ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Scala *for* MULTICORE

PART 1: *Foundations and Message-Passing Concurrency*

Philipp HALLER, STANFORD UNIVERSITY AND EPFL

Scala *for* Multicore

Resources online at:
http://lamp.epfl.ch/~phaller/upmarc

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Scala runs on the Java Virtual Machine and is completely interoperable with Java

- Compiler preview for Microsoft .NET

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It's a promising language.

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Why are people adopting Scala?

LinkedIn

foursquare

xerox

theguardian

SIEMENS

twitter

Office DEPOT

Novell

SONY PICTURES

naturenews

ebay

Replaced their Ruby-based back-end services with Scala.

Using actors, they could scale their concurrent message queue system to a **larger** number of users.

guardian.co.uk:

"[...] used Scala to meet the demanding real-time content searching, indexing or updating. **Using actors** for example, he explains how they were able to **reduce the search index build time from 20 hours to just one**. Request patterns, he says, are hard to predict so **THE ABILITY TO EASILY SCALE THE SERVICES WAS ESSENTIAL.**

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[guardian.co.uk has the second highest readership of any on-line news site after the New York Times *]

* ACCORDING TO ITS EDITOR

Scala and Parallelism.

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FUNCTIONAL PROGRAMMING is the only productive way to work with **immutable data structures**

Resou ~phaller/upmarc

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Domain-Specific Languages

Scala's flexible syntax makes it easy to define embedded DSLs

EXAMPLES:
Erlang-style actors,
X10-style async/finish

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- Embedding enables **interoperability**

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These things are a step in the right direction towards Popular Parallel Programming.

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OUR GOAL:
Make "Popular Parallel Programming" possible.

Scala's Toolbox for Parallel Programming

Actors

Parallel graph processing

STM

Parallel DSLs

Futures

Collections → Parallel

Collections → Distributed

Scala's Toolbox for Parallel Programming

- Actors
- Parallel graph processing
- STM
- Parallel DSLs
- Futures
- Collections → Parallel, Distributed

The Lectures.

TODAY

Intro to Scala

Scala Actors

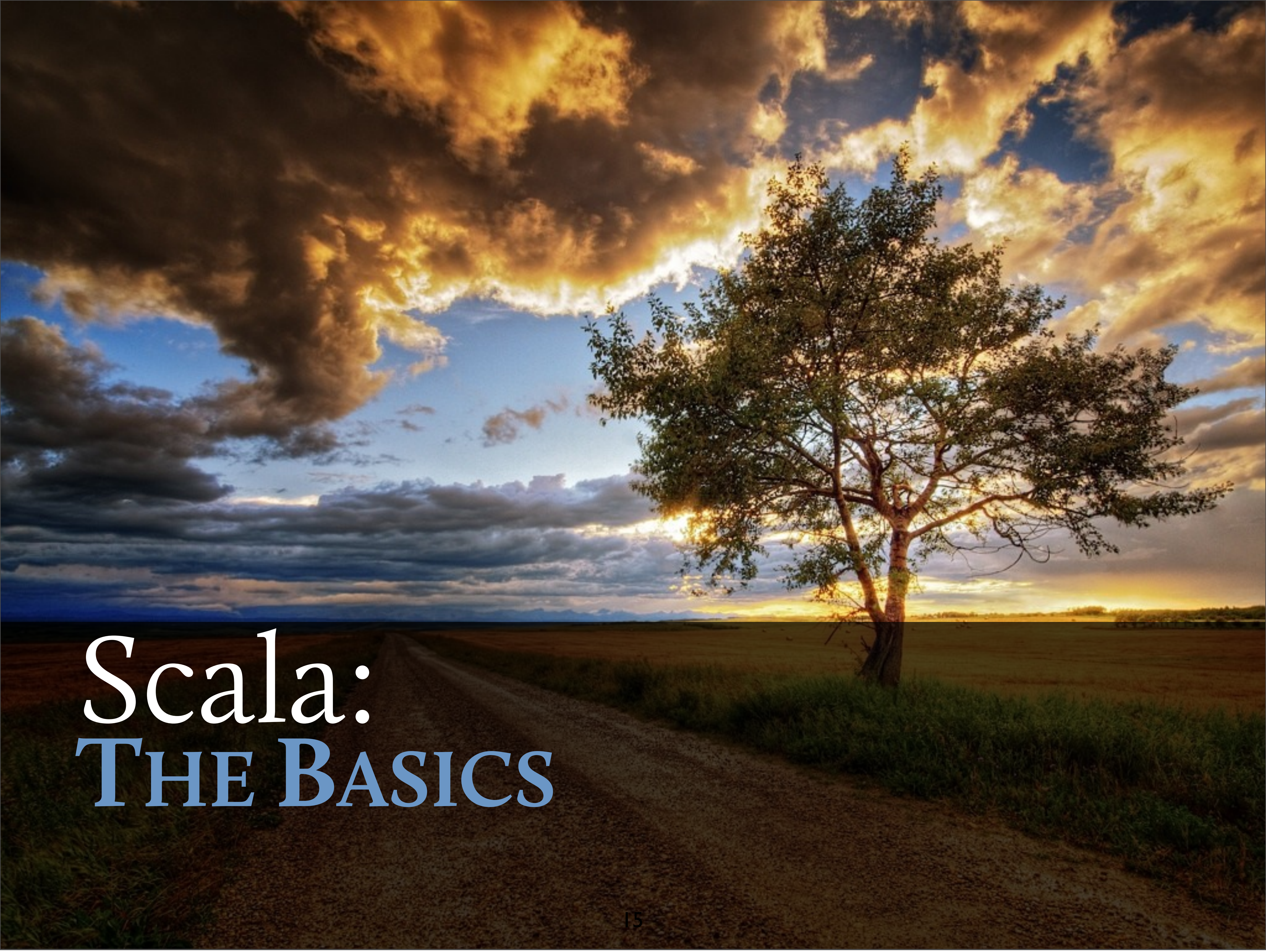
Parallel Graph Processing

TOMORROW

Parallel Collections

Parallel DSLs

PhD Tips


Scala:
The Basics

An Example Class.

