Some practical info

- If you struggle with Gradle, let us know! In your message include:
  - OS (and version), what shell you use (if any), whether you use an IDE (and version)
- Try to become fluent in using Gradle before the exam
  - Examiners will use the produce explained in the guidelines
- Remember to write programs compatible with **JDK 8** and later
  - For instance, `var` is not compatible with JDK 8
- Code is not self-explanatory
  - For the exam, avoid answers that simply point to a piece of code. They should be accompanied by a textual explanation
  - This is not criticism, but a kind advice to improve your chances in the exam

Practical Concurrent and Parallel Programming XI

Message Passing I

Raúl Pardo

Agenda

- Problems in shared memory concurrency (revisited)
- Actors
- Akka
- Example systems
  - Turnstile (counter)
  - Broadcaster
  - Bounded Buffer

Problems in shared memory concurrency

"Writing thread-safe code is, at its core, about ***managing access to shared mutable data****"*

Goetz

Problems in shared memory concurrency

"Writing thread-safe code is, at its core, about ***managing access to shared mutable data****"*

Goetz

What problems have we seen in concurrent access to shared memory?

Problems in shared memory concurrency

"Writing thread-safe code is, at its core, about ***managing access to shared mutable data****"*

Goetz

- Race conditions
- Data races
- Visibility
- Reasoning is tricky
  - Specially lock-free computation 😁

Problems in shared memory concurrency

"Writing thread-safe code is, at its core, about ***managing access to shared mutable data****"*

Goetz

What solutions have we seen to the problems in concurrent access to shared memory?

Problems in shared memory concurrency

"Writing thread-safe code is, at its core, about ***managing access to shared mutable data****"*

Goetz

- Happens-before reasoning
- For race conditions and data races:
  - Ensuring mutual exclusion
    - Locks (introduce the problem of deadlocks)
  - Immutability
  - Compare and Swap (CAS) algorithms
- For visibility:
  - Volatile and final variables, idioms for safe publication, etc

Problems in shared memory concurrency

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- For visibility:
  - Volatile and final variables, idioms for safe publication, etc

Why don´t we simply avoid sharing state?
This is the idea behind message passing!

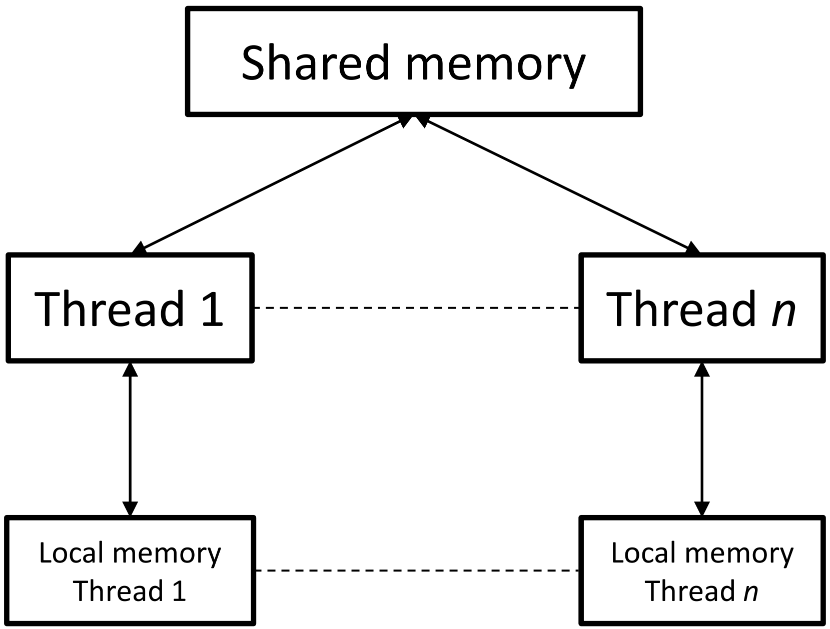
Message passing concurrency

- Threads do not share state
- If threads need to share data, then it is communicated by sending messages
- Threads work only on their own local memory

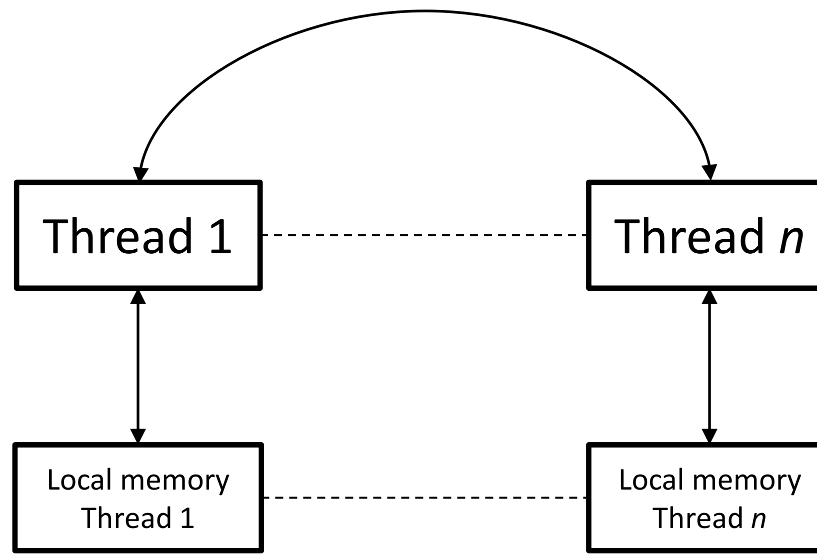
One of the designers of Erlang

Shared memory vs Message Passing

- Shared Memory
  - Synchronisation by writing in shared memory

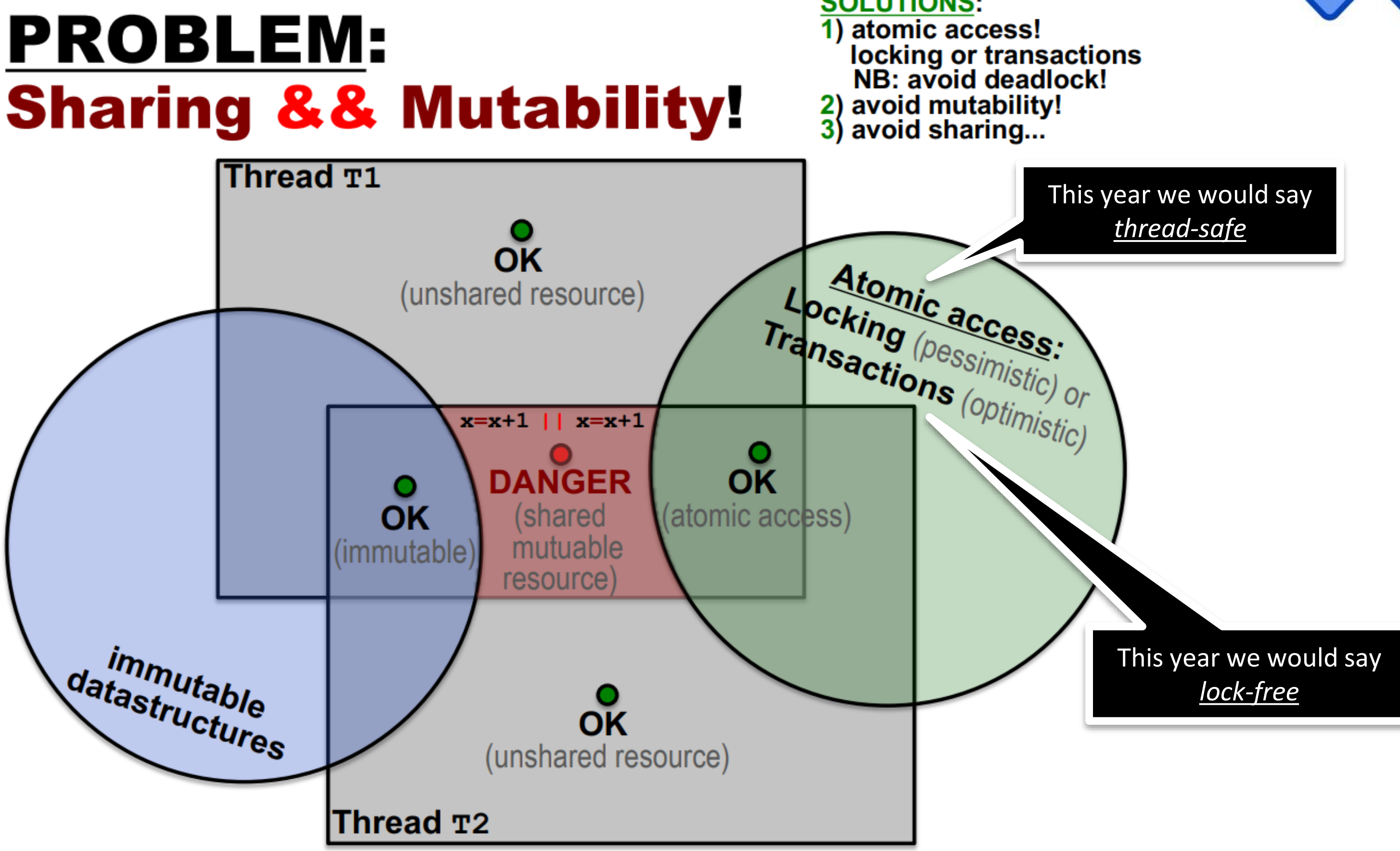


- Message Passing
  - Synchronisation by sending messages



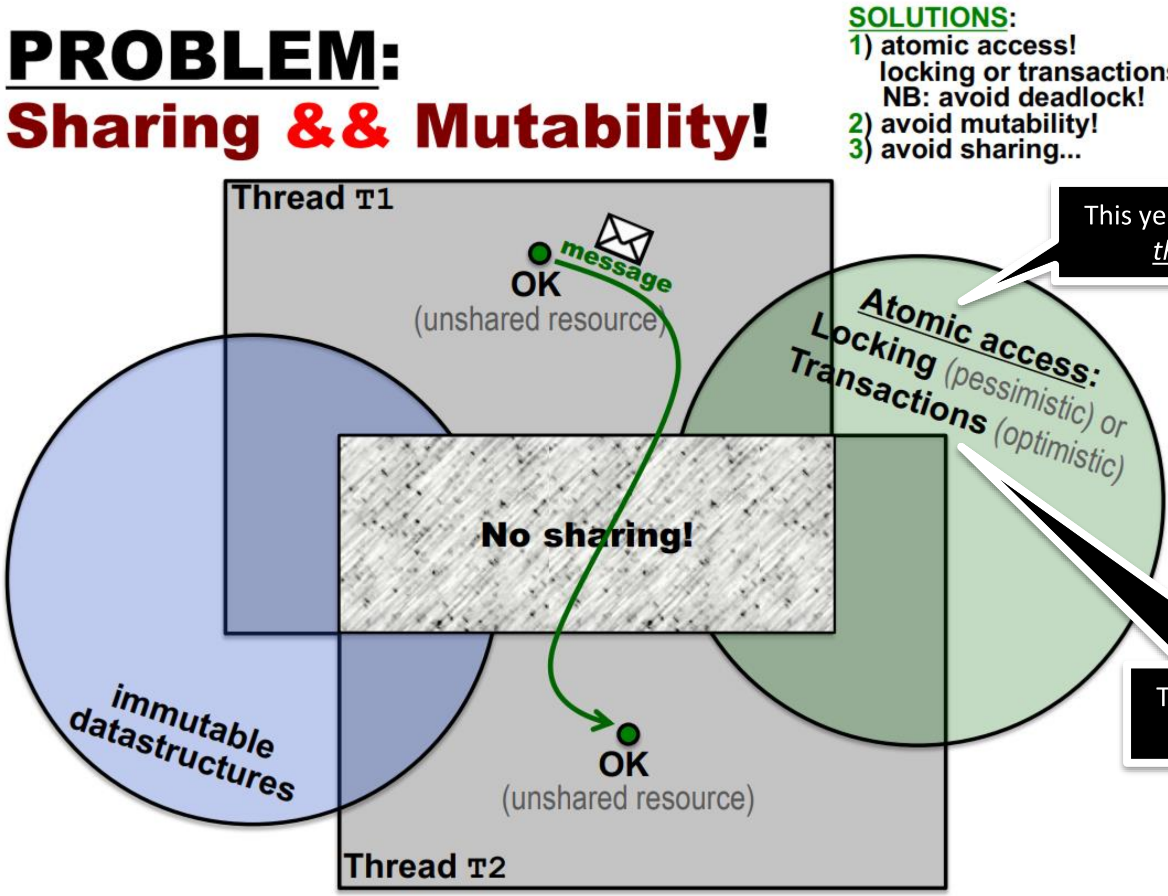
Message passing concurrency

SOLUTIONS:
1) atomic access!
   locking or transactions
   NB: avoid deadlock!
2) avoid mutability!
3) avoid sharing...



Slide from lecture 13 in PCPP 2019

Message passing concurrency



This year we would say *thread-safe*

This year we would say *lock-free*

Slide from lecture 13 in PCPP 2019

Message passing concurrency

- How should we implement message passing concurrency?

- A possible solution is use standard communication systems
  - Sockets
  - Remote Procedure Calls (RPC)
  - Java Remote Method Invocation (RMI)
  - Message passing interfaces (MPI)

  combined with concurrency as we have seen so far

Message passing concurrency

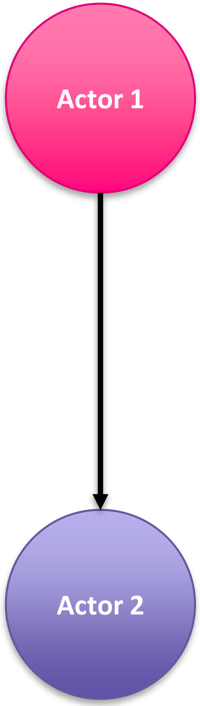
- How should we implement message passing concurrency?
- Another option is to ***use a concurrency model with message passing built-in***
    - That is, the ***actors model***!
- The actors model was first introduced by [Hewitt'73] and later formalized by [Agha'85] (part of the readings)
    - [Hewitt'73] - Carl Hewitt, Peter Bishop & Richard Steiger. A universal modular ACTOR formalism for artificial intelligence. IJCAI'73: Proceedings of the 3rd international joint conference on Artificial intelligence. 1973.
    - [Agha'85] – Gul A. Agha. ACTORS: A Model of Concurrent Computation in Distributed Systems. MIT Press. 1985.

