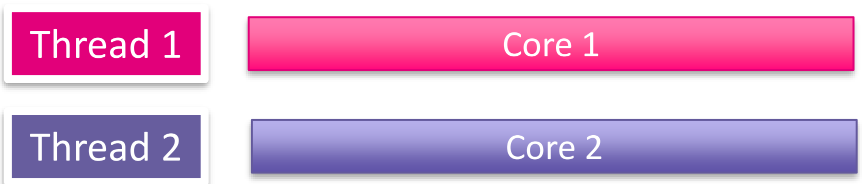


Sequential vs Parallel vs Concurrent

- **Sequential** execution (in 1 processing core)



- **Parallel** execution (in 2 processing cores)



Concurrent

- Computation may be split in arbitrary blocks (as opposed to sequential)
- Multiple concurrent streams can be executed in one core (as opposed to parallel)
- When there are more than two cores different threads may run in parallel
- Concurrent computation may be inherent: UIs, message-passing, etc.

Threads in Java – Example
Tivoli entrance turnstile

Threads in Java - Example

- Java threads can be created either by implementing **`Runnable`** or extending from **`Thread`**
- The behaviour of the thread is in the **`run()`** method (override)

```
final long PEOPLE = 10_000;
long counter = 0;
…

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

This thread simulates 10000 people entering to Tivoli

Threads in Java - Example

- Java threads can be created either by implementing **`Runnable`** or extending from **`Thread`**
- The behaviour of the thread is in the **`run()`** method (override)

```
final long PEOPLE = 10_000;
long counter = 0;
...

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

Shared memory

This thread simulates 10000 people entering to Tivoli

Threads in Java - Example

- Java threads can be created either by implementing **`Runnable`** or extending from **`Thread`**
- The behaviour of the thread is in the **`run()`** method (override)

```
final long PEOPLE = 10_000;
long counter = 0;
...

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

This thread simulates 10000 people entering to Tivoli

Shared memory

Local memory

Threads in Java - Example

- Java threads can be created either by implementing **`Runnable`** or extending from **`Thread`**
- The behaviour of the thread is in the **`run()`** method (override)

```
final long PEOPLE = 10_000;
long counter = 0;
...

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

This thread simulates 10000 people entering to Tivoli

Shared memory

Local memory

Behaviour of the thread

Threads in Java - Example

- The function **`start()`** starts the execution of the thread
- The function **`join()`** waits for the thread to terminate

```
Turnstile turnstile = new Turnstile();

turnstile.start();

turnstile.join();

System.out.println(counter+" people entered");
```

Create an instance of the thread

Start execution of the thread

Wait until the thread terminates

Print the value of **`counter`**

Threads in Java - Example

- Altogether (not executable, see **`CounterThreads.java`** for the executable program)

```
class CounterThreads {
    long counter = 0;
    final long PEOPLE  = 10_000;


    // main thread behaviour
    Turnstile turnstile = new Turnstile();
    turnstile.start();
    turnstile.join();
    System.out.println(counter+" people entered");


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

Threads in Java - Example

- Altogether (not executable, see **`CounterThreads.java`** for the executable program)

Shared memory

Create, start, wait till termination and print results

Definition of the thread´s behaviour

```
class CounterThreads {
    long counter = 0;
    final long PEOPLE  = 10_000;


    // main thread behaviour
    Turnstile turnstile = new Turnstile();
    turnstile.start();
    turnstile.join();
    System.out.println(counter+" people entered");


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

Threads in Java - Example

What value of **counter** will this program print?

…cutable, see **CounterThreads.java** for …gram)

Shared memory

Create, start, wait till termination and print results

Definition of the thread´s behaviour

```
class CounterThreads {
    long counter = 0;
    final long PEOPLE  = 10_000;


    // main thread behaviour
    Turnstile turnstile = new Turnstile();
    turnstile.start();
    turnstile.join();
    System.out.println(counter+" people entered");


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

Threads in Java – Alternative Definition

Other ways to define threads

Runnable object in the thread constructor

```
long counter = 0;
final long PEOPLE  = 10_000;


Thread t = new Thread(new Runnable(){
    public void run() {
            for (int i=0; i<PEOPLE; i++){
                  counter++;
            }
    }
});
t.start();
t.join();
System.out.println(counter+" people entered");
```

Using Java lambda expressions

```
long counter = 0;
final long PEOPLE  = 10_000;


Thread t = new Thread(() -> {
    for (int i=0; i<PEOPLE; i++){
        counter++;
    }
});
t.start();
t.join();
System.out.println(counter+" people entered");
```

Threads in Java – Alternative Definition

Other ways to define threads

Runnable object in the thread constructor

```
long counter = 0;
final long PEOPLE  = 10_000;


Thread t = new Thread(new Runnable(){
    public void run() {
            for (int i=0; i<PEOPLE; i++){
                  counter++;
            }
    }
});
t.start();
t.join();
System.out.println(counter+" people entered");
```

Using Java lambda expressions

```
long counter = 0;
final long PEOPLE  = 10_000;


Thread t = new Thread(() -> {
    for (int i=0; i<PEOPLE; i++){
        counter++;
    }
});
t.start();
t.join();
System.out.println(counter+" people entered");
```

I would only recommend these when the thread´s code is small, e.g., without several methods. And when the local state of the thread is minimal. <u>WARNING</u>: Possibly bias opinion!

Threads in Java – Example
Tivoli entrance turnstile

Threads in Java – Example II
Tivoli entrance turnstile

Threads in Java – Example II

- Altogether (not executable, see **`CounterThreads2.java`** for the executable program)

```
long counter = 0;
final long PEOPLE  = 10_000;


Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile2.start();
turnstile2.join();turnstile2.join();
System.out.println(counter+" people entered");



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

We simply add another Turnstile thread

Threads in Java – Example II

What value of **`counter`** will this program print?