In Java:

```
public class Person {
  public final String name;
  public final int age;
  Person(String name, int age) {
      this.name = name;
      this.age = age;
  }
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```

In Scala:

```
class Person(val name: String,
             val age: Int) {}
```

... and its use

In Java:

```
import java.util.ArrayList;
...
Person[] people;
Person[] minors;
Person[] adults;
{  ArrayList<Person> minorsList = new ArrayList<Person>();
   ArrayList<Person> adultsList = new ArrayList<Person>();
   for (int i = 0; i < people.length; i++)
       (people[i].age < 18 ? minorsList : adultsList)
        .add(people[i]);
   minors = minorsList.toArray(people);
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In Scala:

```
val people: Array[Person]
val (minors, adults) = people partition (_.age < 18)
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an infix method call

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a function value

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a simple pattern match

Class Hierarchies and ADTs.

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- Introducing **pattern matching** for objects.
- Concise manipulation of immutable data structures.

Pattern Matching.

Class hierarchy for binary trees:

```
abstract class Tree[T]
case object Empty extends Tree[Nothing]
case class Binary[T](elem: T, left: Tree[T], right: Tree[T])
        extends Tree[T]
```

In-order traversal:

```
def inOrder[T](t: Tree[T]): List[T] = t match {
  case Empty                 =>
    List()
  case Binary(e, l, r) =>
    inOrder(l) ::: List(e) ::: inOrder(r)
}
```

- Extensibility
- Encapsulation: only constructor params exposed
- Representation independence [ECOOP'07]

Functions and Collections.

First-class functions make collections more powerful

Especially immutable ones

```
people.filter(_.age >= 18)
.groupBy(_.surname): Map[String, List[Person]]
.values : Iterable[List[Person]]
.count(_.length >= 2)
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- For example, the anonymous successor function `(x: Int) => x + 1 (short _ + 1)` is expanded to:

```
new Function1[Int, Int] {
  def apply(x: Int): Int = x + 1
}
```

Arrays are Objects.

- Arrays = mutable functions over integer ranges

Syntactic sugar:

`a(i) = a(i) + 2` for `a.update(i, a.apply(i) + 2)`

```
final class Array[T](_length: Int) extends
  java.io.Serializable
  with java.lang.Cloneable {

  def length: Int = ...
  def apply(i: Int): T = ...
  def update(i: Int, x: T): Unit = ...
  override def clone: Array[T] = ...
}
```

Partial Functions.

- Functions that are defined only for some objects
- Test using `isDefinedAt`

```
trait PartialFunction[-A, +B] extends (A => B) {
  def isDefinedAt(x: A): Boolean
  def orElse[A1 <: A, B1 >: B]
     (that: PartialFunction[A1, B1]): PartialFunction[A1, B1]
}
```

- Blocks of pattern-matching cases are instances of partial functions
- This lets one write control structures that are not easily expressible otherwise

Scala
Actors

Actors in Scala.

- Send/receive constructs adopted from **Erlang**
- Send is asynchronous: messages are buffered in actor's **mailbox**
- Receive picks the first message in the mailbox that matches one of the patterns $msgpat_i$
- If no pattern matches the actor suspends

```
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A Simple Actor.

```
val summer = actor {
  var sum = 0
  loop {
    receive {
      case ints: Array[Int] =>
        sum += ints.reduceLeft((a, b) => (a+b)%7)
      case from: Actor =>
        from ! sum
    }
  }
}
```

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- **NOT** Erlang-style actors: E, Kilim, ActorFoundry
- Incentive: **programmer productivity**

Goal of Scala Actors?

Programming system for Erlang-style actors that:

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Programming system for Erlang-style actors that:

- offers high scalability on mainstream platforms;
- integrates with thread-based code;
- provides safe and efficient message passing.

Implementing Actors.

Thread-based implementation:

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- One thread per actor

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Pros	**Cons**
– No inversion of control.	– High memory consumption.
– Interoperability with threads.	– Context switching overhead.

Event-Based Actors.

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Actors consume a lot of resources while waiting for messages.

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IDEA: Suspend actor by saving continuation closure and releasing current thread

Transparent thread pooling

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Main problem of thread-per-actor model:

Actors consume a lot of resources while waiting for messages.

Idea: Suspend actor by saving continuation closure and releasing current thread

Transparent thread pooling

```
def act() {
  react { case Put(x) =>
    react { case Get(from) =>
      from ! x
      act()
    }
  }
}
```

Programming with react

Invocations of `react` do not return

Must **provide continuation** in body of `react`

Does this mean we have to write code in continuation-passing style?

No, **control-flow combinators** enable modular composition