Actors model

What is an Actor? (Bird's eye)

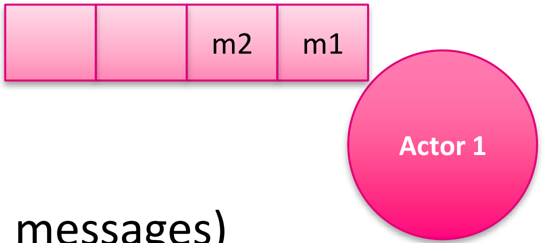
- An actor can be seen as a sequential unit of computation
  - Although, formally, the model allows for parallelism within the actor, one can safely assume that there are not concurrency issues within the actor.
  - You can think of an actor as a thread

- Actors can send messages to other actors



Actor – Specification

- An actor is an abstraction of a thread (intuitively)
- An actors can only execute any of these 4 actions
  1. *Receive messages from other actors*
  2. *Send asynchronous messages* to other actors
  3. *Create new actors*
  4. *Change its behaviour* (local state and/or message handlers)
- Actors *do not share memory*
  - They only have access to:
    - Their *local state* (local memory)
    - Their *mailbox* (multiset of fixed size with received messages)
    - By default, the mailbox is of unbounded size



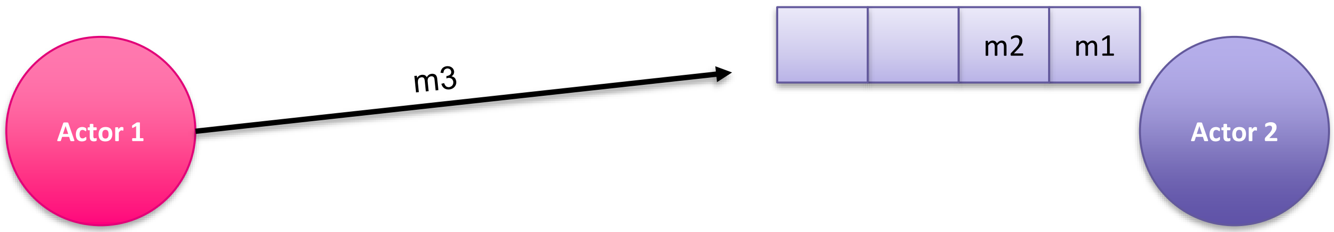
Actors and Messages

- Every actor in the system has a *unique identifier*
  - A.k.a. *mail address* or *actor reference*

- Actors can
  - Send (finitely many) messages
  - Receive (finitely many) message
  – Received messages are placed in the actor's mailbox (asynchronous communication, see next slide)

- Messages include
  - Content of the message (arbitrary payload)

Asynchronous communication



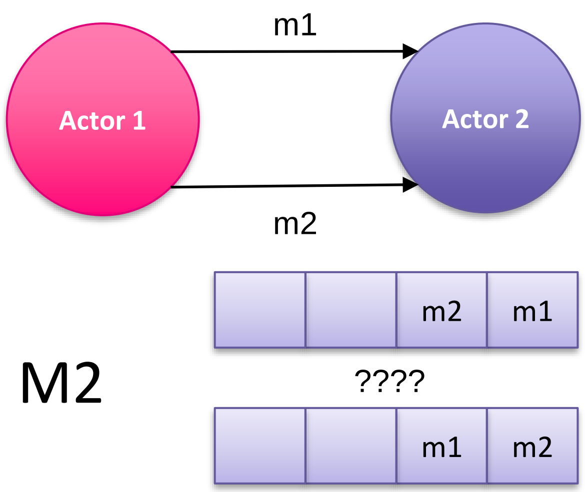
- Asynchronous *send:*
  - The sender places the message in the mailbox of the receiver
  - It is *non-blocking*

- Asynchronous *receive:*
  - The receiver takes the message from the mailbox
  - The receiver *blocks* if the mailbox is empty

No requirements on message arrival order

- No assumptions should be made about the order of arrival of messages

- For instance, consider this sequence of operations
  1. Actor1 sends message M1 to Actor2
  2. Actor1 sends message M2 to Actor2



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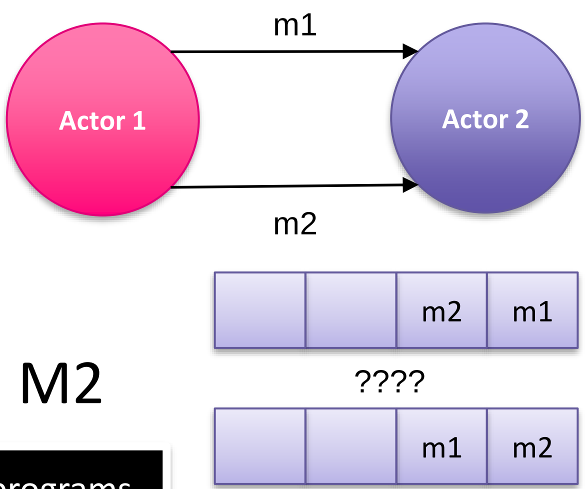


- It is *not* guaranteed that M1 arrives before M2

This is actually not true in Akka, but we will ignore that detail. Note that correct programs without this assumption will be correct if the assumption holds. But not viceversa.

Akka toolkit
(Actors implementation)

Akka Toolkit

< 2.7 ≥ 2.7

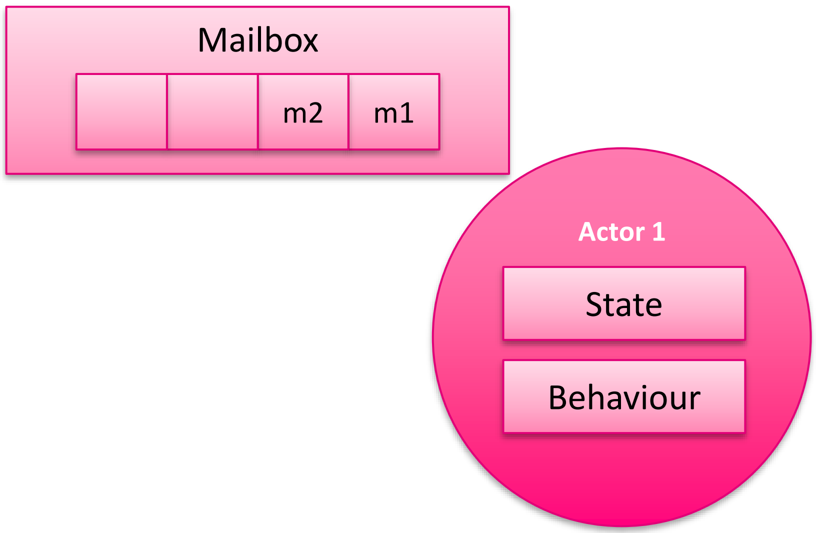
Akka *is a ~~free and open-source~~* ***source available toolkit*** *and runtime simplifying the construction of* ***concurrent*** *and distributed* ***applications*** *on the JVM. Akka supports multiple programming models for concurrency, but it emphasizes* ***actor-based concurrency*** *[...]*

[Wikipedia]

Proven in production

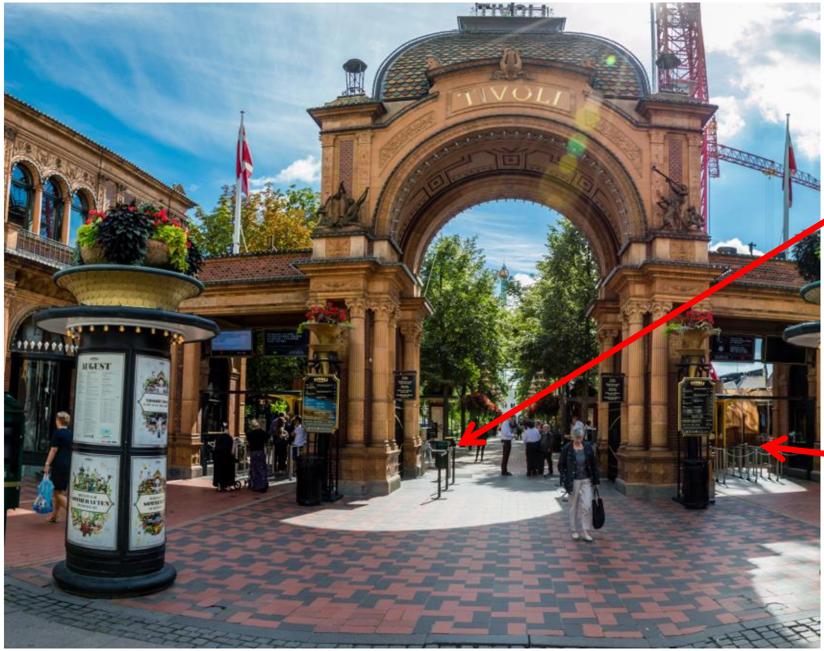
Organizations with extreme requirements rely on Akka and other Lightbend technologies. Read about their experiences in our case studies and learn more about how Lightbend can contribute to success with its commercial offerings.

Akka actors

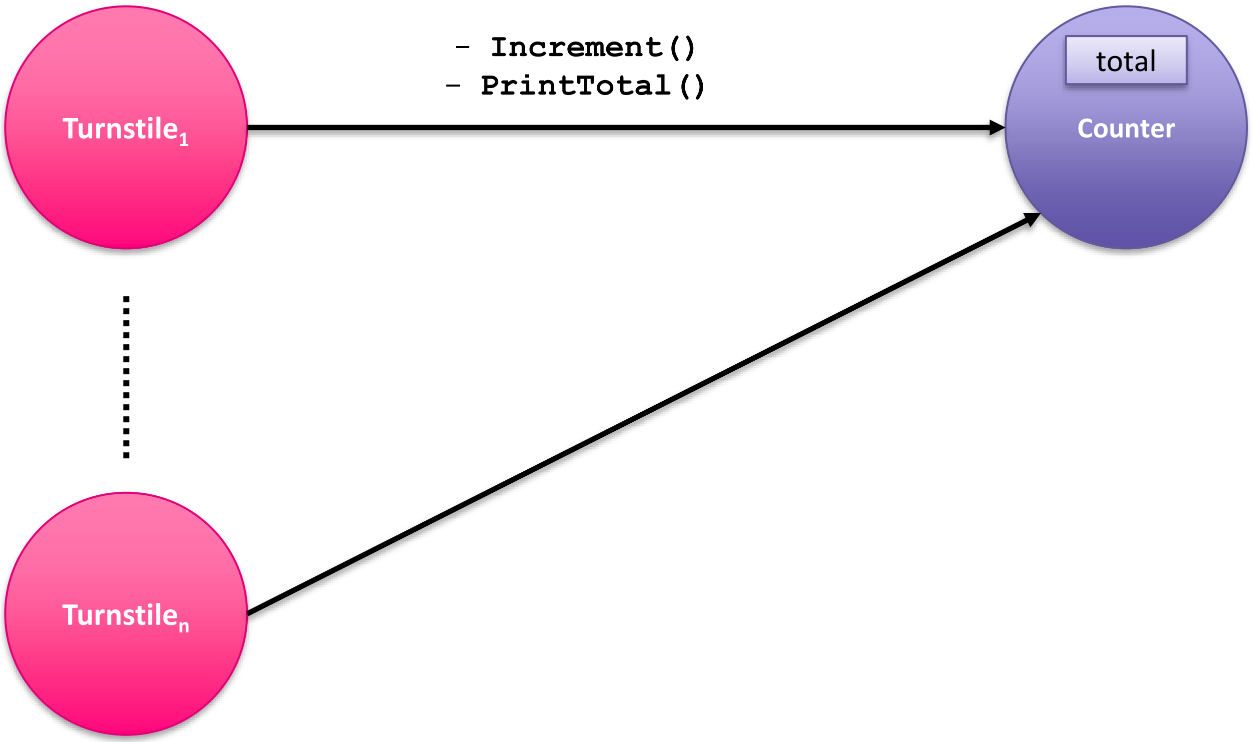


Tivoli Turnstiles with Actors!

- Actors system to count the numbers of visitors in Tivoli



Turnstile with Actors - Design



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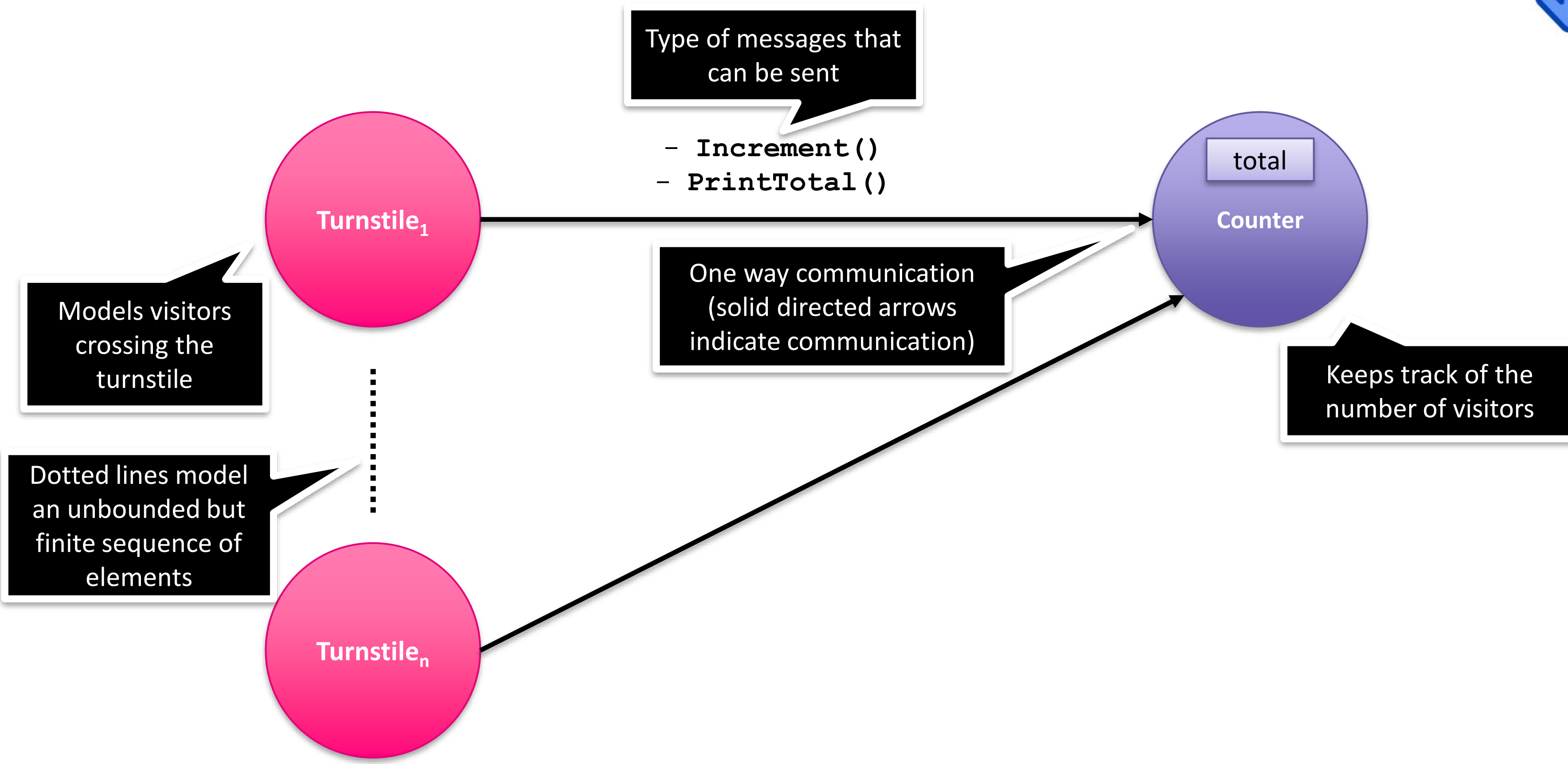