ecutable, see **`CounterThreads2.java`** for gram)

```
long counter = 0;
final long PEOPLE  = 10_000;


Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile2.start();
turnstile2.join();turnstile2.join();
System.out.println(counter+" people entered");



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

We simply add another Turnstile thread

Threads in Java – Example II

What value of **counter** will this program print?

ecutable, see **CounterThreads2.java** for
gram)

```
long counter = 0;
final long PEOPLE  = 10_000;


Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile2.start();
turnstile2.join();turnstile2.join();
System.out.println(counter+" people entered");



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

We simply add another Turnstile thread

Threads in Java – Example II

What value of **`counter`** will this program print?

ecutable, see **`CounterThreads2.java`** for
gram)

```
long counter = 0;
final long PEOPLE  = 10_000;


Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile2.start();
turnstile2.join();turnstile2.join();
System.out.println(counter+" people entered");



public class Turnstile extends Thread {
    public void run() {
                                                  i++) {
}
```

We simply add another Turnstile thread

HARDer: What is the minimum value of **`counter`** that this program can print?

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

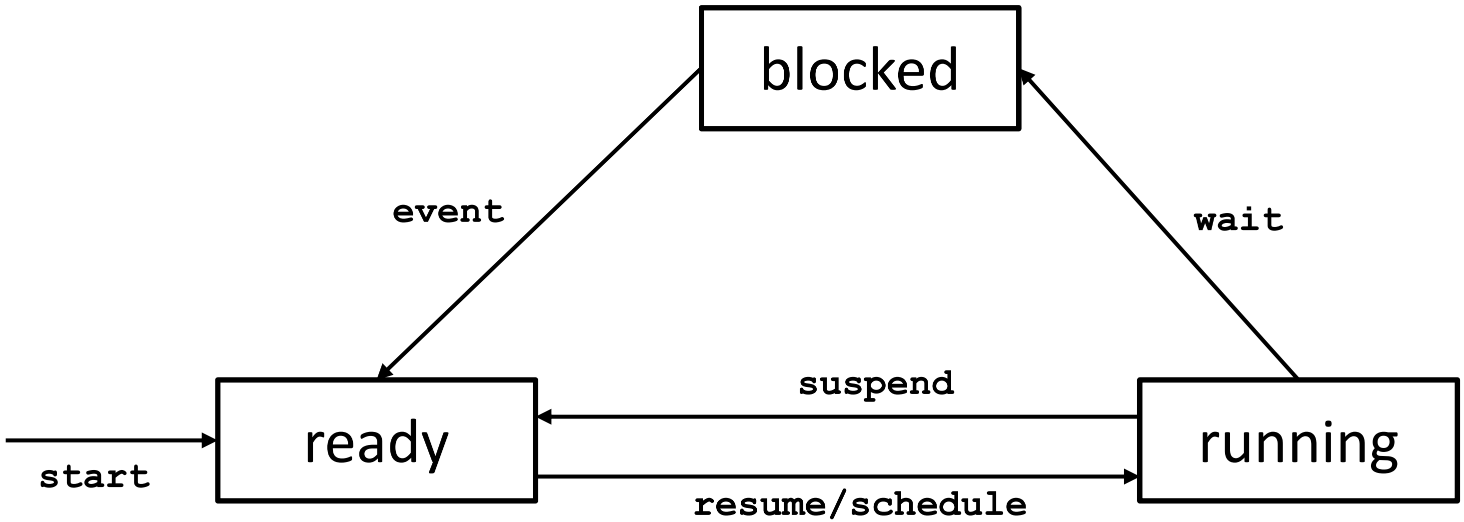
- The program statement **`counter++`** is not *atomic*
- *Atomic statements are executed as a single (indivisible) operation*

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

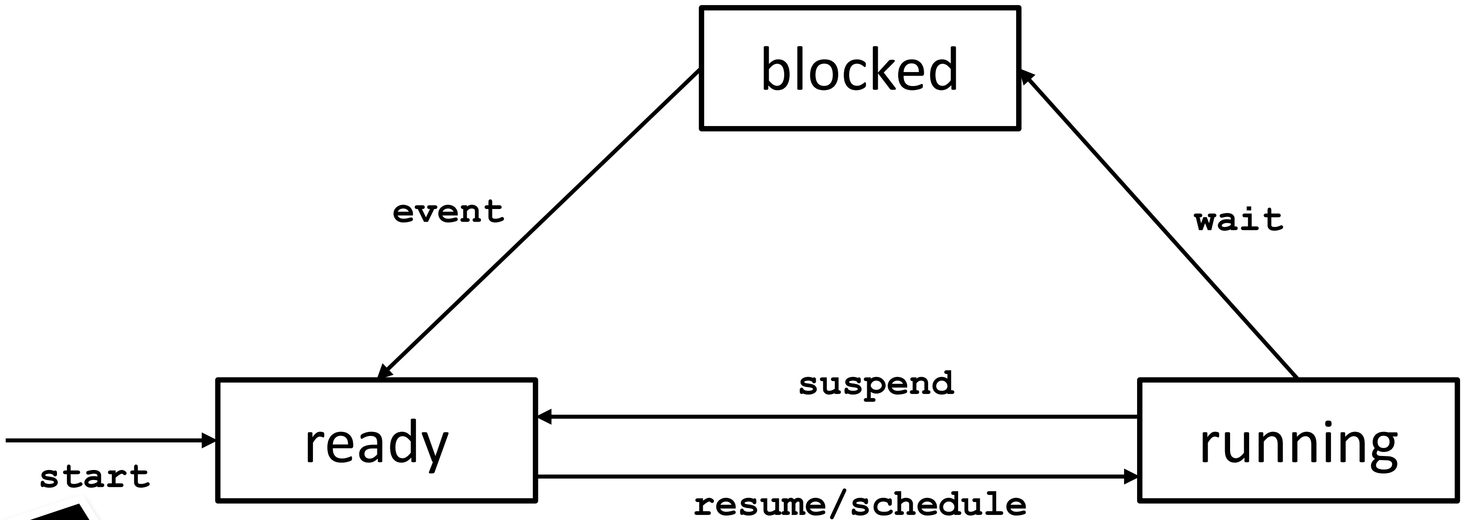
```
int temp = counter;
counter = temp + 1;
```