```
a andThen b //runs a followed by b
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```
def loop(body: => Unit) = body andThen loop(body)
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Thread-based Programming

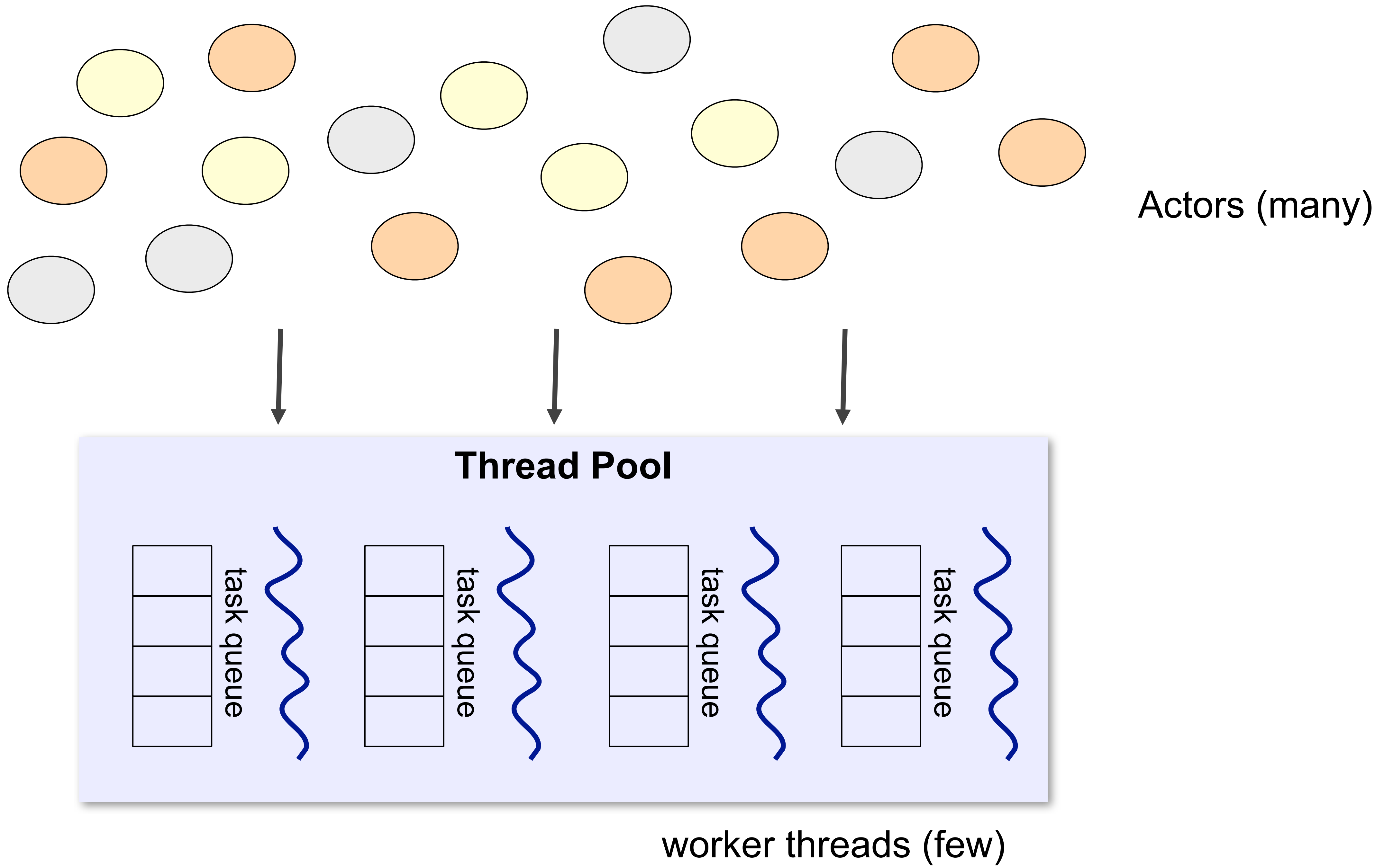
Actors should be able to block their thread temporarily:

- When interacting with thread-based code
- When it is difficult to provide the continuation

```
val tasks: List[Task]
tasks foreach { task => worker ! task }
val results = tasks map { task =>
  receive {
    case Done(result) => result
  }
}
```

Blocks current thread if actor has to wait for a message

Managing Blocking.