Turnstile with Actors - Implementation


```
public class Counter extends AbstractBehavior<Counter.CounterCommand> {

    /* --- Messages ------------------------------------- */
    public interface CounterCommand {}
    public static final class Increment implements CounterCommand { }
    public static final class PrintTotal implements CounterCommand { }


    /* --- State ---------------------------------------- */
    private int total;

    … // constructor missing (see next slides)

    /* --- Message handling ----------------------------- */
    @Override
    public Receive<CounterCommand> createReceive() {
         return newReceiveBuilder()
              .onMessage(Increment.class, this::onIncrement)
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              .build();
    }

    /* --- Handlers ------------------------------------- */
    public Behavior<CounterCommand> onIncrement(Increment msg) {
         this.getContext()
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              .info("A visitor arrived!");
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    }

    public Behavior<CounterCommand> onPrintTotal(PrintTotal msg) {
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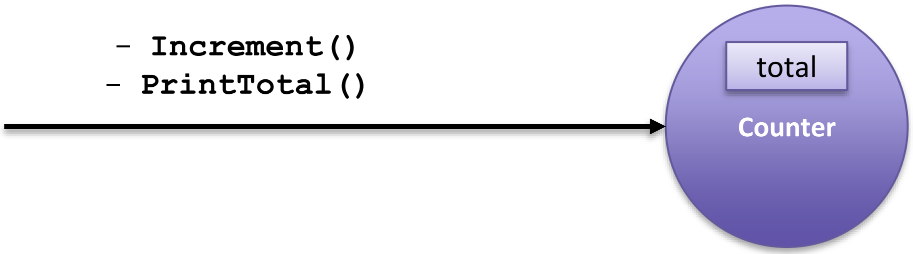

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```
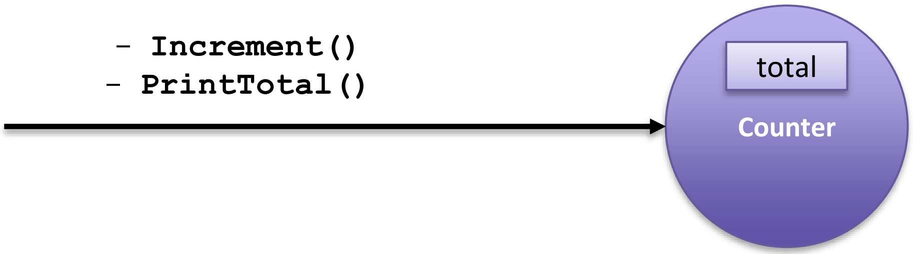

<u>Actors vs Threads</u>

- Like threads, Actors are defined in their own class



- An actor class extends from an Akka AbstractBehavior
- Parameterized with the type of messages the actor handles (see next slide)

Turnstile with Actors - Implementation

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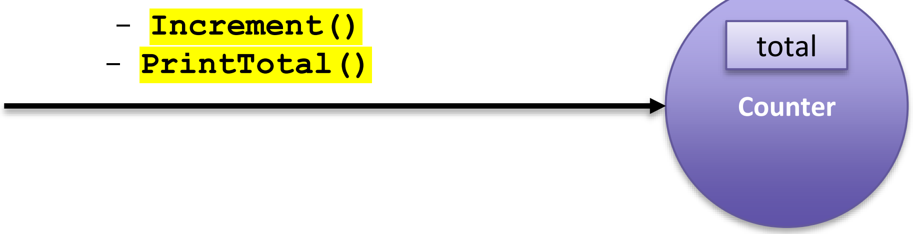

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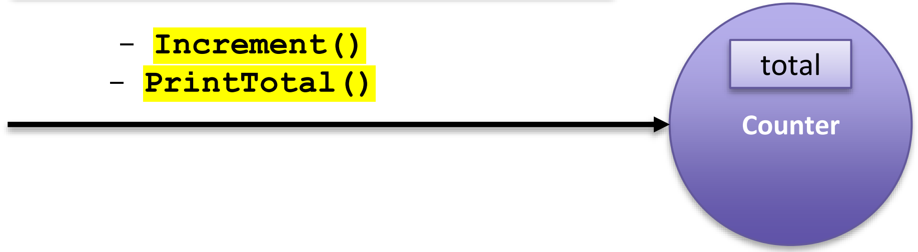
```

It is a good practice to define the type of messages that the actors handles as inner classes



If the actor handles more than one type of message, then define a top level interface that is implemented by each type of message

Message classes must be thread-safe. The recommended Akka practice is to define them as static and final; making them immutable.

Turnstile with Actors - Implementation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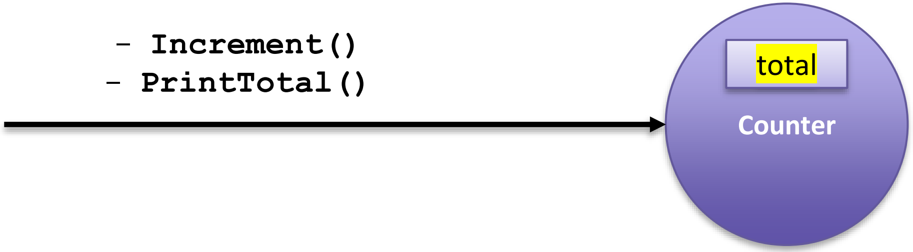
<u>Actors vs Threads</u>

- Like threads, Actors' local state is defined as private fields



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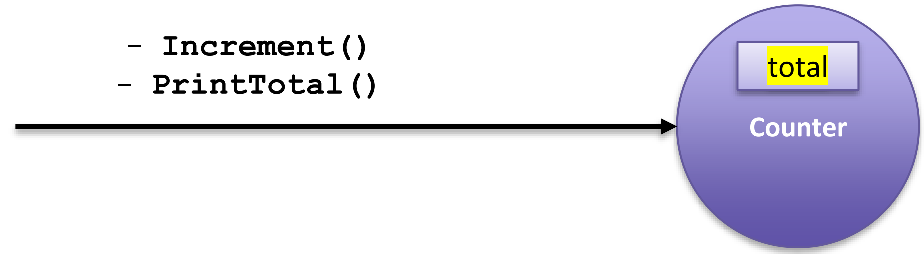

Are there visibility issues in the actor state?

Turnstile with Actors - Implementation

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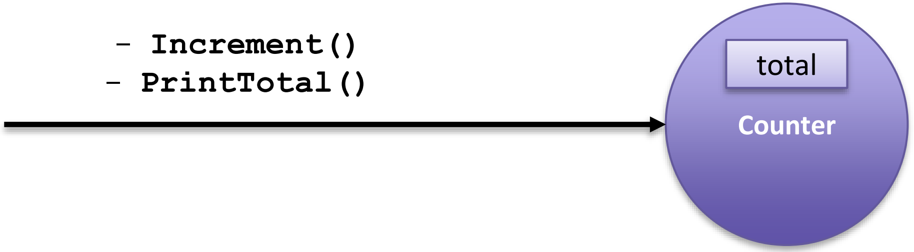

Actors vs Threads

- Actors do not simply require implementing a `run()` method.
- Actors are "reactive", they act upon receiving a message
- This is implemented via message handlers

Turnstile with Actors - Implementation

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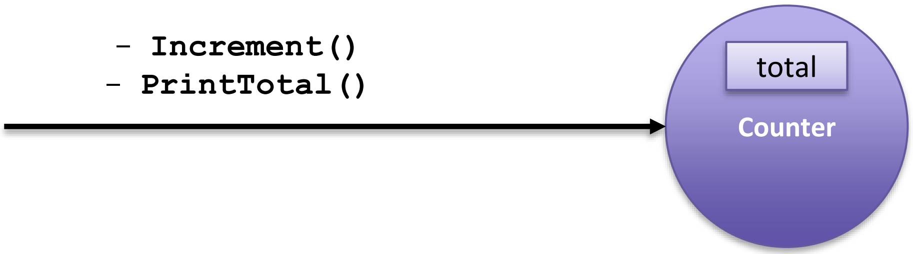
`Counter.java` in `turnstile` package



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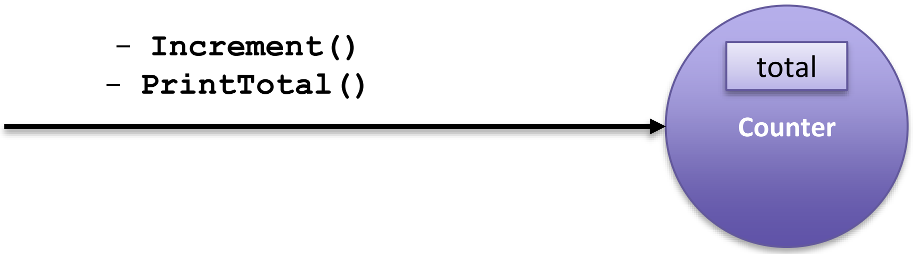


Message handlers return the *behavior* of the actor after processing the message

In this lecture, we only consider actors that do not change behavior, i.e., they simply return this (the current bheavior)

Turnstile with Actors - Implementation

```
public class Turnstile extends AbstractBehavior<Turnstile.TurnstileCommand> {

    /* --- State ---------------------------------------- */
    private final ActorRef<Counter.CounterCommand> countActor;

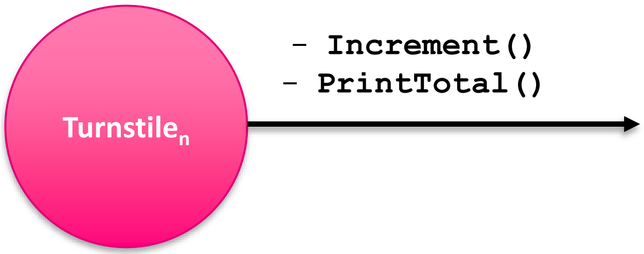
    /* --- Constructor ---------------------------------- */
    private Turnstile(ActorContext<TurnstileCommand> context,
                      ActorRef<Counter.CounterCommand> countActor) {
        super(context);
        this.countActor = countActor;
    }

    /* --- Actor initial behavior ----------------------- */
    public static Behavior<TurnstileCommand> create(ActorRef<Counter.CounterCommand> countActor) {
        return Behaviors.setup(context -> new Turnstile(context, countActor));
    }


    /* --- Message handling ----------------------------- */
    @Override
    public Receive<TurnstileCommand> createReceive() {
        return newReceiveBuilder()
            .onMessage(Start.class, this::onStart)
            .build();
    }

    /* --- Handlers ------------------------------------- */
    private Behavior<TurnstileCommand> onStart(Start msg) {
        // send 20 increments to the counter
        IntStream.range(0,20)
            .forEach( i -> {
                countActor.tell(new Counter.Increment());
            });
        countActor.tell(new Counter.PrintTotal());

        // continue with the same behavior
        return this;
    }
}
```



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    public static Behavior<TurnstileCommand> create(ActorRef<Counter.CounterCommand> countActor) {
        return Behaviors.setup(context -> new Turnstile(context, countActor));
    }


    /* --- Message handling ----------------------------- */
    @Override
    public Receive<TurnstileCommand> createReceive() {
        return newReceiveBuilder()
            .onMessage(Start.class, this::onStart)
            .build();
    }

    /* --- Handlers ------------------------------------- */
    private Behavior<TurnstileCommand> onStart(Start msg) {
        // send 20 increments to the counter
        IntStream.range(0,20)
            .forEach( i -> {
                    countActor.tell(new Counter.Increment());
                });
        countActor.tell(new Counter.PrintTotal());

        // continue with the same behavior
        return this;
    }
}
```

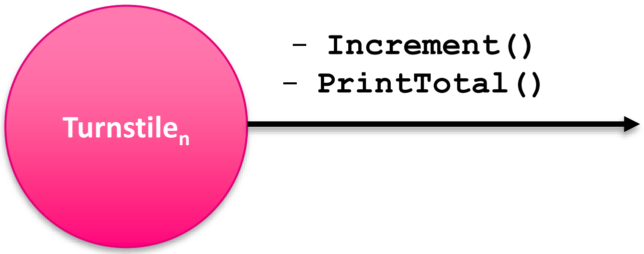

Turnstile with Actors - Implementation

```java
public class Turnstile extends AbstractBehavior<Turnstile.TurnstileCommand> {

    /* --- State ---------------------------------------- */
    private final ActorRef<Counter.CounterCommand> countActor;

    /* --- Constructor ---------------------------------- */
    private Turnstile(ActorContext<TurnstileCommand> context,
                      ActorRef<Counter.CounterCommand> countActor) {
        super(context);
        this.countActor = countActor;
    }

    /* --- Actor initial behavior ---------------------- */
    public static Behavior<TurnstileCommand> create(ActorRef<Counter.CounterCommand> countActor) {
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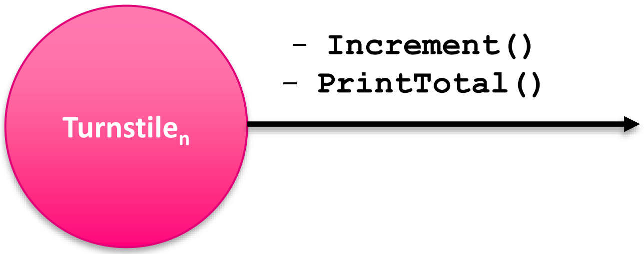

Actors vs Threads

- Like threads, the initial state of the actor is defined via a constructor
- In Akka, the constructor must be defined as `private`; as it is never directly used for actor creation (see next slide)

Turnstile with Actors - Implementation


```
public class Turnstile extends AbstractBehavior<Turnstile.TurnstileCommand> {

    /* --- State ---------------------------------------- */
    private final ActorRef<Counter.CounterCommand> countActor;

    /* --- Constructor ---------------------------------- */
    private Turnstile(ActorContext<TurnstileCommand> context,
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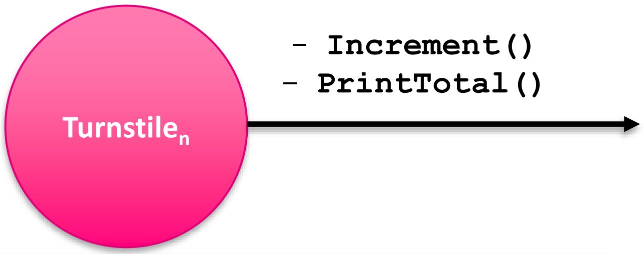

- Actors are created via an *initial behavior*
- The initial behavior is defined as a create method
- The create method uses the private constructor
- Behaviors.setup initializes the actor in an *actor context* (the context contains information about the actor system)

Turnstile with Actors - Implementation


```
public class Turnstile extends AbstractBehavior<Turnstile.TurnstileCommand> {

    /* --- State ---------------------------------------- */
    private final ActorRef<Counter.CounterCommand> countActor;

    /* --- Constructor ---------------------------------- */
    private Turnstile(ActorContext<TurnstileCommand> context,
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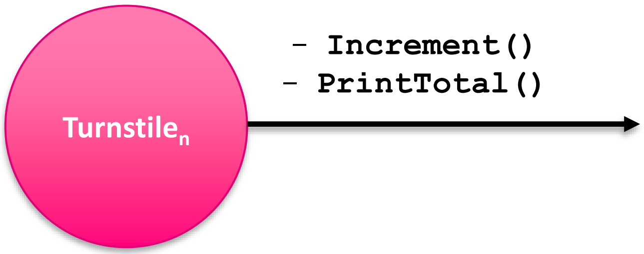

- To send asynchronous messages, we call the `tell(…)` method on a reference to the actor
- The tell method takes as parameter an object of the type of messages that the actor can process

Turnstile with Actors - Implementation

```
public class Turnstile extends AbstractBehavior<Turnstile.TurnstileCommand> {

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    private final ActorRef<Counter.CounterCommand> countActor;

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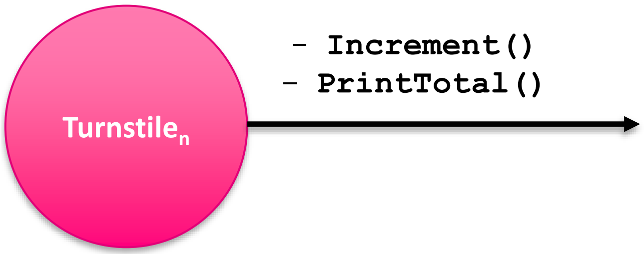
    }
}
```

`Turnstile.java` in `turnstile` package



- To send asynchronous messages, we call the `tell(…)` method on a reference to the actor
- The tell method takes as parameter an object of the type of messages that the actor can process

Akka actor class – Summary

- In summary an Akka actor class should have these elements
  1. Messages
  2. State
  3. Constructor
  4. Initial behaviour
  5. Message handler
  6. Handlers

- You may notice that all files in the code-lecture folder have the structure on the right to make it easier to write actor classes

```
public class Actor extends AbstractBehavior<ActorMessage> {

    /* --- Messages ------------------------------------- */
    …


    /* --- State ---------------------------------------- */
    …


    /* --- Constructor ---------------------------------- */
    private Actor(…) {…}


    /* --- Actor initial behavior ----------------------- */
    public static Behaviour<ActorMessage> create(…) {…}


    /* --- Message handling ----------------------------- */
    @Override
    public Receive<ActorMessage> createReceive() {…}


    /* --- Handlers ------------------------------------- */
    …
}
```

Akka actors

- There is a one-to-one correspondence of the basic actor operations and the Akka API

Actors Model	Akka
Actor	Actor class (AbstractBehavio~~u~~r)
Mailbox Address	Reference to Actor class
Message	Message static final class
State	Actor class local attributes
Behaviour	Handler functions in the Actor class
Create actor	API function
Send message	API function
Receive message	Message handler builder (from API)

Akka actors

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Create actor	API function
Send message	API function
Receive message	Message handler builder (from API)

How do we start Actors?