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

States of a thread (simplified)

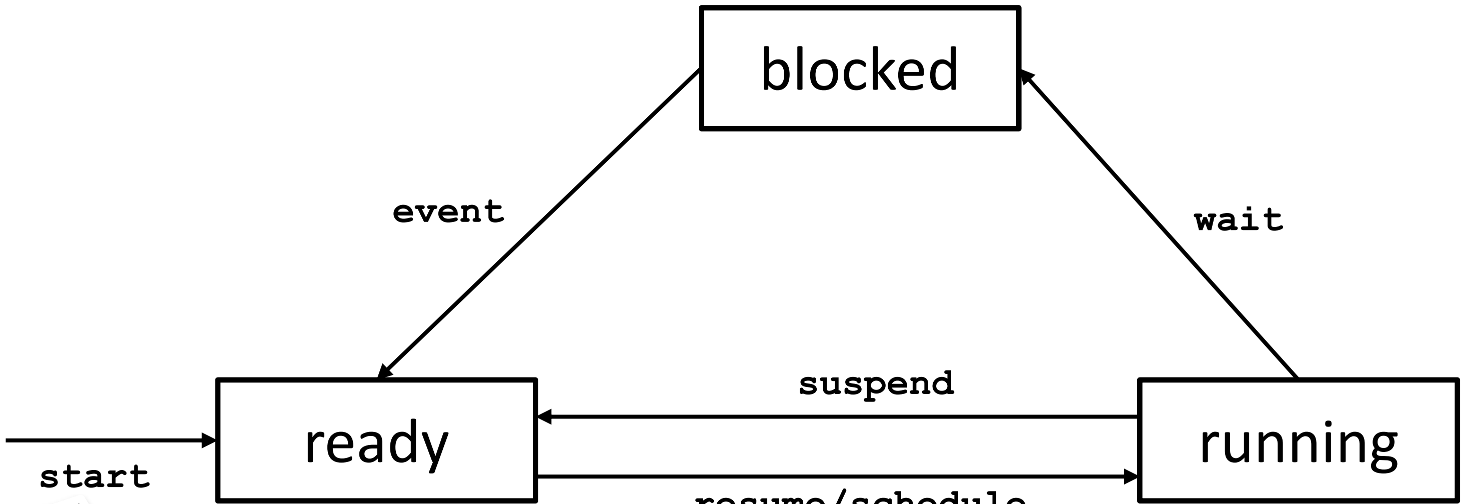


States of a thread (simplified)



This event corresponds to after executing **`start()`**

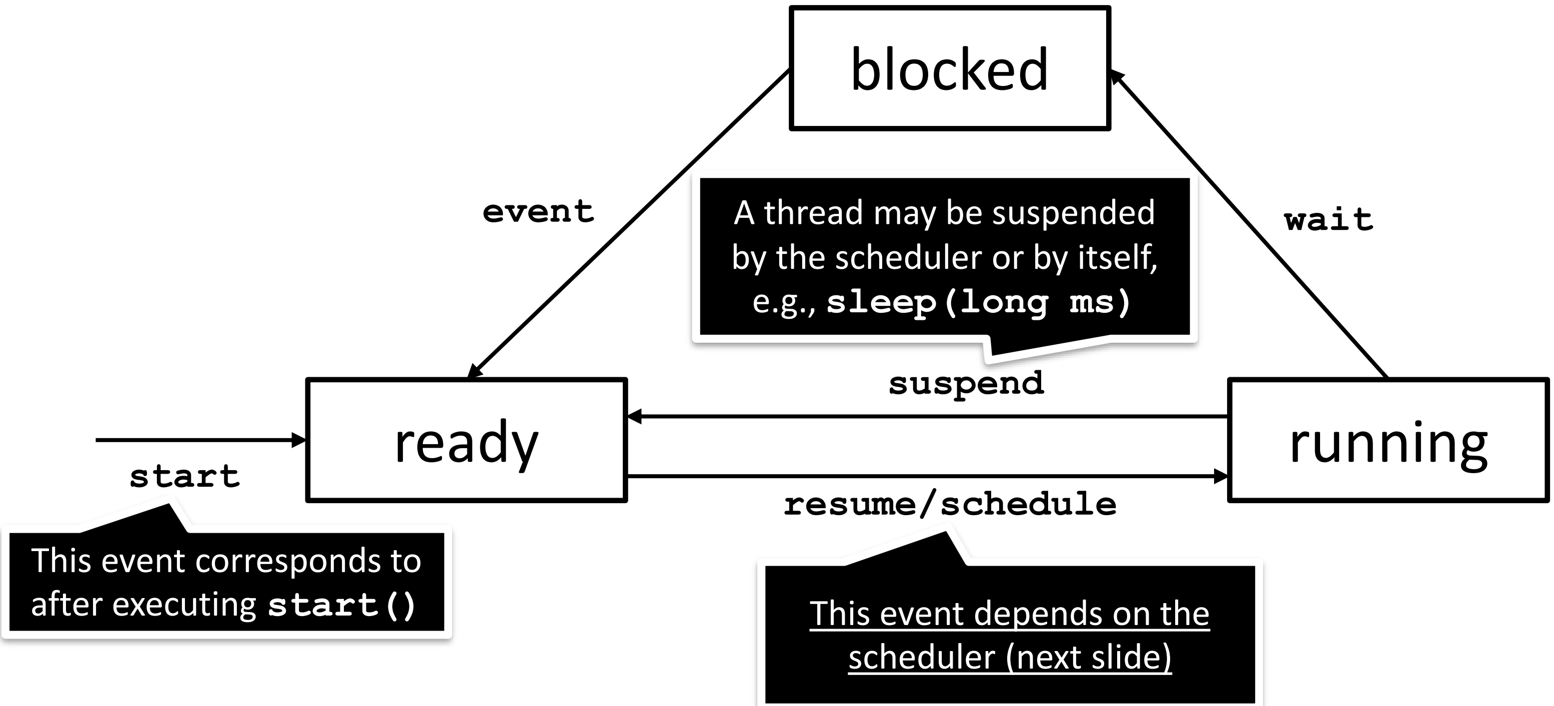
States of a thread (simplified)