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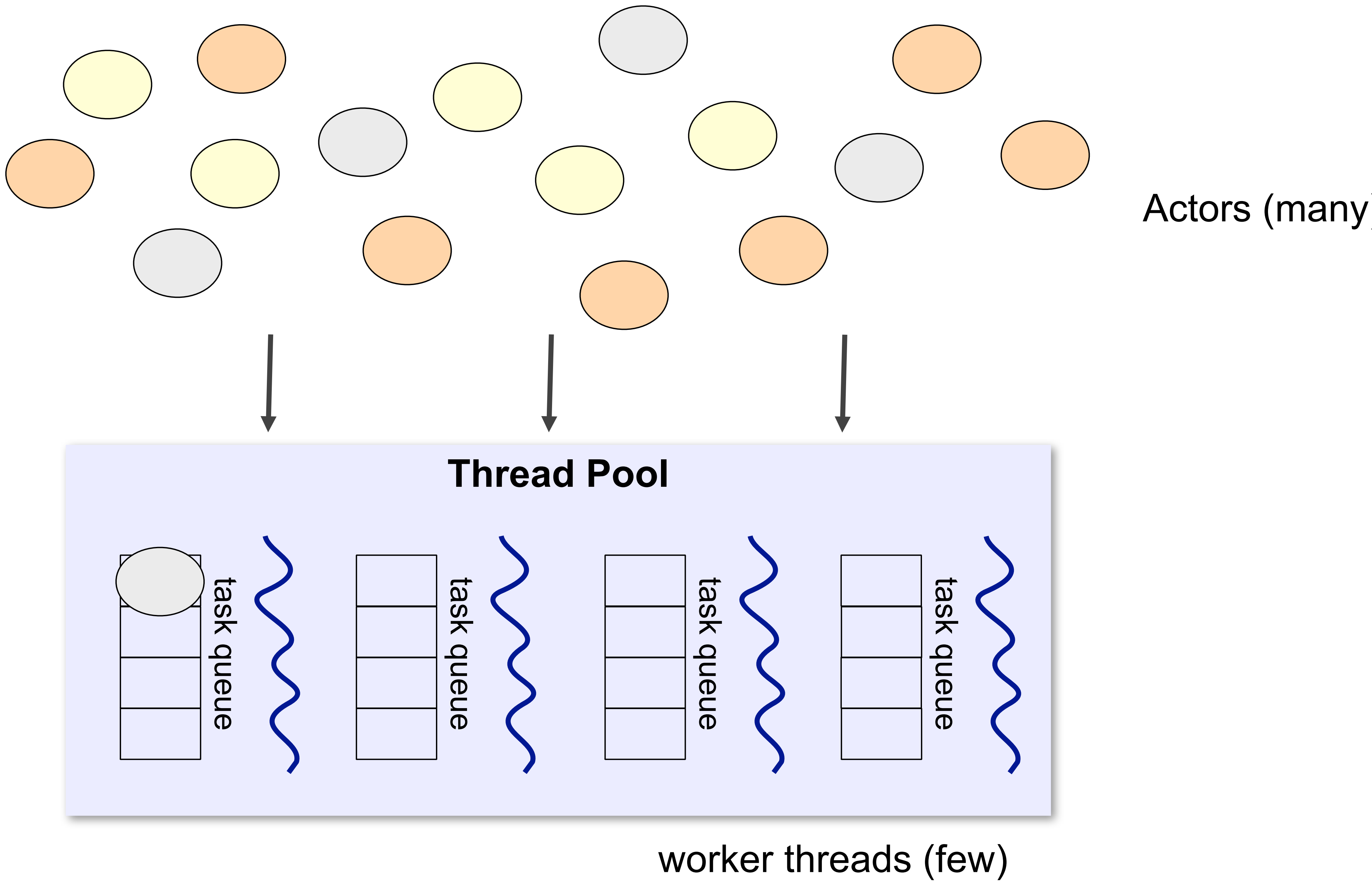

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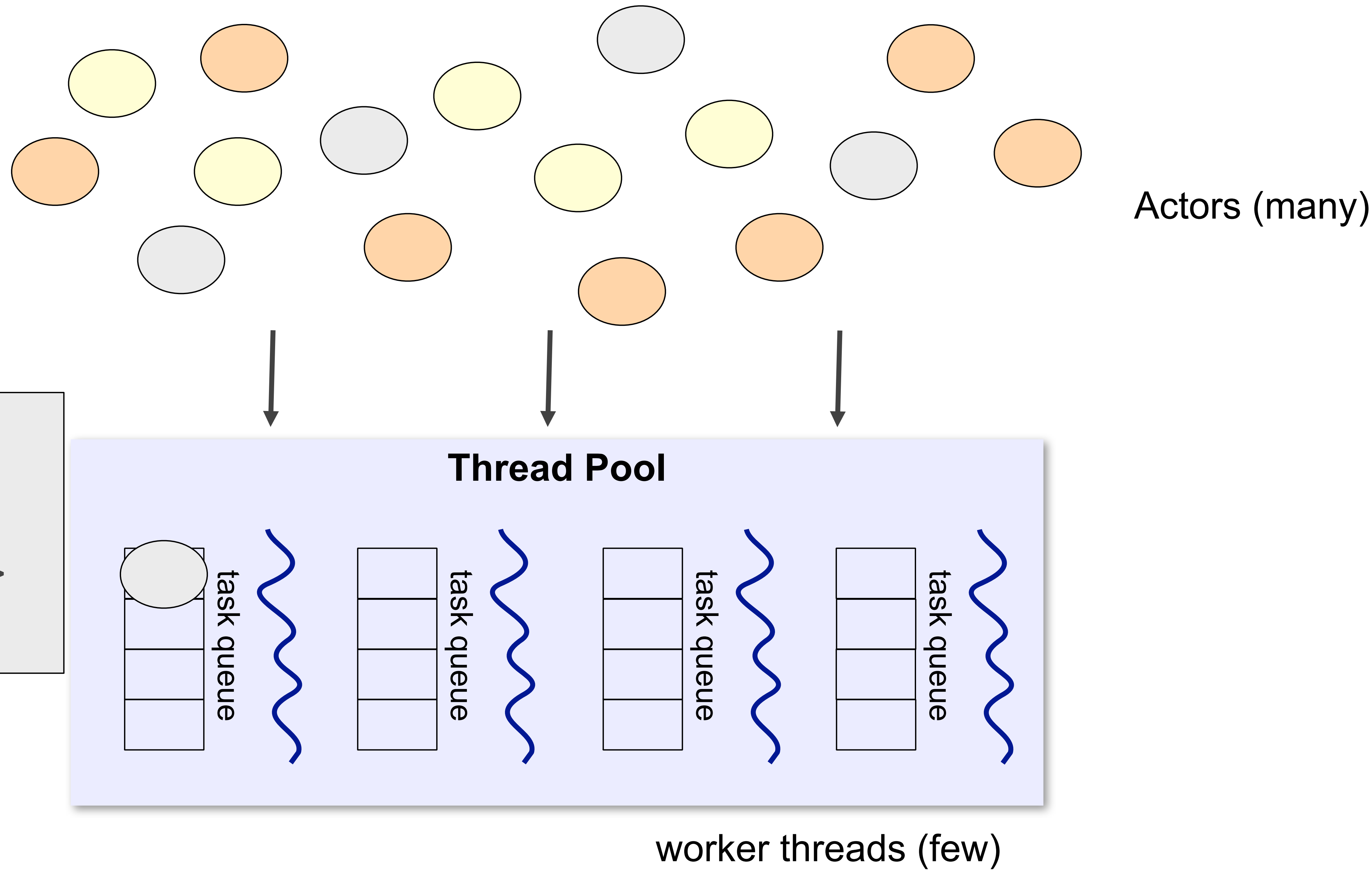