This is what you would expect

```
public class Main {

      public static void main(String[] args) {
            Actor a1 = new Actor();
            Actor a2 = new Actor();
            a1.start();
            a2.start();

      }
}
```

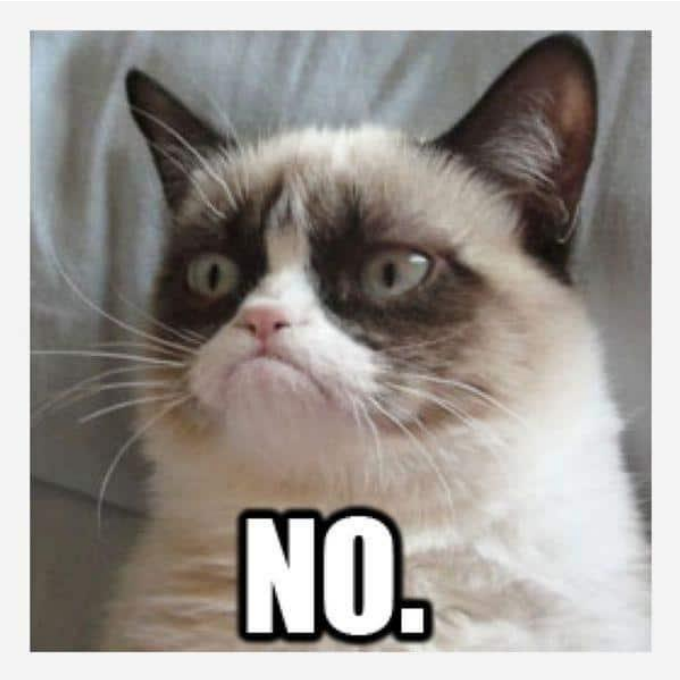
How do we start Actors?

This is what you would expect

```
public c      in {

       public        main(String[] args) {
              Ac       new Actor();
              Act      new Actor();
              a
                    art(

       }
}
```



How do we start Actors?


```
public class MainNG {

      public static void main(String[] args) {
            // start the counter actor
            ActorSystem<Counter.CounterCommand> counter = ActorSystem.create(Counter.create(), "counter_actor");

            …
      }
}
```

This line creates an initial counter actor

How do we start Actors?


```
public class MainNG {

	public static void main(String[] args) {
		// start the counter actor
		ActorSystem<Counter.CounterCommand> counter = ActorSystem.create(Counter.create(), "counter_actor");



		// simulate 5 people entering the park
		IntStream.range(0,5)
			.forEach(i -> {
				counter.tell(new Counter.Increment());
			});
		counter.tell(new Counter.PrintTotal());

		…
	}
}
```

This line creates an initial counter actor

We can send messages to the counter actor

`MainNG.java` in `turnstile` package

How do we start Actors?


```
public class MainNG {

	public static void main(String[] args) {
		// start the counter actor
		ActorSystem<Counter.CounterCommand> counter = ActorSystem.create(Counter.create(), "counter_actor");


		// simulate 5 people entering the park
		IntStream.range(0,5)
			.forEach(i -> {
				counter.tell(new Counter.Increment());
			});
		counter.tell(new Counter.PrintTotal());

		…
	}
}
```

This line creates an initial counter actor

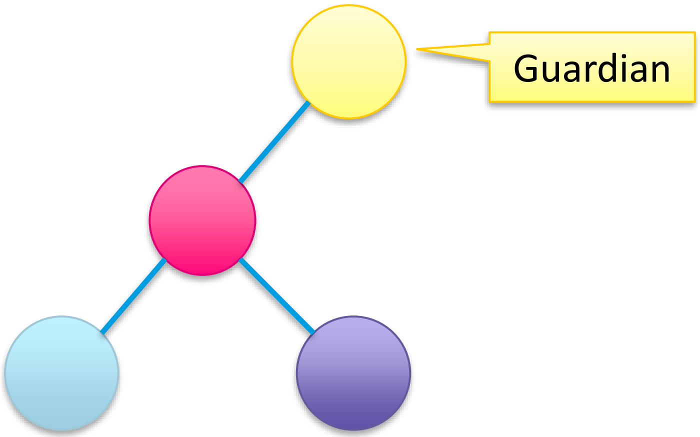
We can send messages to the counter actor

Unfortunately, ActorSystem.create can only be used to create one actor. What about the others?

`MainNG.java` in `turnstile` package

Akka actors – Guardian

- Akka actor systems have an implicit hierarchical structure



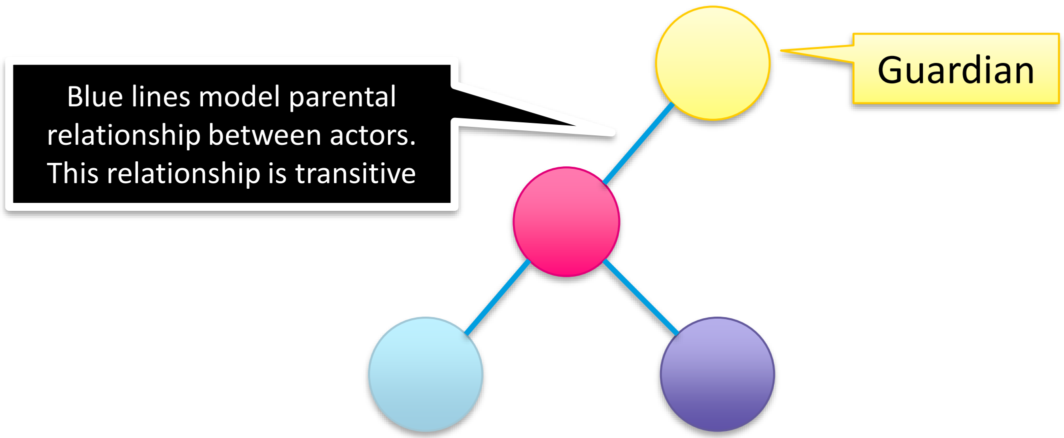
- The first actor to be created in the system is a top-level actor known as *guardian*, this actor is created with ActorSystem.create

```
ActorSystem<Counter.CounterCommand> counter = ActorSystem.create(Counter.create(), "counter_actor")
```

In our example, we use counter as the guardian, but this is not idiomatic

Akka actors – Guardian

- Akka actor systems have an implicit hierarchical structure



- The first actor to be created in the system is a top-level actor known as *guardian*, this actor is created with ActorSystem.create

```
ActorSystem<Counter.CounterCommand> counter = ActorSystem.create(Counter.create(), "counter_actor")
```

In our example, we use counter as the guardian, but this is not idiomatic

Akka actors – Guardian

- Typically the Guardian creates the initial actors in the system

```
public class Guardian extends AbstractBehavior<Guardian.KickOff> {
    public static final class KickOff { }

    private Guardian(ActorContext<KickOff> context) {
        super(context);
    }

    public static Behavior<Guardian.KickOff> create() {
        return Behaviors.setup(Guardian::new);
    }

    @Override
    public Receive<KickOff> createReceive() {
        return newReceiveBuilder()
            .onMessage(KickOff.class, this::onKickOff)
            .build();
    }

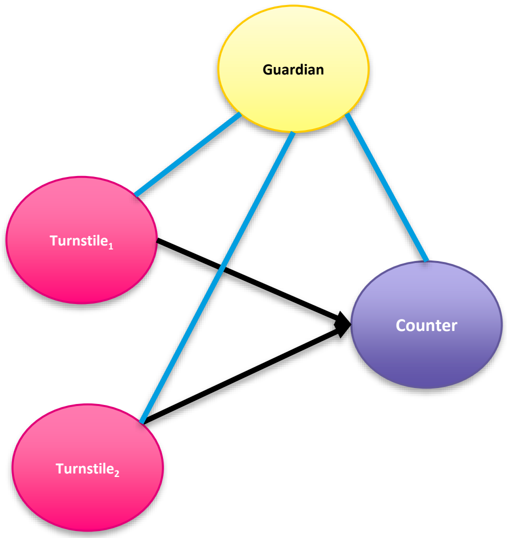
    private Behavior<KickOff> onKickOff(KickOff msg) {
        // spawn the counter actor
        ActorRef<Counter.CounterCommand> counter =
            getContext().spawn(Counter.create(), "counter_actor");

        // spawn two turnstile actors
        ActorRef<Turnstile.TurnstileCommand> t1 =
            getContext().spawn(Turnstile.create(counter), "t1");
        t1.tell(new Turnstile.Start());

        ActorRef<Turnstile.TurnstileCommand> t2 =
            getContext().spawn(Turnstile.create(counter), "t2");
        t2.tell(new Turnstile.Start());

        // The behaviour stays the same
        return this;
    }
}
```

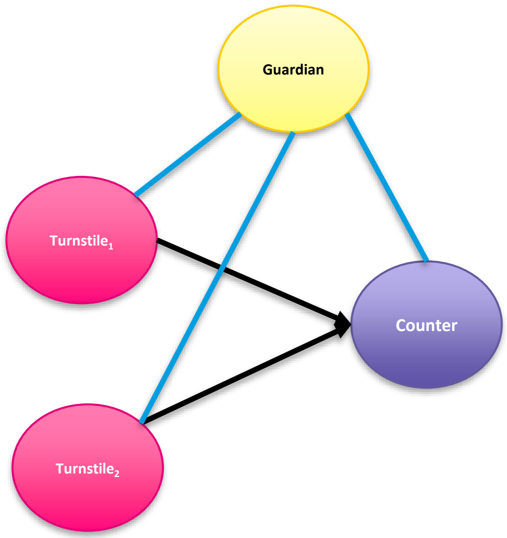
- The Guardian is an actor like any other
- It typically receives a kick-off messages that indicates to start the system



Akka actors – Guardian

- Typically the Guardian creates the initial actors in the system

```java
public class Guardian extends AbstractBehavior<Guardian.KickOff> {
    public static final class KickOff { }

    private Guardian(ActorContext<KickOff> context) {
        super(context);
    }

    public static Behavior<Guardian.KickOff> create() {
        return Behaviors.setup(Guardian::new);
    }

    @Override
    public Receive<KickOff> createReceive() {
        return newReceiveBuilder()
            .onMessage(KickOff.class, this::onKickOff)
            .build();
    }

    private Behavior<KickOff> onKickOff(KickOff msg) {
        // spawn the counter actor
        ActorRef<Counter.CounterCommand> counter =
            getContext().spawn(Counter.create(), "counter_actor");

        // spawn two turnstile actors
        ActorRef<Turnstile.TurnstileCommand> t1 =
            getContext().spawn(Turnstile.create(counter), "t1");
        t1.tell(new Turnstile.Start());

        ActorRef<Turnstile.TurnstileCommand> t2 =
            getContext().spawn(Turnstile.create(counter), "t2");
        t2.tell(new Turnstile.Start());

        // The behaviour stays the same
        return this;
    }
}
```



- Children actors are created with `spawn()`
- The code on the right creates the counter actor and two turnstile actors

Akka Main + Guardian


```java
public class Main {

    public static void main(String[] args) {
        // actor system
        final ActorSystem<Guardian.KickOff> guardian =
            ActorSystem.create(Guardian.create(), "counter_akka");

        // trigger message
        guardian.tell(new Guardian.KickOff());

        // wait until user presses enter
        try {
            System.out.println(">>> Press ENTER to exit <<<");
            System.in.read();
        }
        catch (IOException e) {
            System.out.println("Error " + e.getMessage());
            e.printStackTrace();
        } finally {
            guardian.terminate();
        }
    }
}
```

`Main.java` in `turnstile` package

- This is a template that you can use to start any actor system in Akka.
- Simply replace the content of the `onKickOff()` method on the right to spawn the desired actors

```java
public class Guardian extends AbstractBehavior<Guardian.KickOff> {
    public static final class KickOff { }

    private Guardian(ActorContext<KickOff> context) {
        super(context);
    }

    public static Behavior<Guardian.KickOff> create() {
        return Behaviors.setup(Guardian::new);
    }

    @Override
    public Receive<KickOff> createReceive() {
        return newReceiveBuilder()
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    }

    private Behavior<KickOff> onKickOff(KickOff msg) {
        // spawn the counter actor
        ActorRef<Counter.CounterCommand> counter =
            getContext().spawn(Counter.create(), "counter_actor");

        // spawn two turnstile actors
        ActorRef<Turnstile.TurnstileCommand> t1 =
            getContext().spawn(Turnstile.create(counter), "t1");
        t1.tell(new Turnstile.Start());

        ActorRef<Turnstile.TurnstileCommand> t2 =
            getContext().spawn(Turnstile.create(counter), "t2");
        t2.tell(new Turnstile.Start());

        // The behaviour stays the same
        return this;
    }
}
```

`Guardian.java` in `turnstile` package

Akka actors

- There is a one-to-one correspondence of the basic actor operations and the Akka API