This event corresponds to after executing **`start()`**

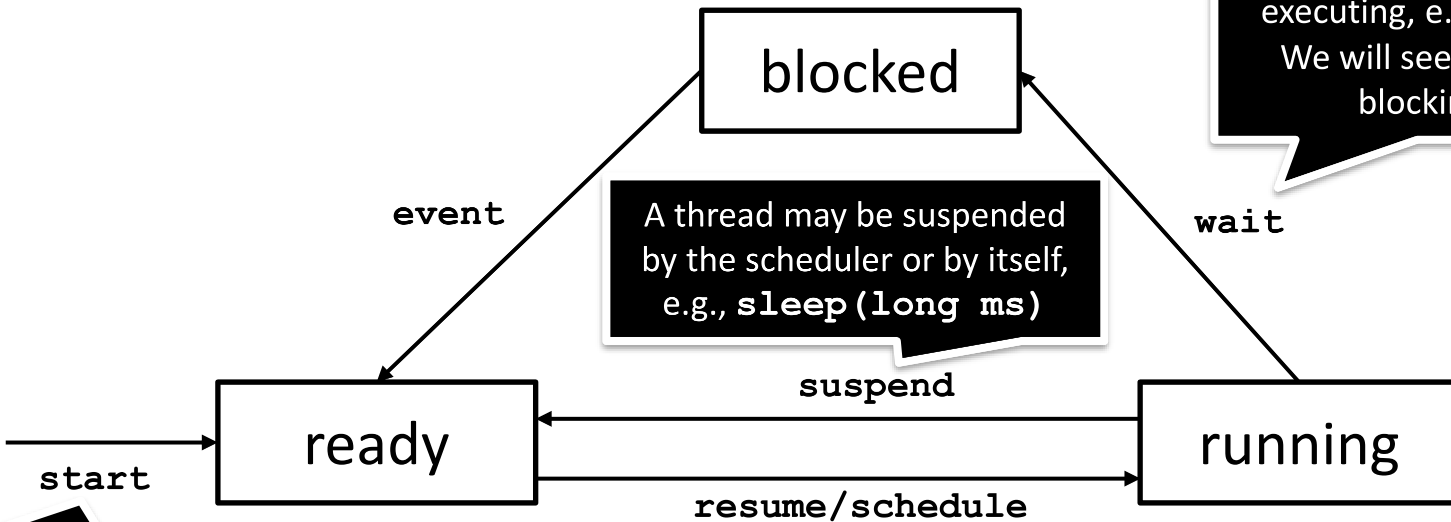
This event depends on the scheduler (next slide)

States of a thread (simplified)



States of a thread (simplified)

This event corresponds to executing, e.g., **`join()`**. We will see many other blocking calls