Actor A:

- Start 3 actors
- Then:

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receive {
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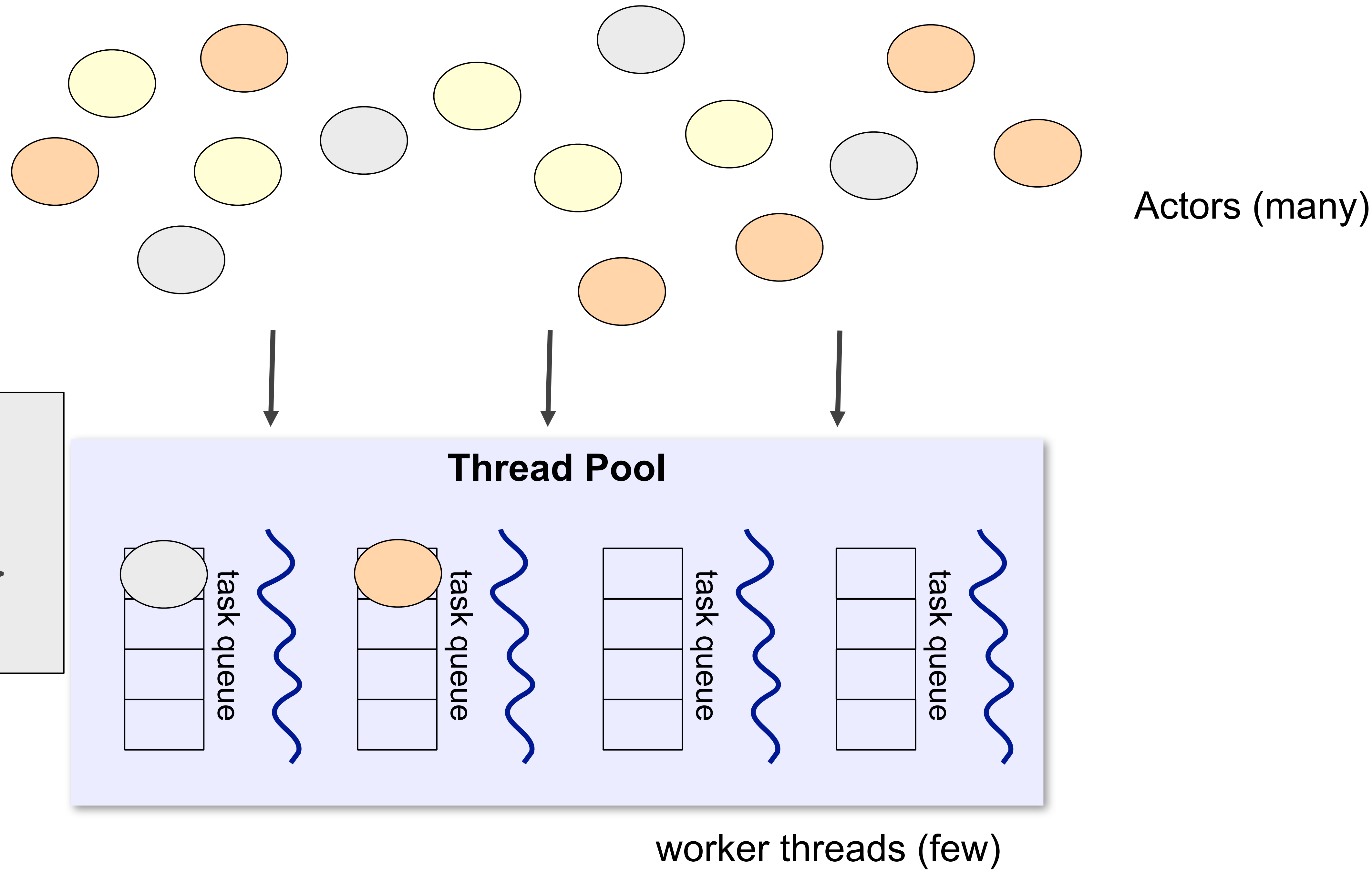