Actors Model	Akka
Actor	Actor class (AbstractBehavio~~u~~r)
Mailbox Address	Reference to Actor class
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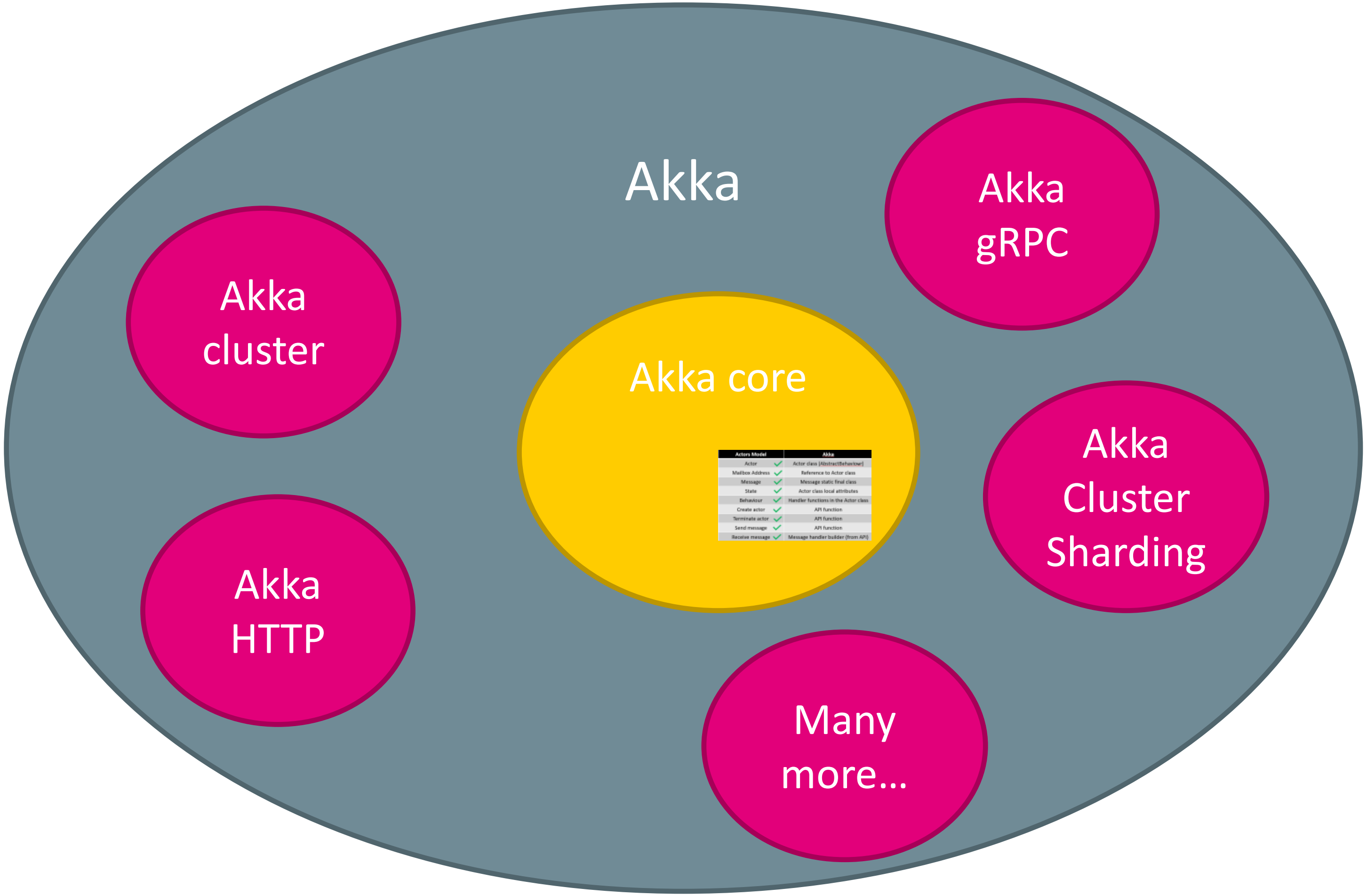
Send message	API function
Receive message	Message handler builder (from API)

We only use a tiny bit of Akka

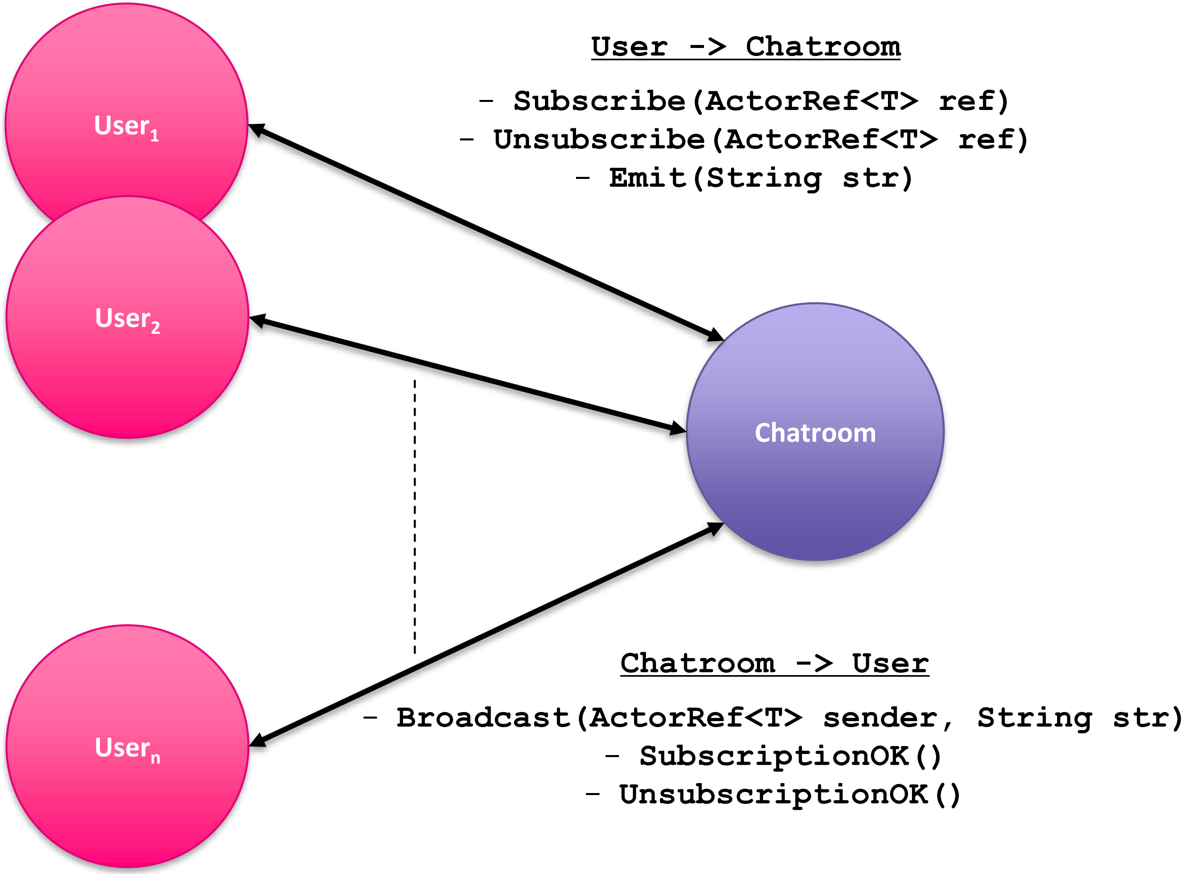


Actors Model		Akka
Actor	✓	Actor class (AbstractBehavior)
Mailbox Address	✓	Reference to Actor class
Message	✓	Message static final class
State	✓	Actor class local attributes
Behaviour	✓	Handler functions in the Actor class
Create actor	✓	API function
Terminate actor	✓	API function
Send message	✓	API function
Receive message	✓	Message handler builder (from API)

A broadcast chatroom

Broadcaster

- A set of user actors may subscribe to a chatroom actor
    - The chatroom must confirm the subscription
- Users may emit messages that the chatroom broadcasts to all subscribers (except for the sender)
- Users may unsubscribe
    - The chatroom must confirm the un-subcription.



Broadcaster

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  - The chatroom must confirm the subscription
- Users may emit messages that the chatroom broadcasts to all subscribers (except for the sender)
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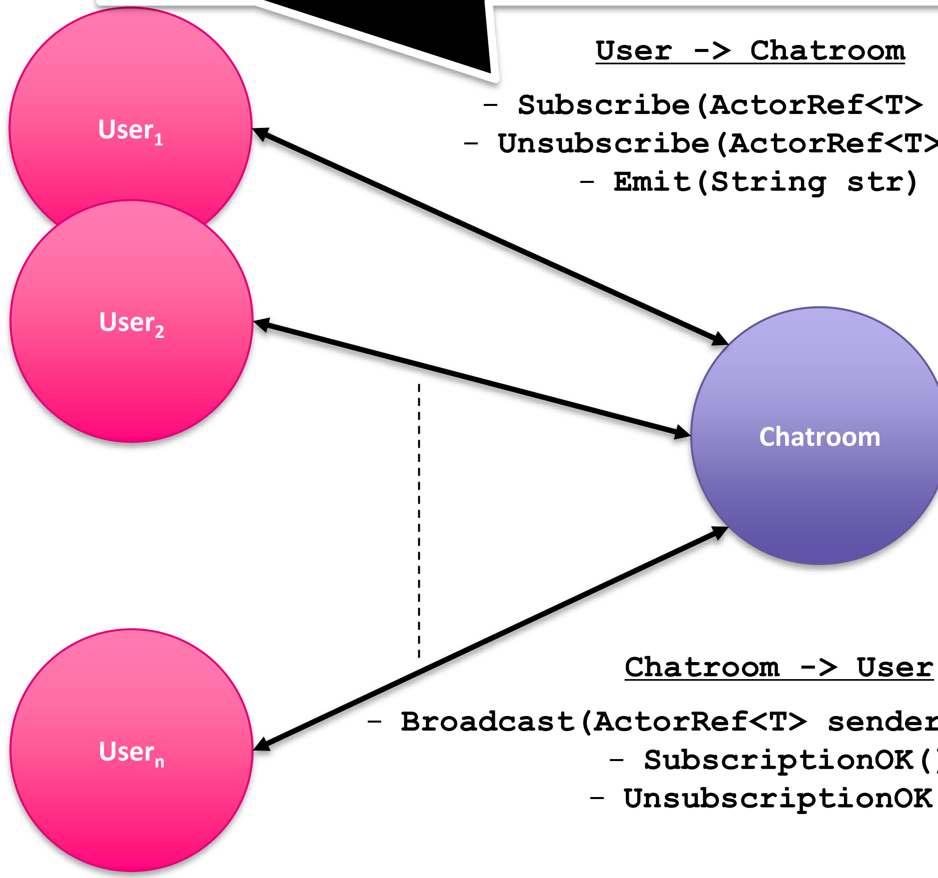
  - The chatroom must confirm the un-subcription.

Important detail, messages do not contain information about the sender. If, for instance, the sender needs a reply, the message must contain a reference to the sender



User -> Chatroom

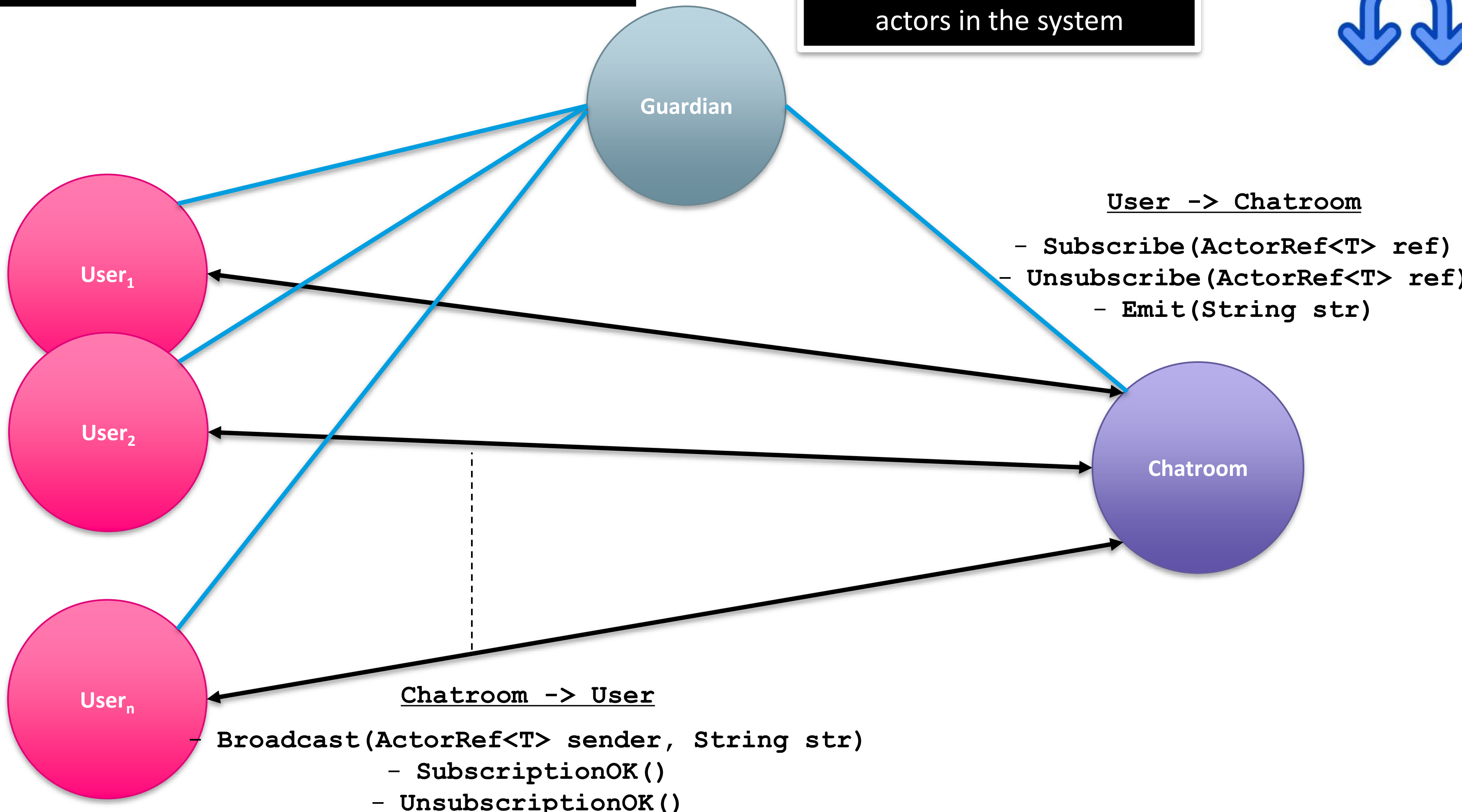
- `Subscribe(ActorRef<T> ref)`
- `Unsubscribe(ActorRef<T> ref)`
- `Emit(String str)`

Chatroom -> User

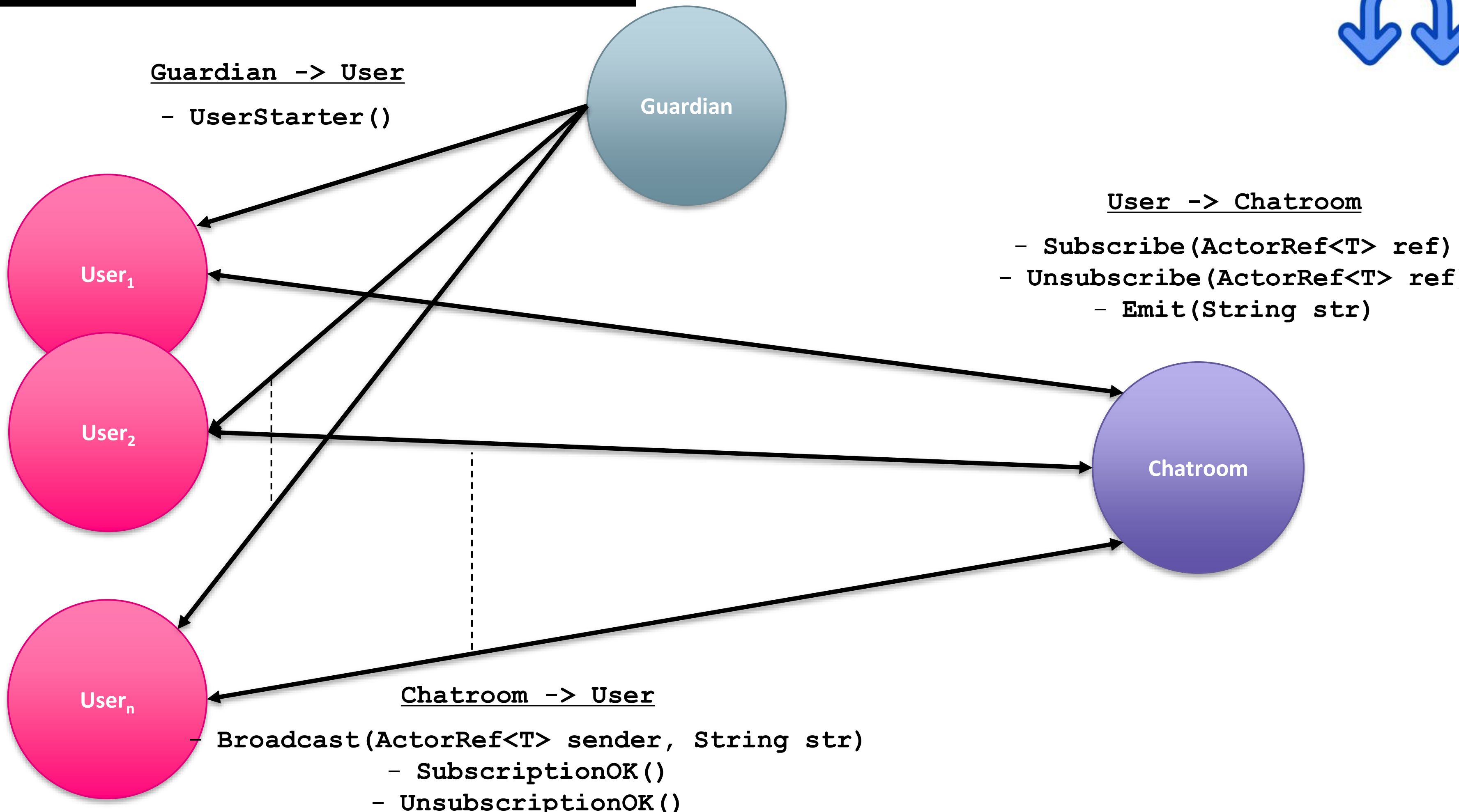
- `Broadcast(ActorRef<T> sender, String str)`
- `SubscriptionOK()`
- `UnsubscriptionOK()`