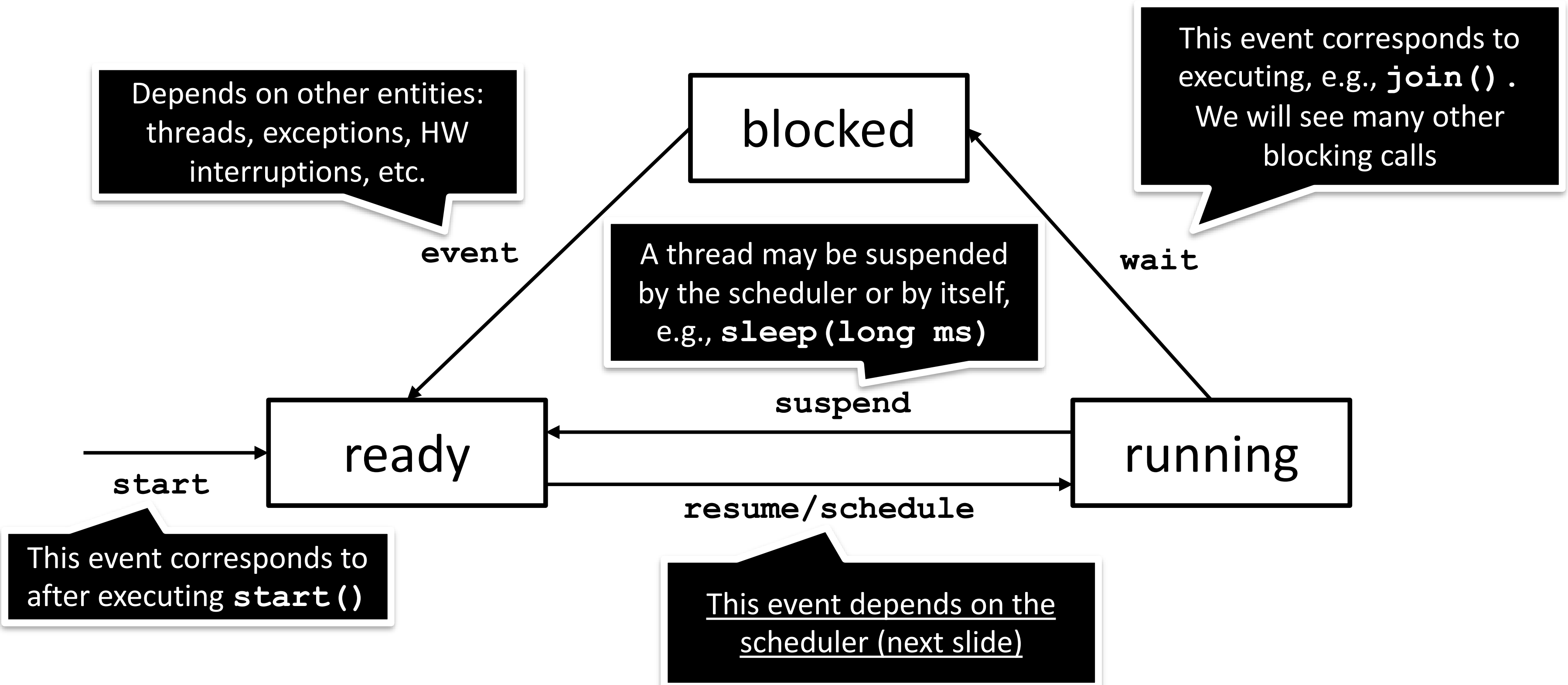


A thread may be suspended by the scheduler or by itself, e.g., **`sleep(long ms)`**

This event corresponds to after executing **`start()`**

<u>This event depends on the scheduler (next slide)</u>

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 – Example I

main

```
long counter = 0;
final long PEOPLE  = 10_000;

Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile1.start();
```

time

turnstile1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter == 0
counter = temp + 1 // counter == 1
```

time

turnstile2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter == 1
counter = temp + 1 // counter == 2
…
```

time

Interleaving – Example II

main

```
long counter = 0;
final long PEOPLE  = 10_000;

Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile1.start();
```

time

turnstile1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
```

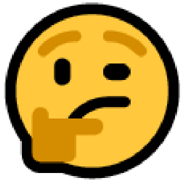
time

turnstile2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
…
```

time



Interleaving – Example II

main

```
long counter = 0;
final long PEOPLE  = 10_000;

Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile1.start();
```

Are there any other interleavings?

time

turnstile1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
```

time

turnstile2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
…
```

time

Interleaving – Example II

main

```
long counter = 0;
final long PEOPLE  = 10_000;

Turnstile turnstile1 = new Turnstile();
Turnstile turnstile2 = new Turnstile();
turnstile1.start();turnstile1.start();
```

Are there any other interleavings?

There are as many interleavings as possible ways to order the operations in the program

turnstile1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
```

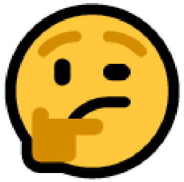
time

turnstile2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
…
```

time



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 I (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==2

Memory

counter=0	
i=0	i=0

Program

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

Interleaving – Example I (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==2

Memory

counter=0

i=0 i=0

Program

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

t1(1), t1(2), t2(1), t2(2)

Interleaving – Example I (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==2

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), t1(2), t2(1), t2(2)

Interleaving – Example I (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==2

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

counter=1	
temp=0	temp=0

t1(1), t1(2), t2(1), t2(2)

Interleaving – Example I (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==2

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

counter=1	
temp=0	temp=0

counter=1	
temp=0	**temp=1**

t1(1), t1(2), t2(1), t2(2)

Interleaving – Example I (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==2

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=1	
temp=0	temp=0

t1(2),

counter=1	
temp=0	**temp=1**

t2(1),

counter=2	
temp=0	temp=1

t2(2)

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)
}
```

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

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

Threads in Java – Example II

- What was is the problem in the previous program?
    - <u>The statement **`counter++`** is not atomic</u>
    - <u>Some interleavings result in threads reading stale (outdated) data</u>
    - <u>Consequently, the program has race conditions that result in incorrect outputs</u>

- In what follows, we will see how to tackle this type of problems

Critical sections

- A *critical section* is a part of the program that only one thread can execute at the same time
  - Useful to avoid race conditions in concurrent programs

```
public class Turnstile extends Thread {
    public void run() {
        for (int i = 0; i < PEOPLE; i++) {
            // start critical section
            int temp = counter;
            counter = temp + 1;
            // end critical section
        }
    }
}
```

Critical sections

- A *critical section* is a part of the program that only one thread can execute at the same time
  - Useful to avoid race conditions in concurrent programs

```
public class Turnstile extends Thread {
   public void run() {
        for (int i = 0; i < PEOPLE; i++) {
            // start critical section
            int temp = counter;
            counter = temp + 1;
            // end critical section
        }
   }
}
```

Critical sections should cover the parts of the code handling shared memory

Critical sections

- A *critical section* is a part of the program that only one thread can execute at the same time
  - race conditions in concurrent programs

Shouldn't the critical section start before the **for**?

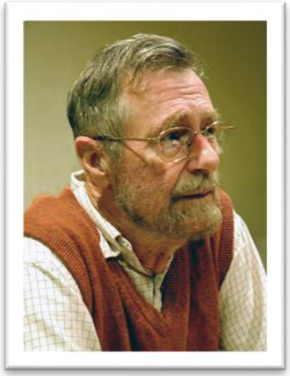
```
nstile extends Thread {
    public void run() {
        for (int i = 0; i < PEOPLE; i++) {
            // start critical section
            int temp = counter;
            counter = temp + 1;
            // end critical section
        }
    }
}
```

Critical sections should cover the parts of the code handling shared memory

Mutual Exclusion

- The *mutual exclusion* property states that
  - *Two or more threads cannot be executing their critical section at the same time*

- Mutual exclusion was first formulated by EW Dijkstra (see optional readings)
  - He devised a protocol to ensure mutual exclusion (*solving the mutual exclusion problem*)
  - He laid down the properties for a satisfactory solution to ensuring mutual exclusion



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

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

In practice, we will see that it is not always possible to achieve absence of starvation

Mutual Exclusion | Java **Locks**

- In Java, mutual exclusion can be achieved using the **`Lock`** interface in the **`java.util.concurrent.locks`** package

  - **`lock()`**
    – Acquires the lock if available, otherwise it blocks
    – It is blocking

  - **`unlock()`**
    – Releases the lock, if there are other threads waiting for the lock it signals one of them
    – It is not blocking

Java **Locks** | Critical sections

- Simple protocol: call **`lock()`** before entering the critical section, and **`unlock()`** after exiting
- *Each critical section must have a lock associated to it, but many critical sections may use the same lock.*
- Simplified, see **`CounterThreadsLock.java`**