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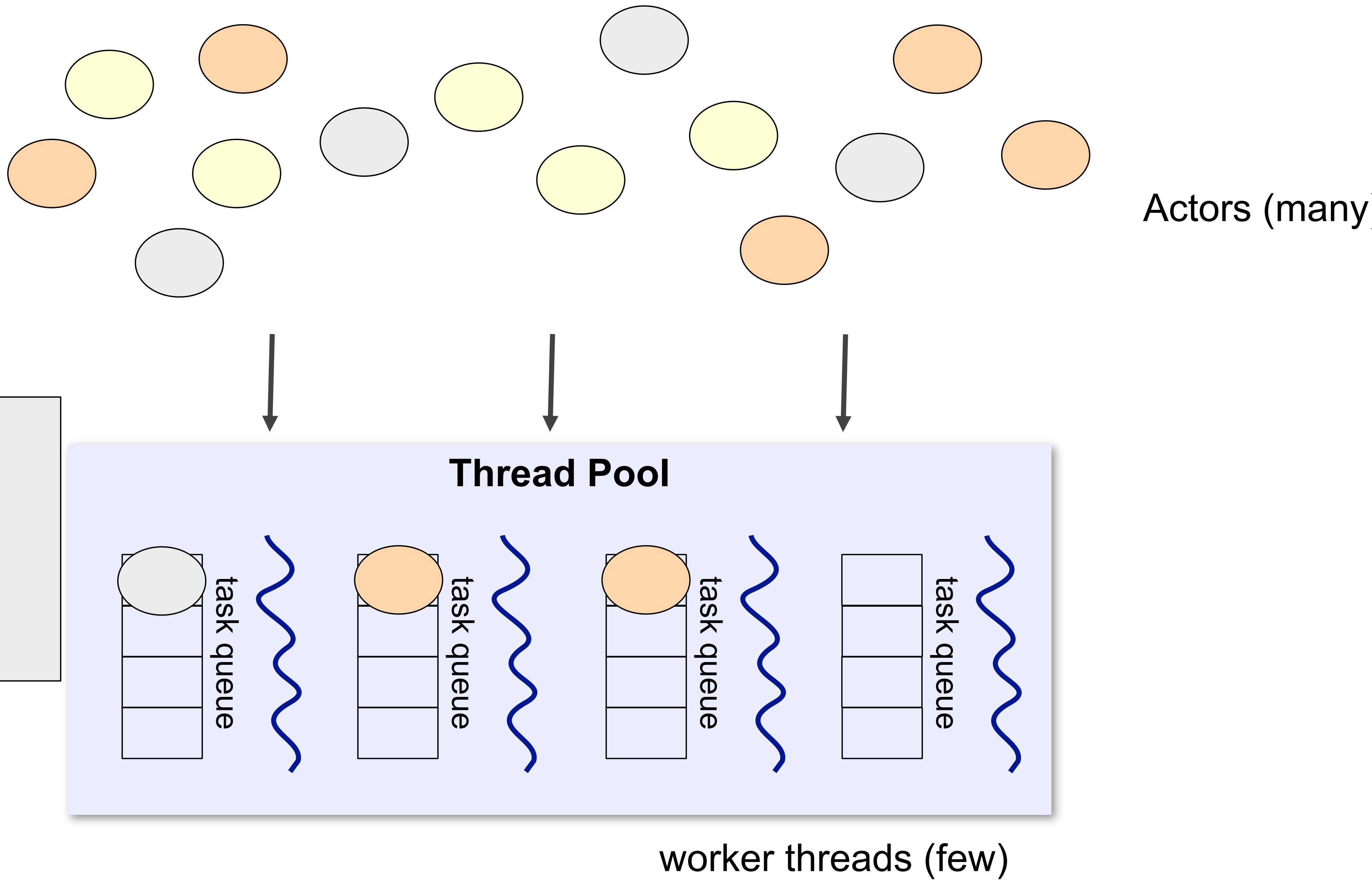