Broadcaster + Guardian

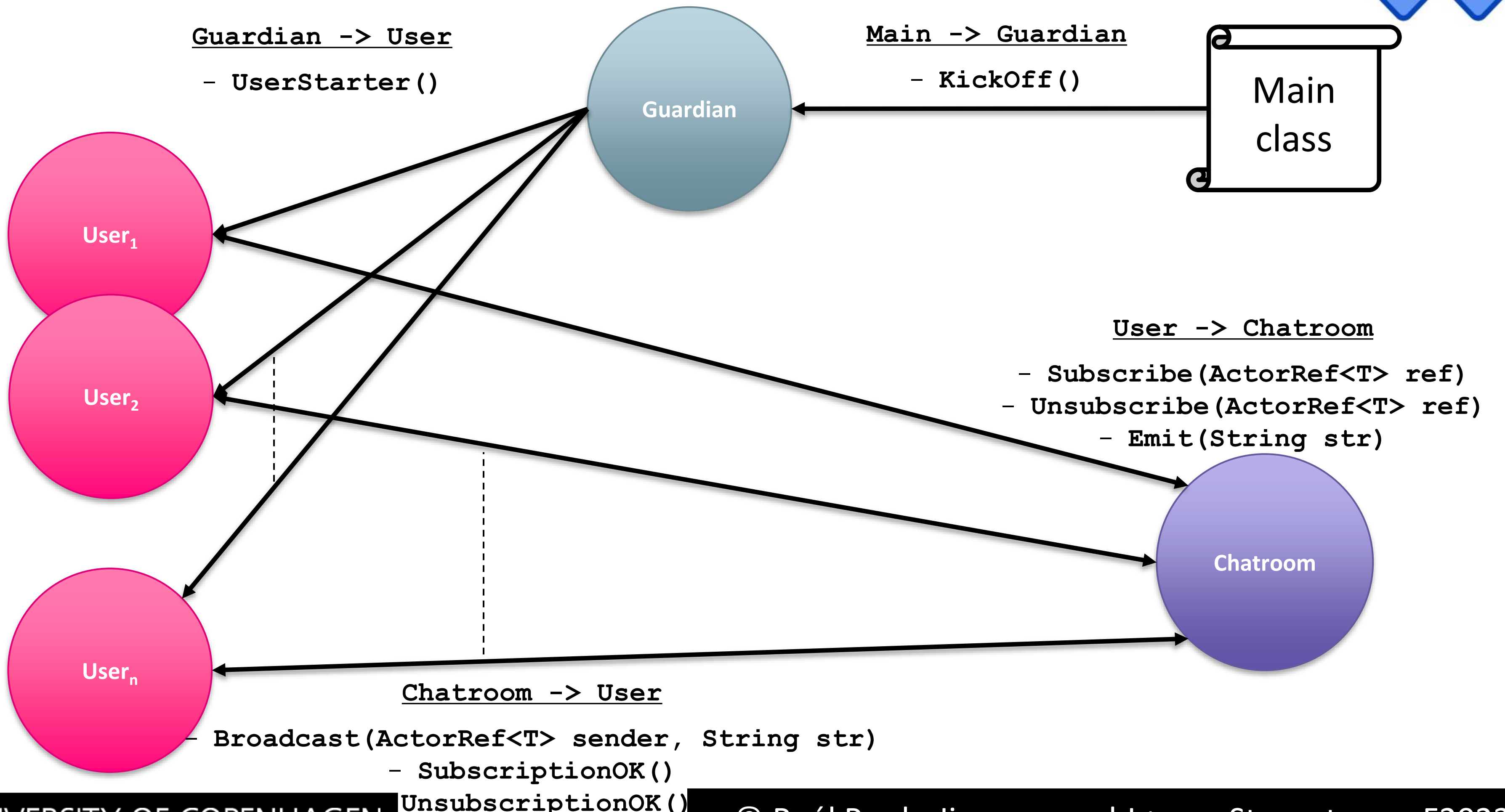
The guardian spawns all the actors in the system