```
Lock l = new Lock();

public class Turnstile extends Thread {
   public void run() {
         for (int i = 0; i < PEOPLE; i++) {
              l.lock()          // start critical section
              int temp = counter;
              counter = temp + 1;
              l.unlock()        // end critical section
         }
   }
}
```

Java **`Locks`** | Critical sections

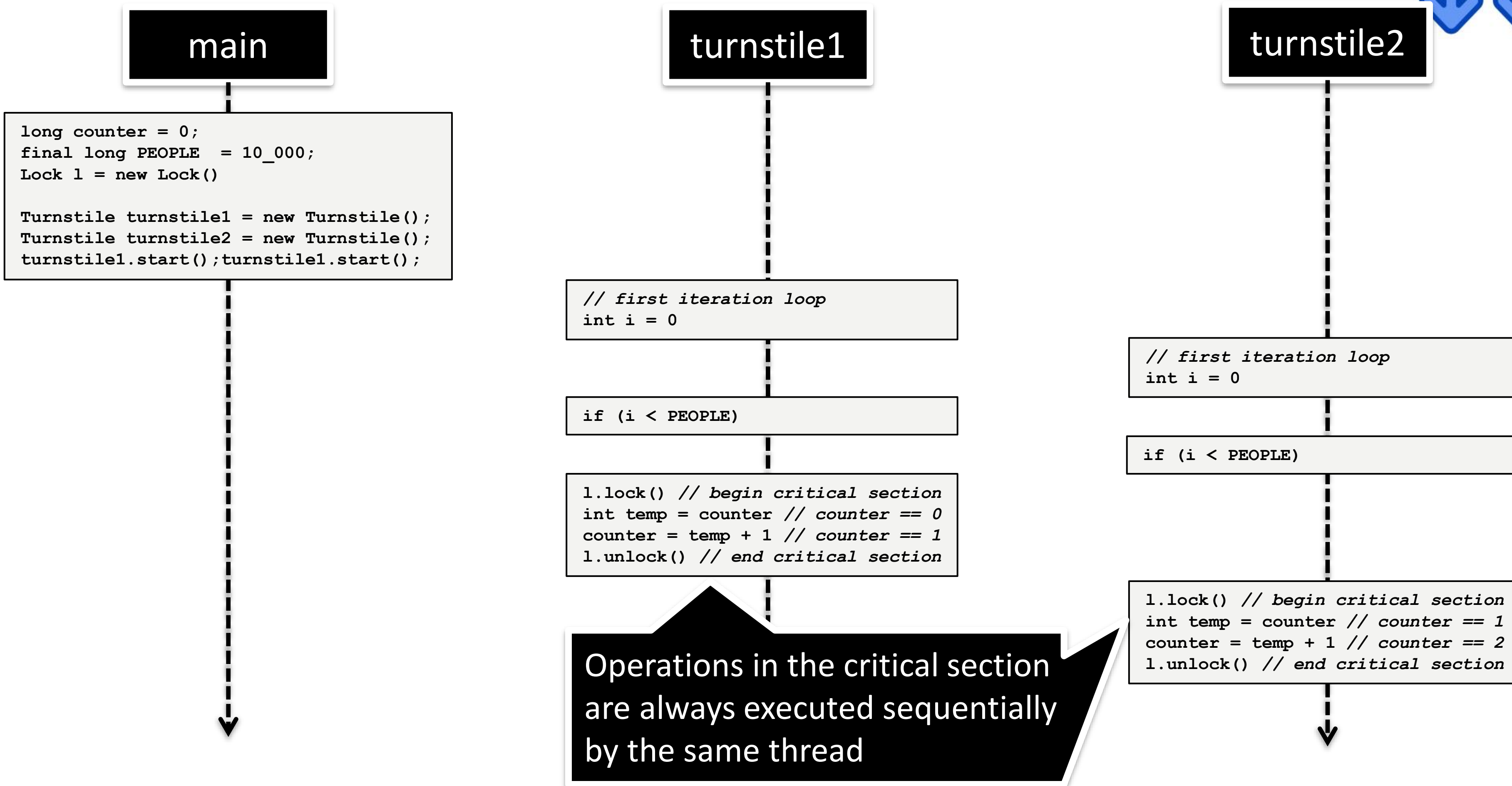
- Simple protocol: call **`lock()`** before entering the critical section, and **`unlock()`** after exiting
- <u>*Each critical section must have a lock associated to it, bu... critical sections may use the same lock.*</u>
- Simplified, see **`CounterThreadsLock.java`**

```
Lock l = new Lock();