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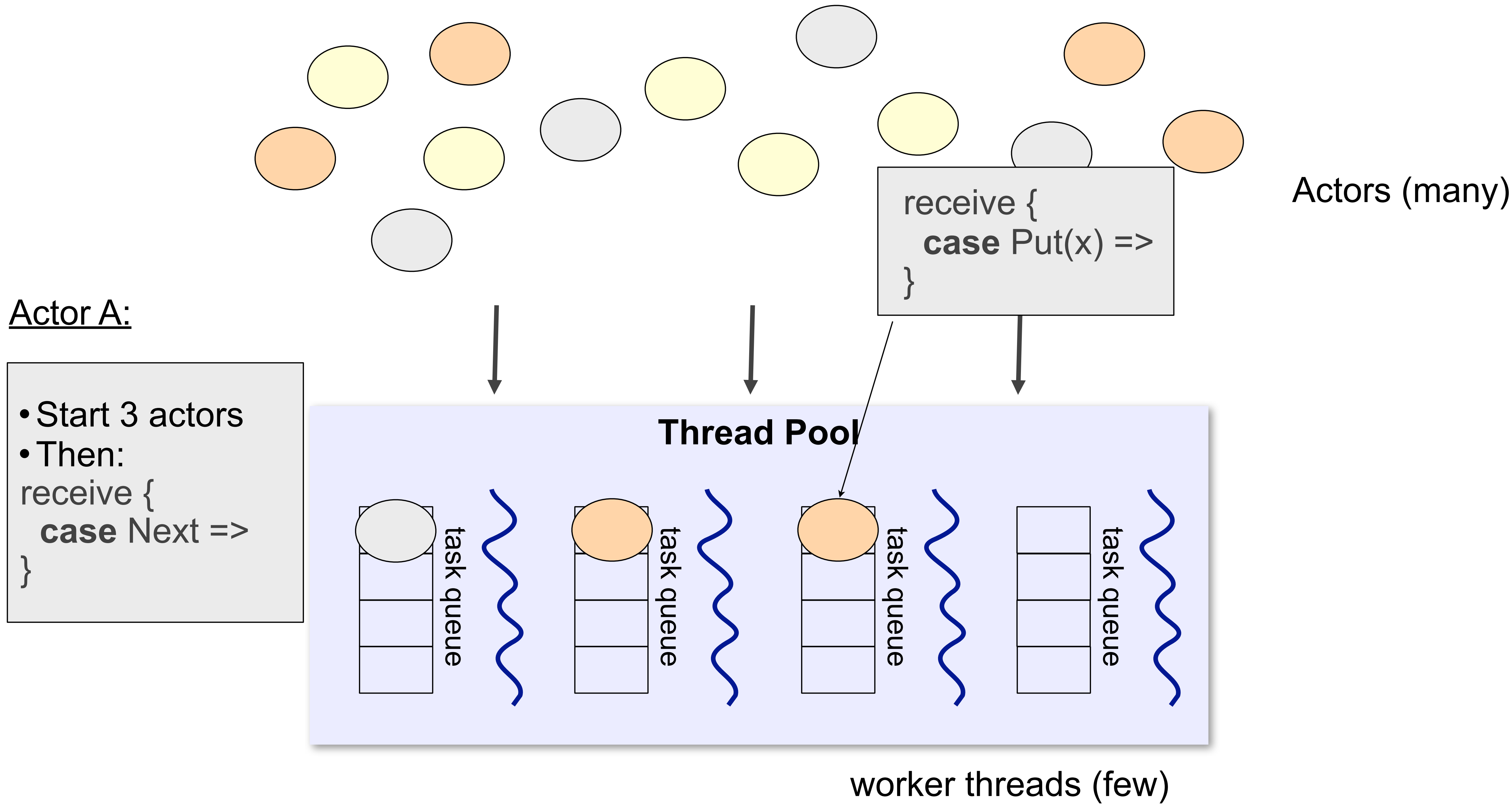

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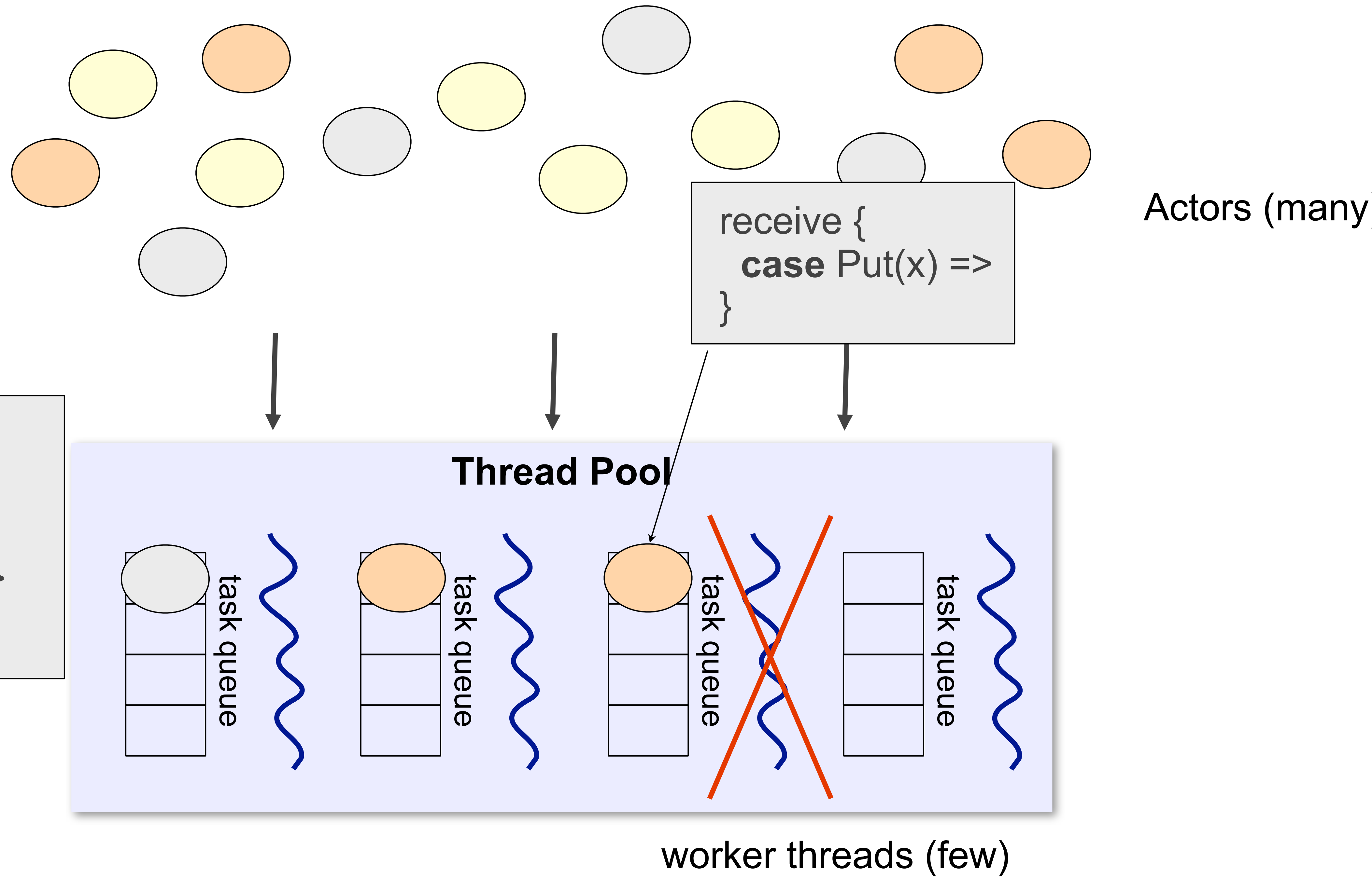