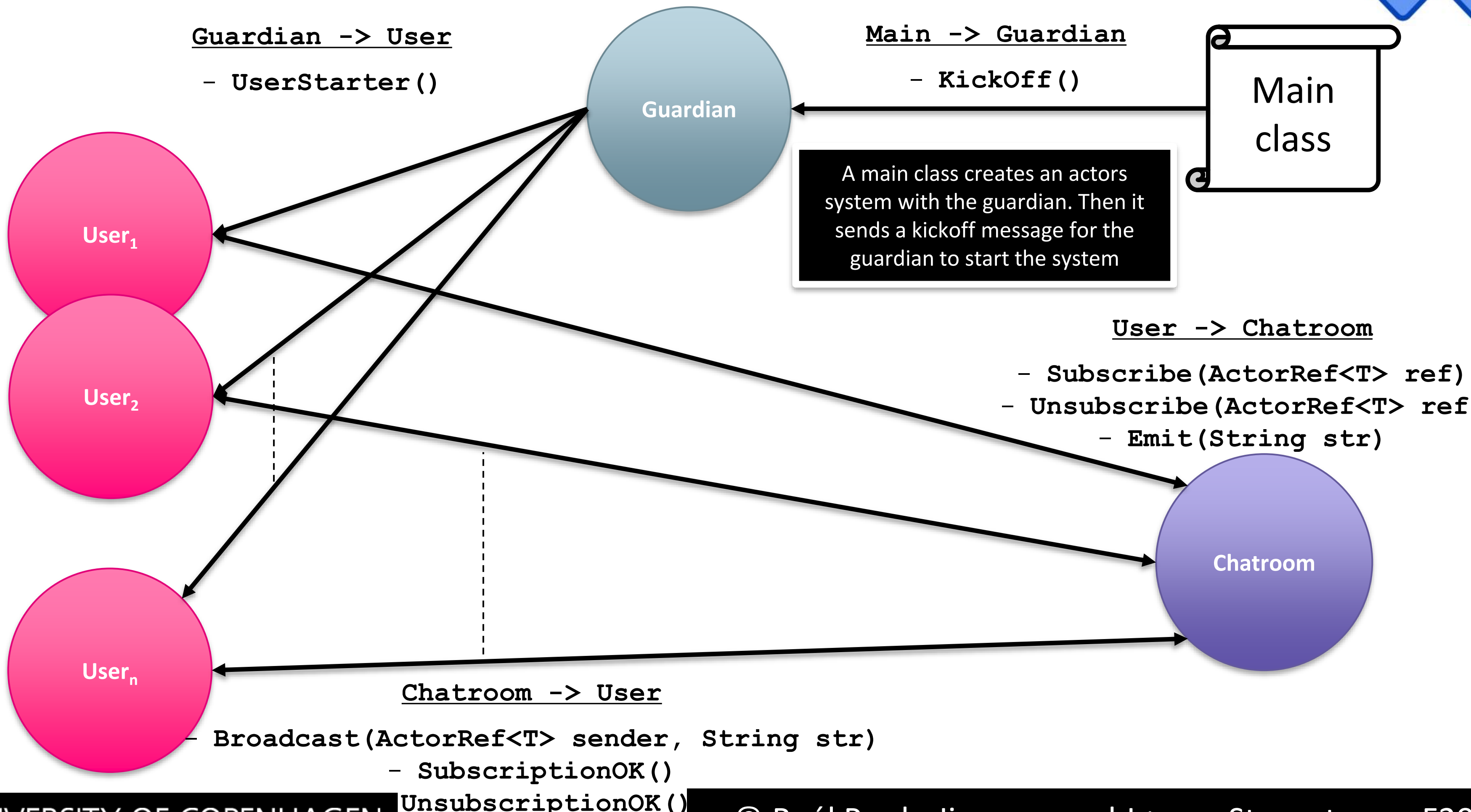
Broadcaster + Guardian



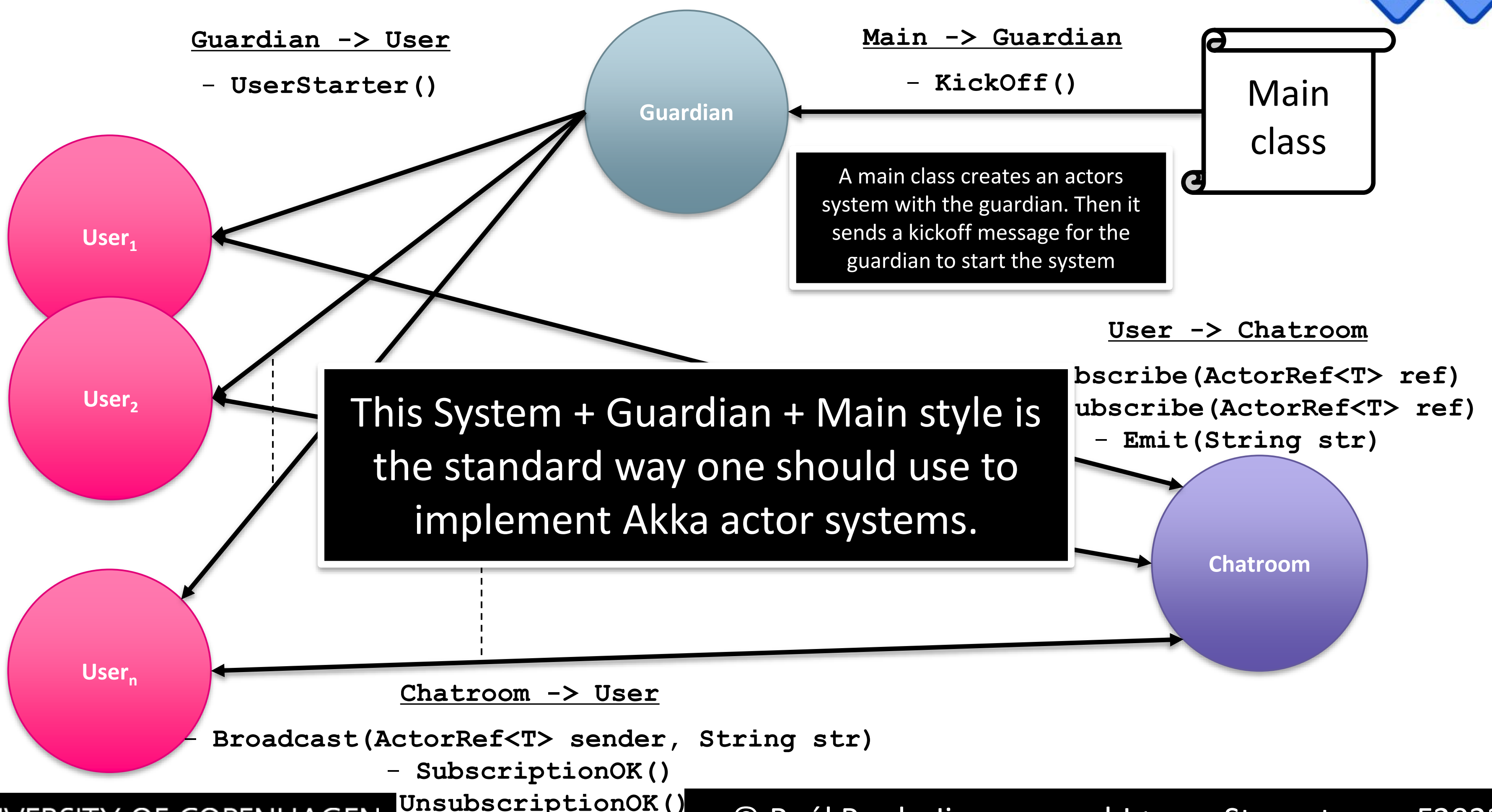
Broadcaster + Guardian + Main



Broadcaster + Guardian + Main

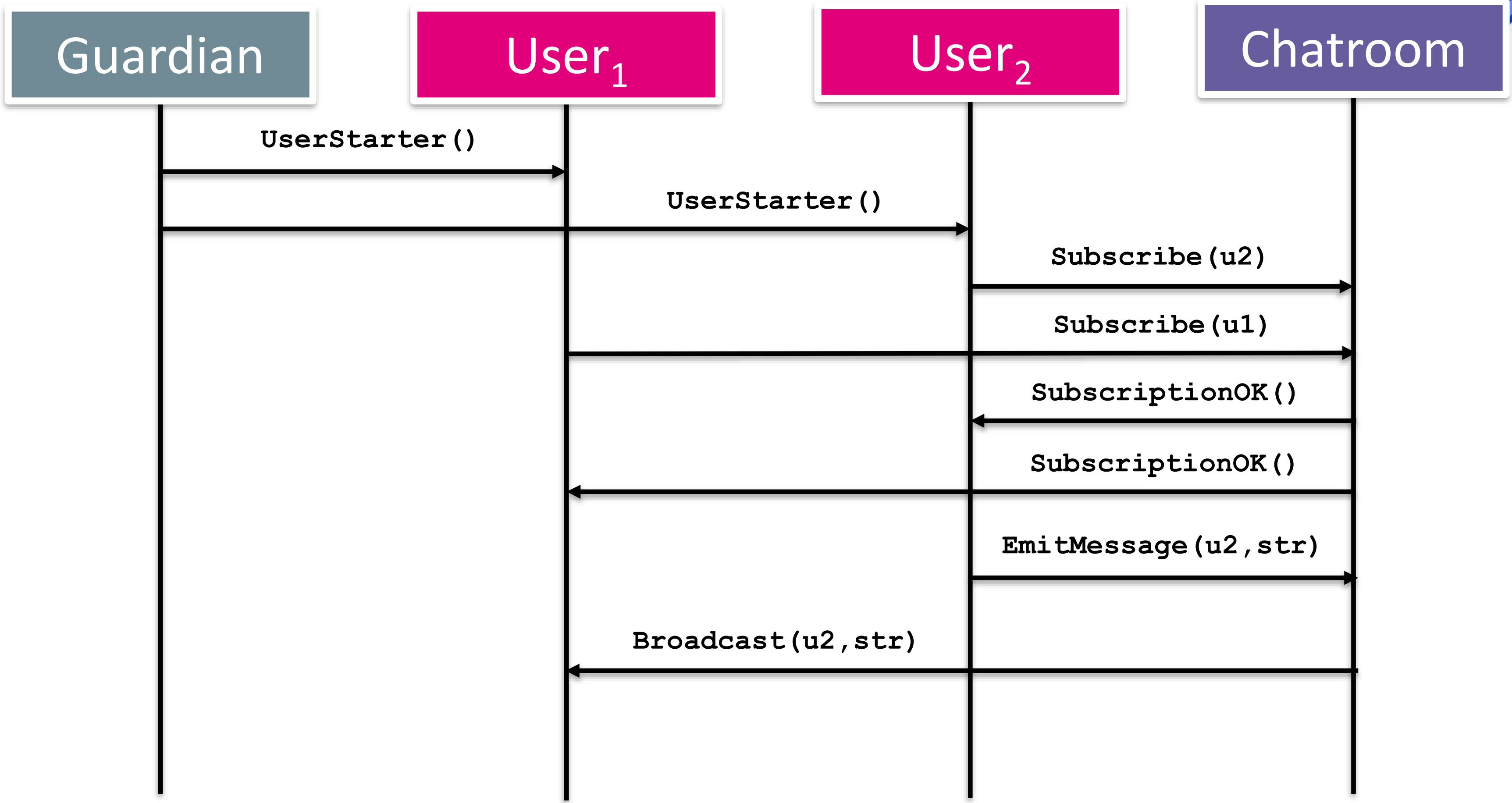


Broadcaster + Guardian + Main

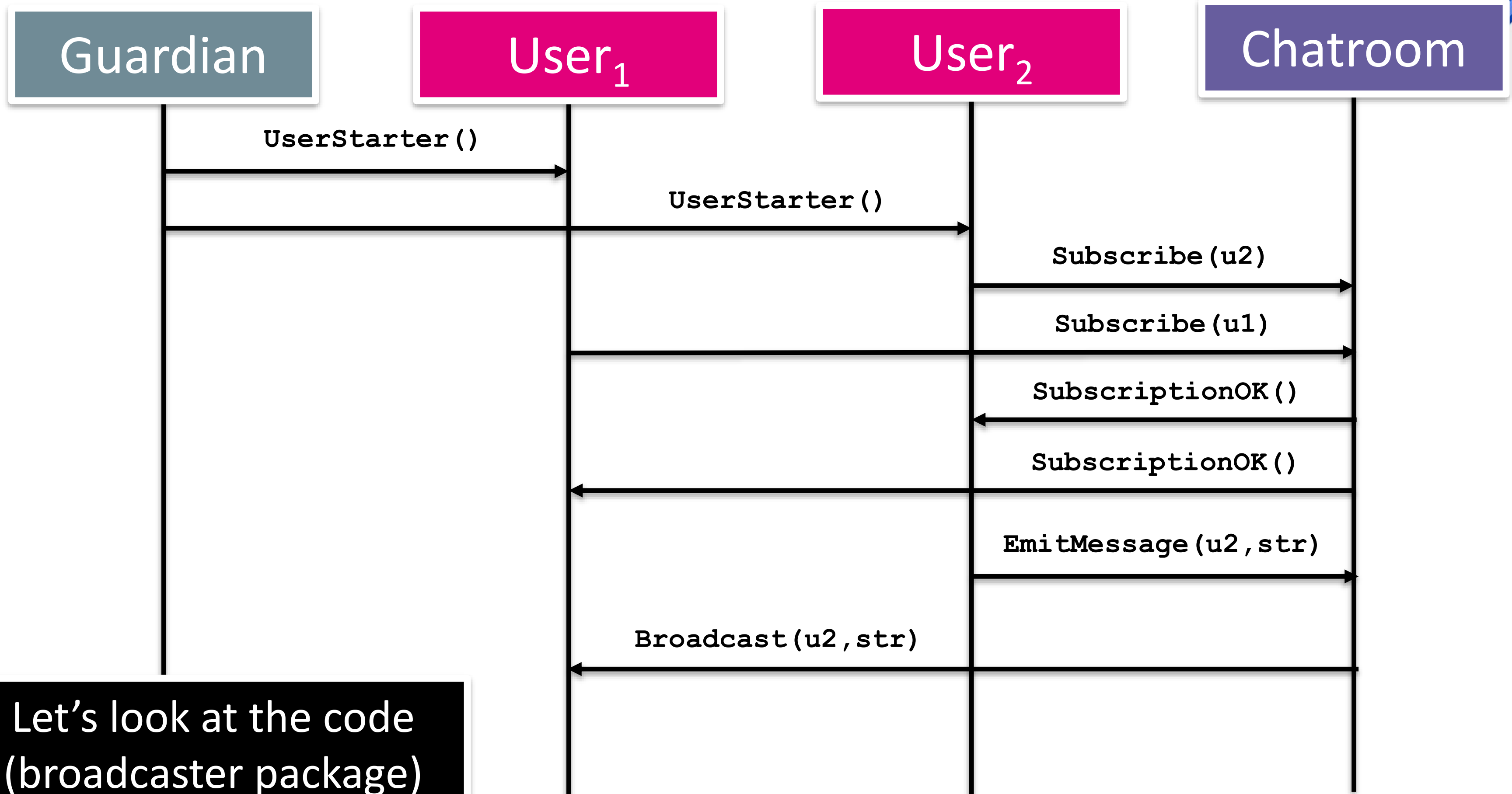


This System + Guardian + Main style is the standard way one should use to implement Akka actor systems.

Brodcaster – execution example



Brodcaster – execution example



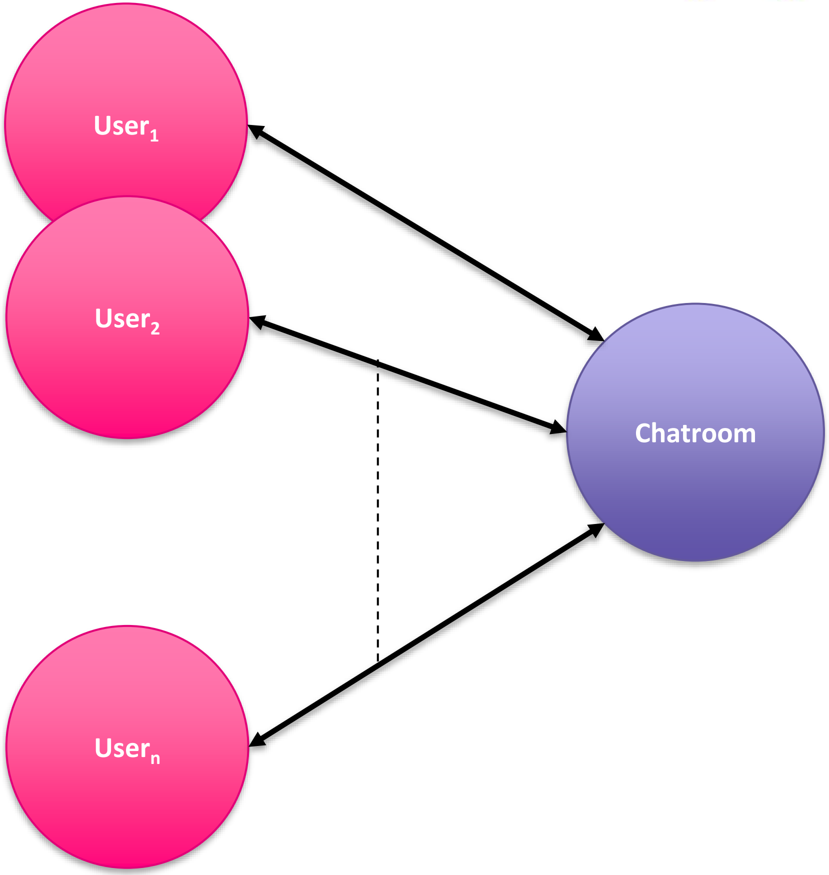
Let's look at the code
(broadcaster package)

Broadcaster interesting executions

Assuming FIFO mailboxes (Akka's default)

- Consider this execution

1. User1 sends Subscription to Chatroom
2. User2 sends Subscription to Chatroom
3. …



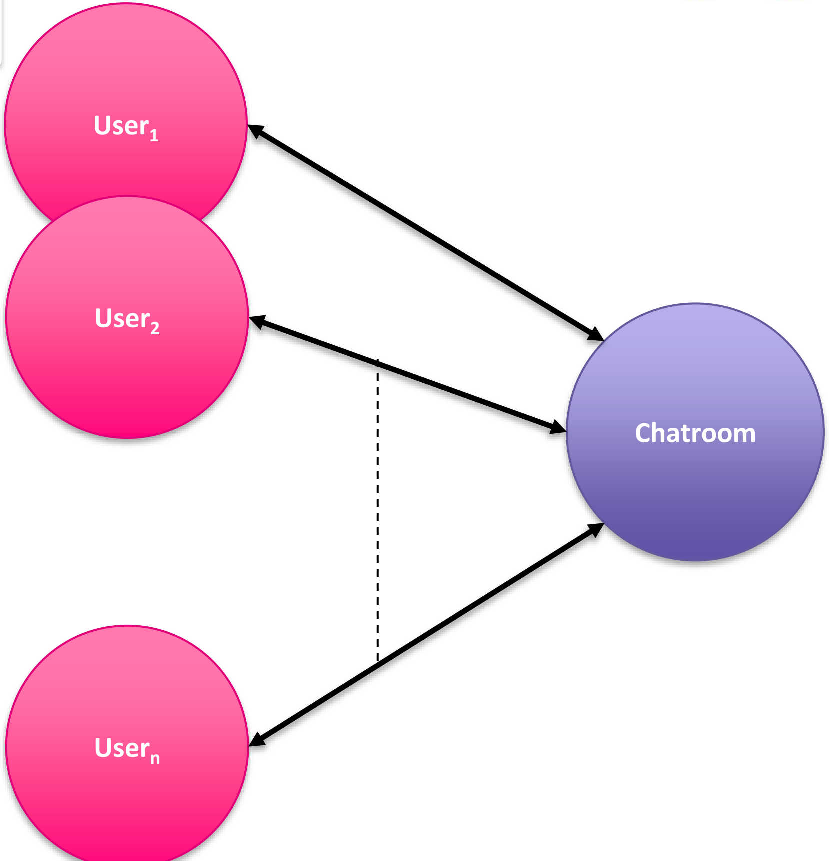
What actor will receive first SubscriptionOK?

Broadcaster interesting executions

Assuming FIFO mailboxes (Akka's default)

- Consider this execution

1. User1 sends Subscription to Chatroom
2. Chatroom replies SubscriptionOK to User1
3. User1 emits message to Chatroom
4. User2 sends Subscription to observable
5. …



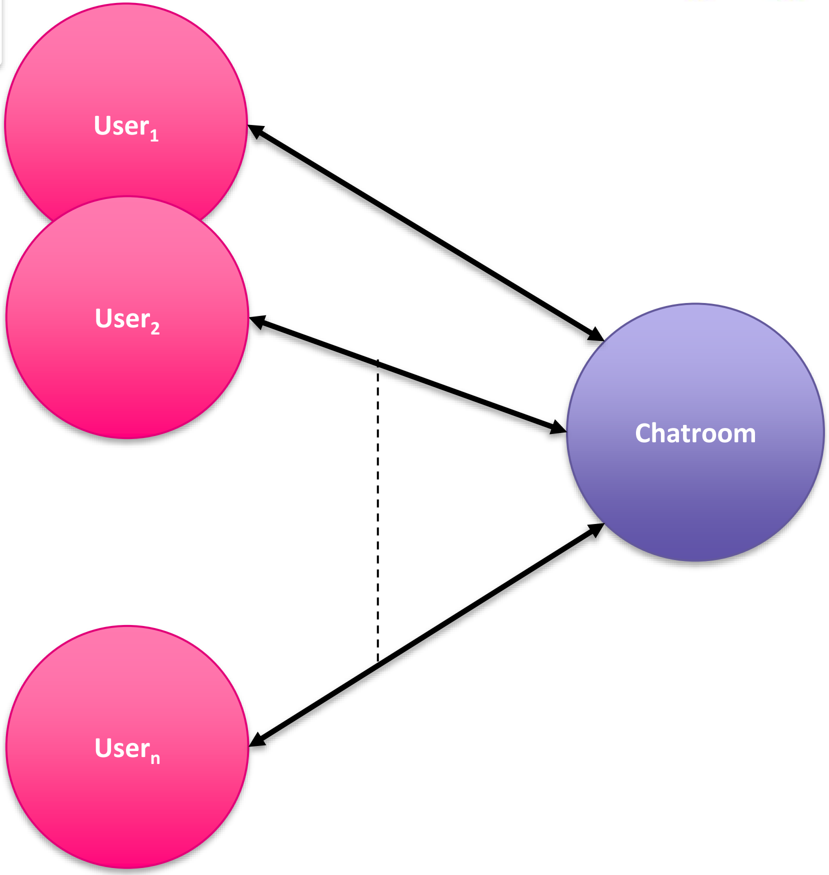
Can User2 receive the message sent by User1 in step 3?

Broadcaster interesting executions

Assuming FIFO mailboxes (Akka's default)

- Consider this execution

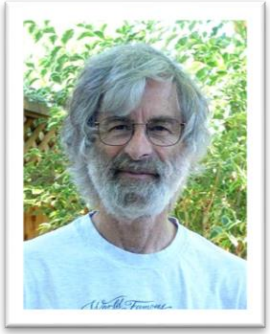
1. User1 send Subscription to Chatroom
2. Chatroom replies SubscriptionOK to User1
3. User1 emits message to Chatroom
4. User2 sends Subscription to Chatroom
5. Chatroom replies SubscriptionOK to User2
6. …



Can User2 receive the message sent by User1 in step 3?