public class Turnstile extends Threa
   public void run() {
        for (int i = 0; i < PEOPLE; i
            l.lock()         // start
            int temp = counter;
            counter = temp + 1;
            l.unlock()       // end cr
        }
   }
}
```

- For now, we do not focus on the implementation of **`lock()/unlock()`**, but in their use to solve concurrency problems.
- See Sections 2.3, 2.5, 2.7 and Section 7.3 onwards in Herlihy for implementation details of **`lock()/unlock()`**

Java Locks | Interleavings



Happens-before

- In fact, we can now characterize an order of execution between some of the operations of a program
- We say that an operation a <u>*happens-before*</u> 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

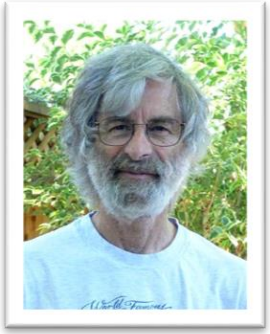
We will focus on the Java happens-before relation (page 341 Goetz and [JLS documentation])

- 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

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 $a \mid\mid b$



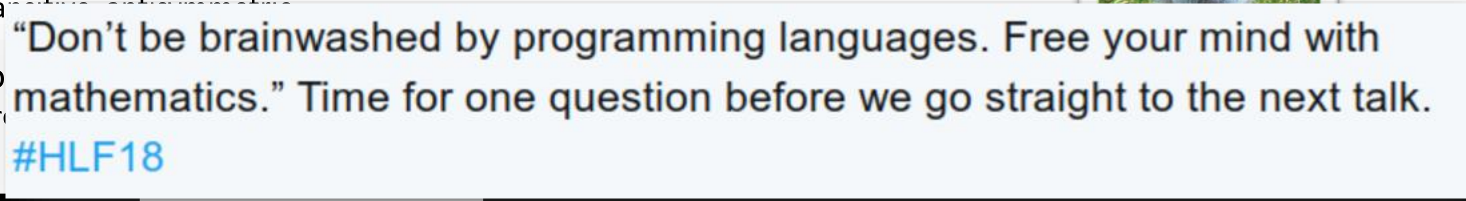
- *Happens-before* is a *partial order* over operations of concurrent programs
  - Reflexive, transitive, antisymmetric
- "Happened-before" was first introduced by Leslie Lamport for distributed systems
  - See optional readings

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, tra
- "Happened-befo
  - See optional r



Happens-before | Interleavings

- *<u>We use locks to remove undesired interlavings</u>*, and happens-before can help us reasoning about correctness

Is this a valid interleaving?

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

Happens-before | Interleavings

- *We use locks to remove undesired interlavings*, and happens-before can help us reasoning about correctness

Is this a valid interleaving?

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

NO! Two consecutive calls to `l.lock` does not satisfy the happens-before relation

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

Happens-before | Interleavings

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

NO! Two consecutive calls to **`l.lock`** does not satisfy the happens-before relation

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

Textual version of the interleaving:

t1(int i=0), t1(if(i<PEOPLE)), t1(l.lock()), t1(int temp=counter), t2(int i=0), t2(if(i<PEOPLE)), t2(l.lock()), t2(int temp=counter), …

Happens-before | Interleavings

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

NO! Two consecutive calls to **`l.lock`** does not satisfy the happens-before relation

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

Textual version of the interleaving:

t1(int i=0), t1(if(i<PEOPLE)), t1(l.lock()), t1(int temp=counter), t2(int i=0), t2(if(i<PEOPLE)), t2(l.lock()), t2(int temp=counter), …

Because we have *t1(l.lock())* $\rightarrow$ *t2(l.lock())* then *l.lock()* $\nrightarrow$ *l.unlock()* so this is not a possible interleaving

Happens-before | Interleavings

- *<u>We use locks to remove undesired interlavings</u>*, and happens-before can help us reasoning about correctness

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

From the happens-before definition we know that **`l.unlock → l.lock`**

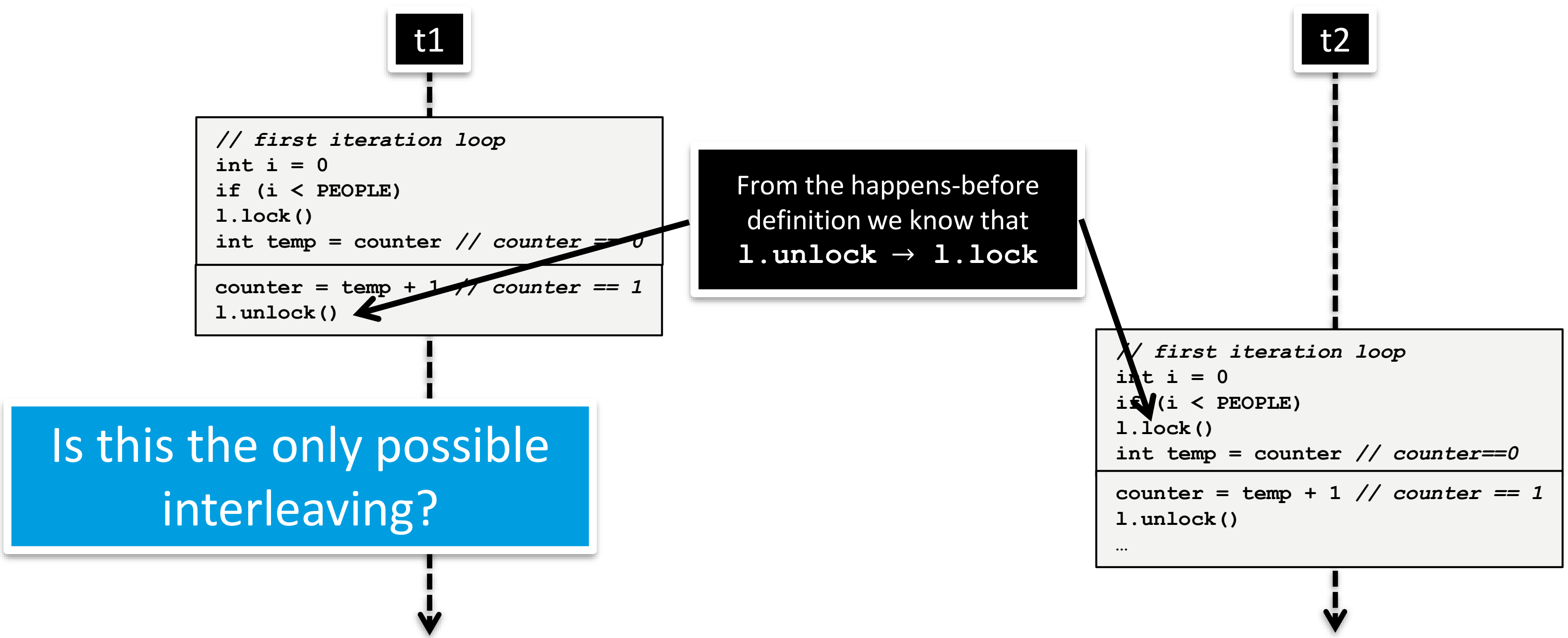
t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

Happens-before | Interleavings

- *We use locks to remove undesired interlavings*, and happens-before can help us reasoning about correctness



Happens-before | Interleavings

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
```

```
counter = temp + 1 // counter == 1
l.unlock()
```