Happened-before in distributed systems

- Note that in the previous questions the behaviour of the systems depends on the reception of messages



- Thus, the happened-before relation defined by Lamport is useful in reasoning about actor systems
  - An action *a* happens-before an action *b* if they belong to the same actor and *a* was executed before *b*
  - A send(m) action happens-before its corresponding receive(m)

- Note the similarity with the happens-before relation of the Java memory model
  - We reason about message exchange instead of locking (but *inherent coordination problems remain*)
  - Visibility issues disappear as actors only access local memory

A bounded buffer

Producer-consumer problem | Intuition

- Perhaps more intuitive example

Consumers

Producers

Shared data structure of fixed size

Producer-consumer problem | Intuition

Producers

Consumers

Shared data structure of fixed size

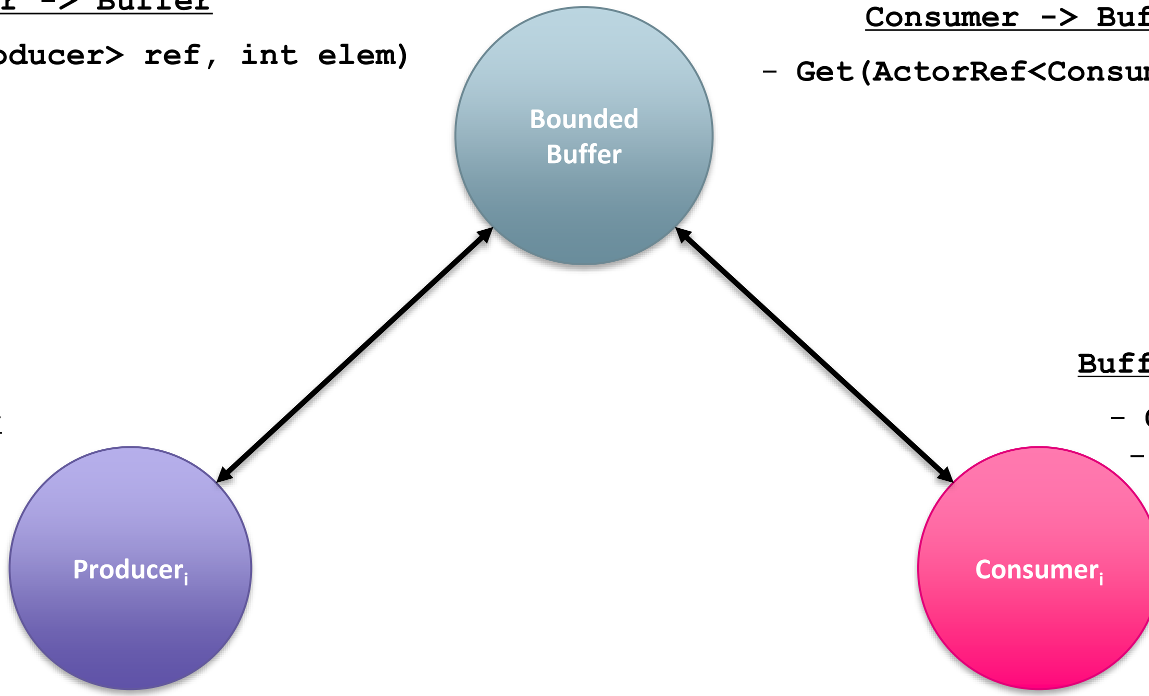
Bounded Buffer with Actors

Producer -> Buffer

- Put(ActorRef<Producer> ref, int elem)

Consumer -> Buffer

- Get(ActorRef<Consumer> ref)



Buffer -> Producer

- ElementAdded
- BufferFull

Buffer -> Consumer

- Get(int elem)
- BufferEmpty

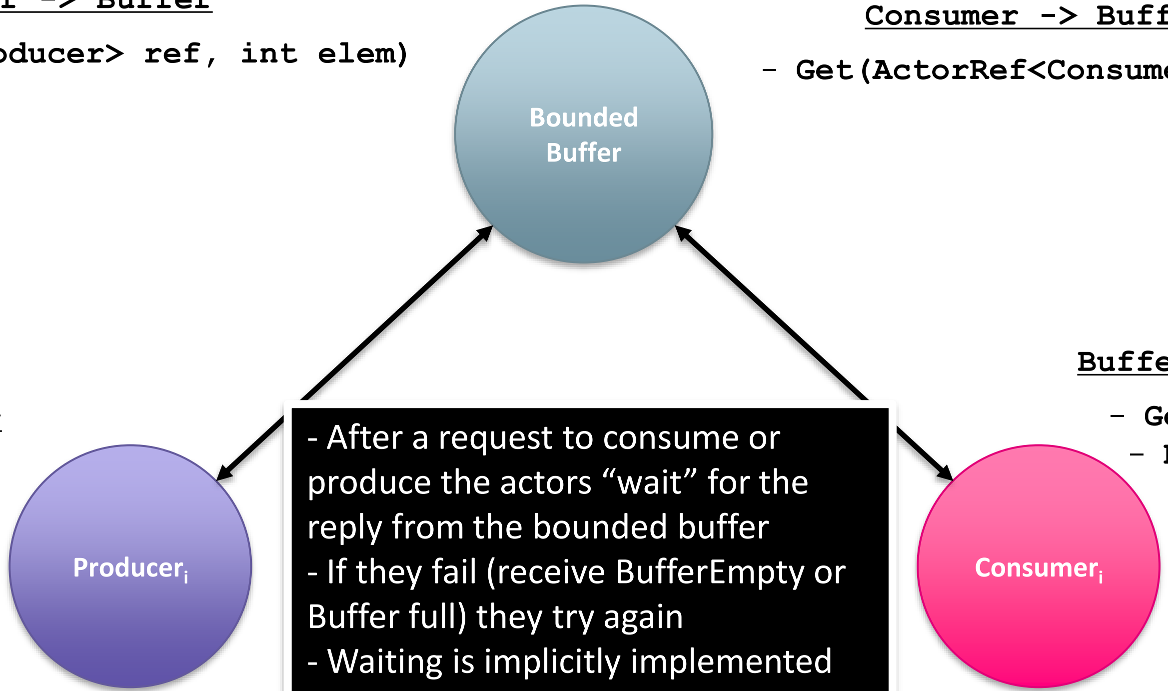
Bounded Buffer with Actors

Producer -> Buffer

`- Put(ActorRef<Producer> ref, int elem)`

Consumer -> Buffer

`- Get(ActorRef<Consumer> ref)`



Buffer -> Consumer

`- Get(int elem)`
`- BufferEmpty`

Buffer -> Producer

`- ElementAdded`
`- BufferFull`

- After a request to consume or produce the actors "wait" for the reply from the bounded buffer
- If they fail (receive BufferEmpty or Buffer full) they try again
- Waiting is implicitly implemented as producers and consumers wait for the answer of the bounded buffer, and the buffer replies with error only when the actors can make progress

Let's look at the code (boundedbuffer package)

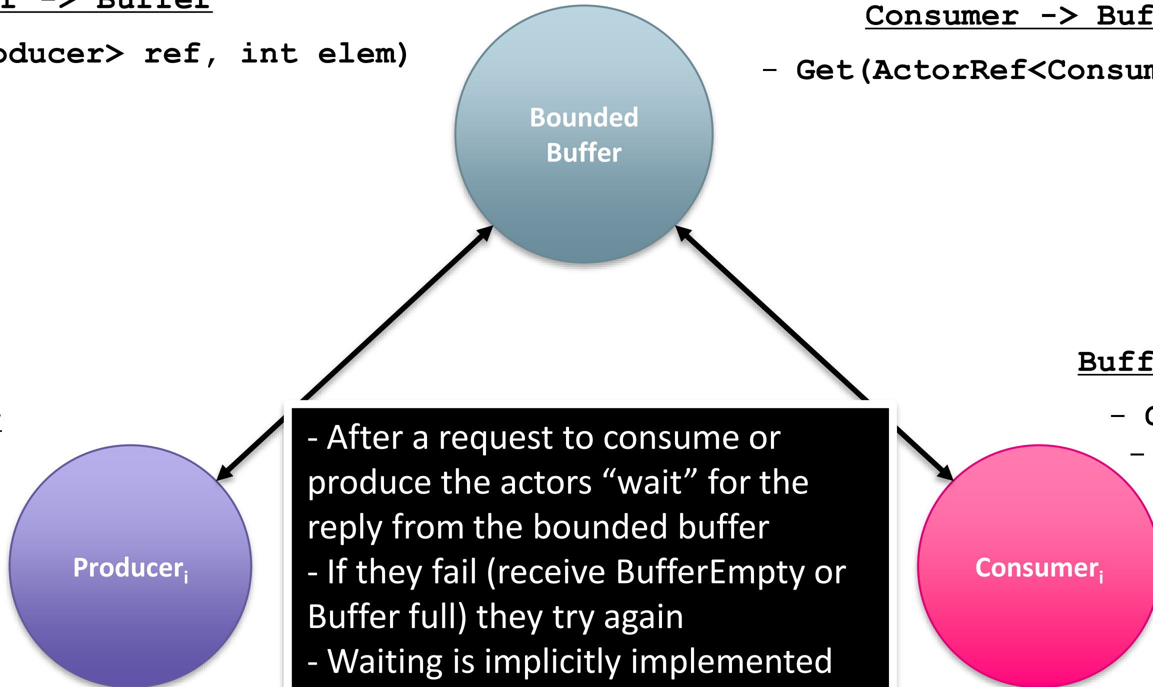
Bounded Buffer with Actors

Producer -> Buffer

```
- Put(ActorRef<Producer> ref, int elem)
```

Consumer -> Buffer

```
- Get(ActorRef<Consumer> ref)
```



Buffer -> Producer

```
- ElementAdded
- BufferFull
```

Buffer -> Consumer

```
- Get(int elem)
- BufferEmpty
```

- After a request to consume or produce the actors “wait” for the reply from the bounded buffer
- If they fail (receive BufferEmpty or Buffer full) they try again
- Waiting is implicitly implemented as producers and consumers wait for the answer of the bounded buffer, and the buffer replies with error only when the actors can make progress

Let’s look at the code (boundedbuffer package)

Is this a good solution to the problem?

Actors in distributed systems

The actors model has natural mapping in distributed systems

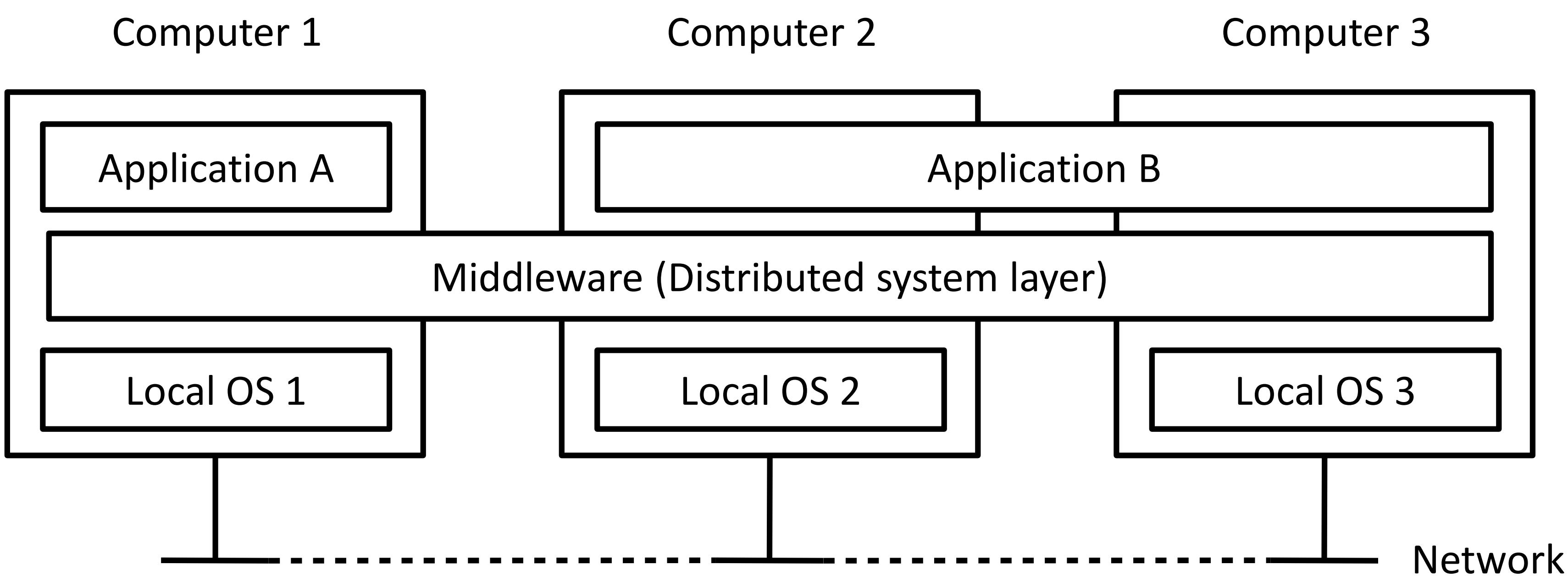
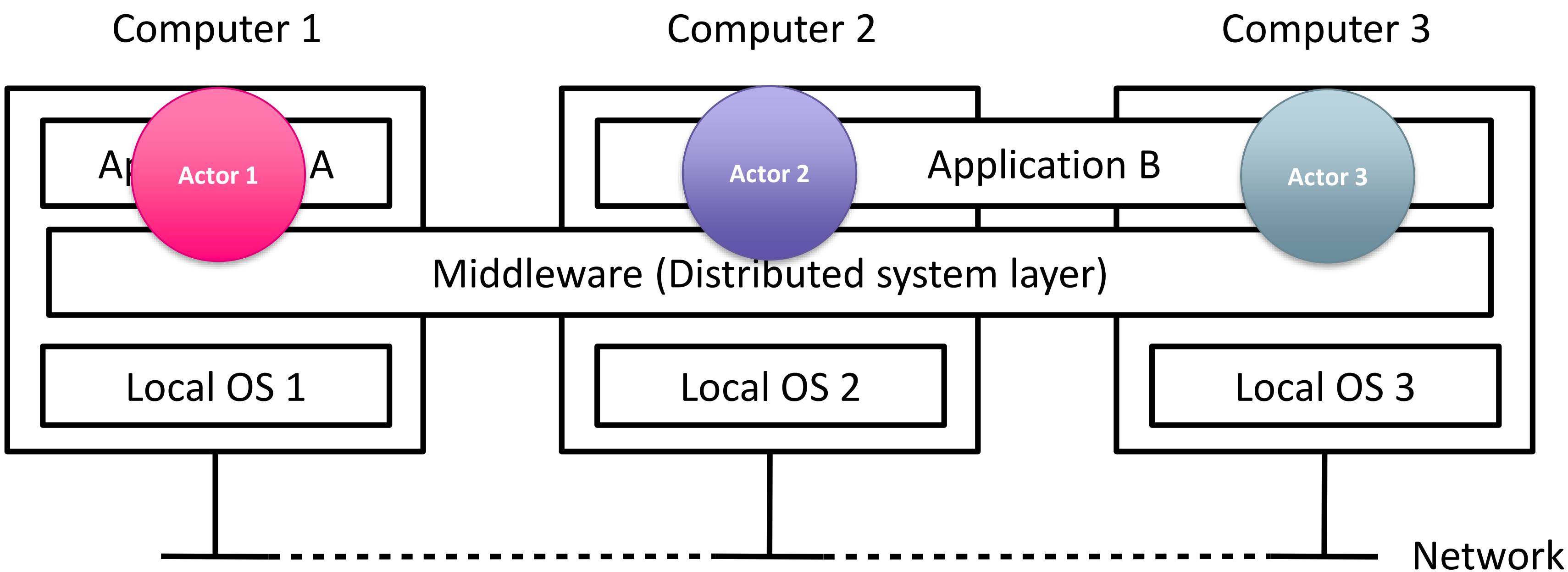


Figure taken from -> Distributed Systems: Principles and Paradigms. Andrew S. Tanenbaum and Maarten Van Steen. 2007.

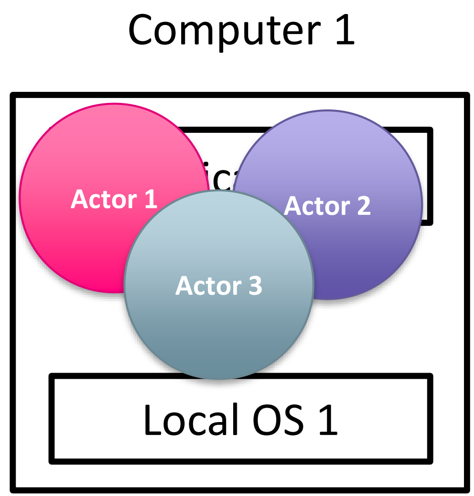
Actors in distributed systems

The actors model has natural mapping in distributed systems



Actors in a single computer

The actors model is applicable in a single computer as well



In this lecture, we focus on this type of actor system

Agenda

- Problems in shared memory concurrency (revisited)
- Actors
- Akka
- Example systems
  - Turnstile (counter)
  - Broadcaster
  - Bounded Buffer