> From the happens-before definition we know that **`l.unlock` → `l.lock`**

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
```

```
counter = temp + 1 // counter == 1
l.unlock()
…
```

<u>Textual version of the interleaving:</u>

t1(int i=0), t1(if(i<PEOPLE)), t1(l.lock()), t1(int temp=counter), t1(counter = temp+1), t1(l.unlock()), t2(l.lock()), …

Happens-before | Interleavings

t1

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter == 0
counter = temp + 1 // counter == 1
l.unlock()
```

From the happens-before definition we know that **l.unlock → l.lock**

t2

```
// first iteration loop
int i = 0
if (i < PEOPLE)
l.lock()
int temp = counter // counter==0
counter = temp + 1 // counter == 1
l.unlock()
…
```

Textual version of the interleaving:

t1(int i=0), t1(if(i<PEOPLE)), t1(l.lock()), t1(int temp=counter), t1(counter = temp+1), t1(l.unlock()), t2(l.lock()), …

Because we have *t1(l.lock()) → t1(l.unlock())* then *l.lock() → l.unlock()*
so this is a possible interleaving
(note that this is only the prefix of a larger interleaving, we should look at the complete to establish validity)

Happens-before | Interleavings

- The happens-before relation tell us that for all interleavings

$$(4) \rightarrow (1)$$

- But also that

$$(1) \rightarrow (2) \text{ and } (2) \rightarrow (3) \text{ and } (3) \rightarrow (4)$$

- Then we can derive that

$$(1) \rightarrow (2) \rightarrow (3) \rightarrow (4) \rightarrow (1) \rightarrow (2) \rightarrow \cdots$$

- Thus, all the interleavings must include instructions 1-4 in a sequence of the form

[tX(1), tX(2), tX(3), tX(4)]

```
Lock l = new Lock();

public class Turnstile extends Thread {
  public void run() {
    for (int i=0; i < PEOPLE; i++) {
      l.lock()                  // (1)
       int temp = counter;      // (2)
       counter = temp + 1;      // (3)
       l.unlock()               // (4)
    }
  }
}
```

This prevents that operations (2) and (3) are executed concurrently (which was the source of the race condition we saw above)

Happens-before | Interleavings

Isn’t there a problem with the first time that l.lock is executed? (technically it isn’t preceded by a l.unlock())

- interleavings

$$(4) \rightarrow (1)$$

- But also that
  $(1) \rightarrow (2)$ and $(2) \rightarrow (3)$ and $(3) \rightarrow (4)$

- Then we can derive that
  $(1) \rightarrow (2) \rightarrow (3) \rightarrow (4) \rightarrow (1) \rightarrow (2) \rightarrow \cdots$

- Thus, all the interleavings must include instructions 1-4 in a sequence of the form

  [tX(1), tX(2), tX(3), tX(4)]

```
Lock l = new Lock();

public class Turnstile extends Thread {
  public void run() {
    for (int i=0; i < PEOPLE; i++) {
      l.lock()                 // (1)
      int temp = counter;      // (2)
      counter = temp + 1;      // (3)
      l.unlock()               // (4)
    }
  }
}
```

This prevents that operations (2) and (3) are executed concurrently (which was the source of the race condition we saw above)

Deadlocks

- The solution to the turnstile problem ensures mutual exclusion but does it ensure absence of deadlock?

```
Lock l = new Lock();

public class Turnstile extends Thread {
   public void run() {
        for (int i = 0; i < PEOPLE; i++) {
            l.lock()          // start critical section
            int temp = counter;
            counter = temp + 1;
            l.unlock()        // end critical section
        }
   }
}
```

<u>Absence of *deadlock*</u>: threads eventually exit the critical section allowing other threads to enter

(Naïve) examples of deadlocks

- Locking twice within the thread

```
for (int i = 0; i < PEOPLE; i++) {
     l.lock()
     int temp = counter;
     counter = temp + 1;
     l.lock()  // blocks forever
               // or forgetting lot unlock()
}
```

Thread 1

This is not unrealistic.
For instance, see these bug reports in the Linux kernel
[1] https://github.com/torvalds/linux/commit/e1db4ce
[2] https://github.com/torvalds/linux/commit/2904207

- Exception during execution

```
for (int i = 0; i < PEOPLE; i++) {
     l2.lock()
     int temp = counter;
     throw new Exception();
     // If exception handling doesn't
     unlock, blocks forever

}
```

Thread 1

```
for (int i = 0; i < PEOPLE; i++) {
     l2.lock() // blocks forever
     …
}
```

Thread 2

Java **`Lock`** Idiom

- When using Java locks, it is recommended to use the idiom on the right
- This prevents deadlocks problems if the thread finish unexpectedly due to exception
  - Solutions not following this idiom cannot be deemed as free from deadlocks (note for assignments)
- We use this idiom in **`CounterThreadLocks.java`**

```
Lock l = new Lock();

l.lock()
try {
   // critical section code
} finally {
   l.unlock()
}
```

Java `ReentratLock`

- Java **`Lock`** is an interface, so it cannot be used as we showed in the examples today
- We use an implementation of the **`Lock`** interface, namely **`ReentrantLock`**
  - Reentrant locks act like a regular lock, except that they allow locks to be locked more than once by the same thread

```
Lock l = new ReentrantLock();

for (int i = 0; i < PEOPLE; i++) {
    l.lock()
    int temp = counter;
    counter = temp + 1;
    l.lock();    // it doesn't block
    l.unlock();  // still holds the lock
    l.unlock();  // now the lock is free
}
```