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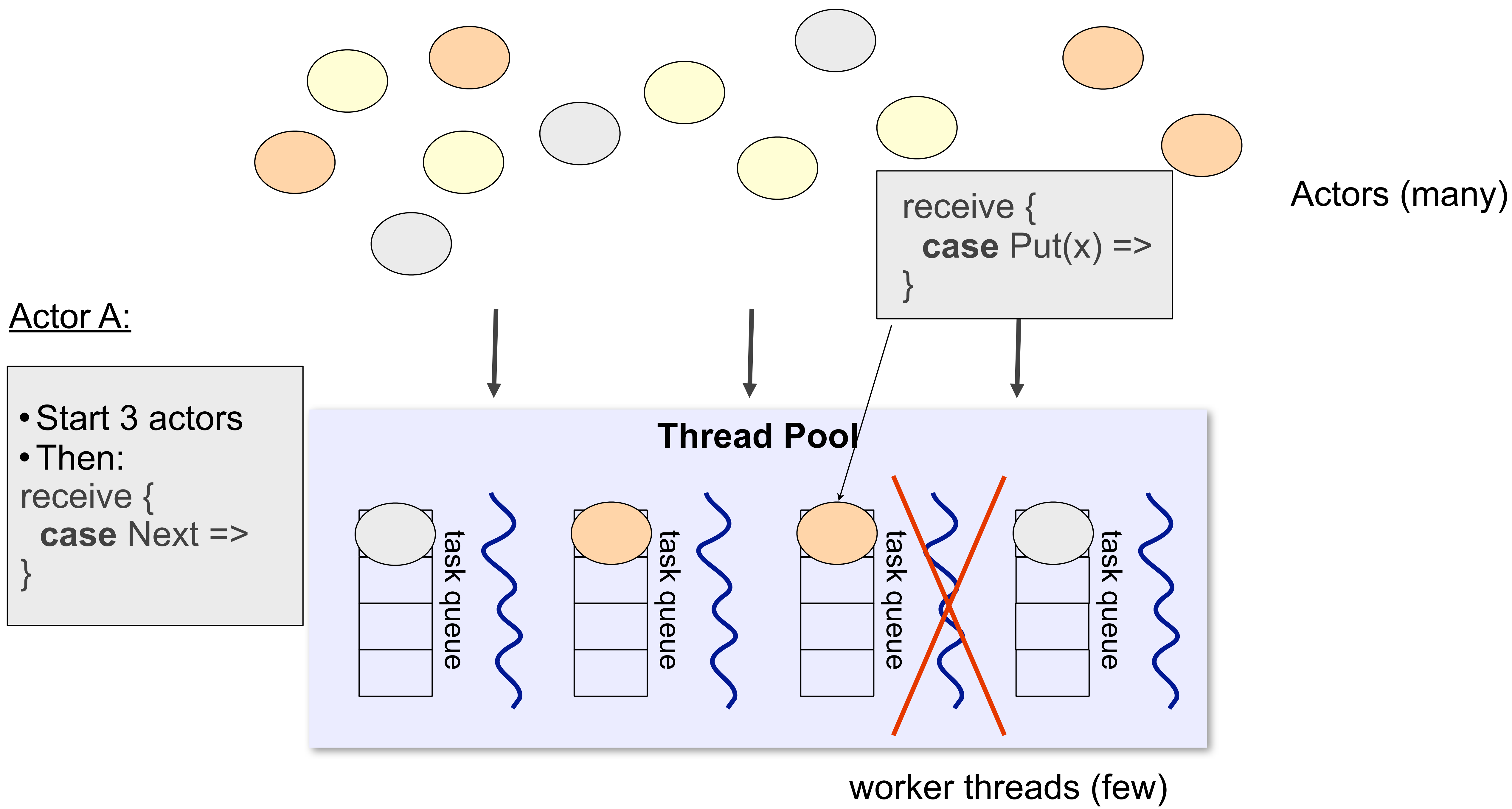

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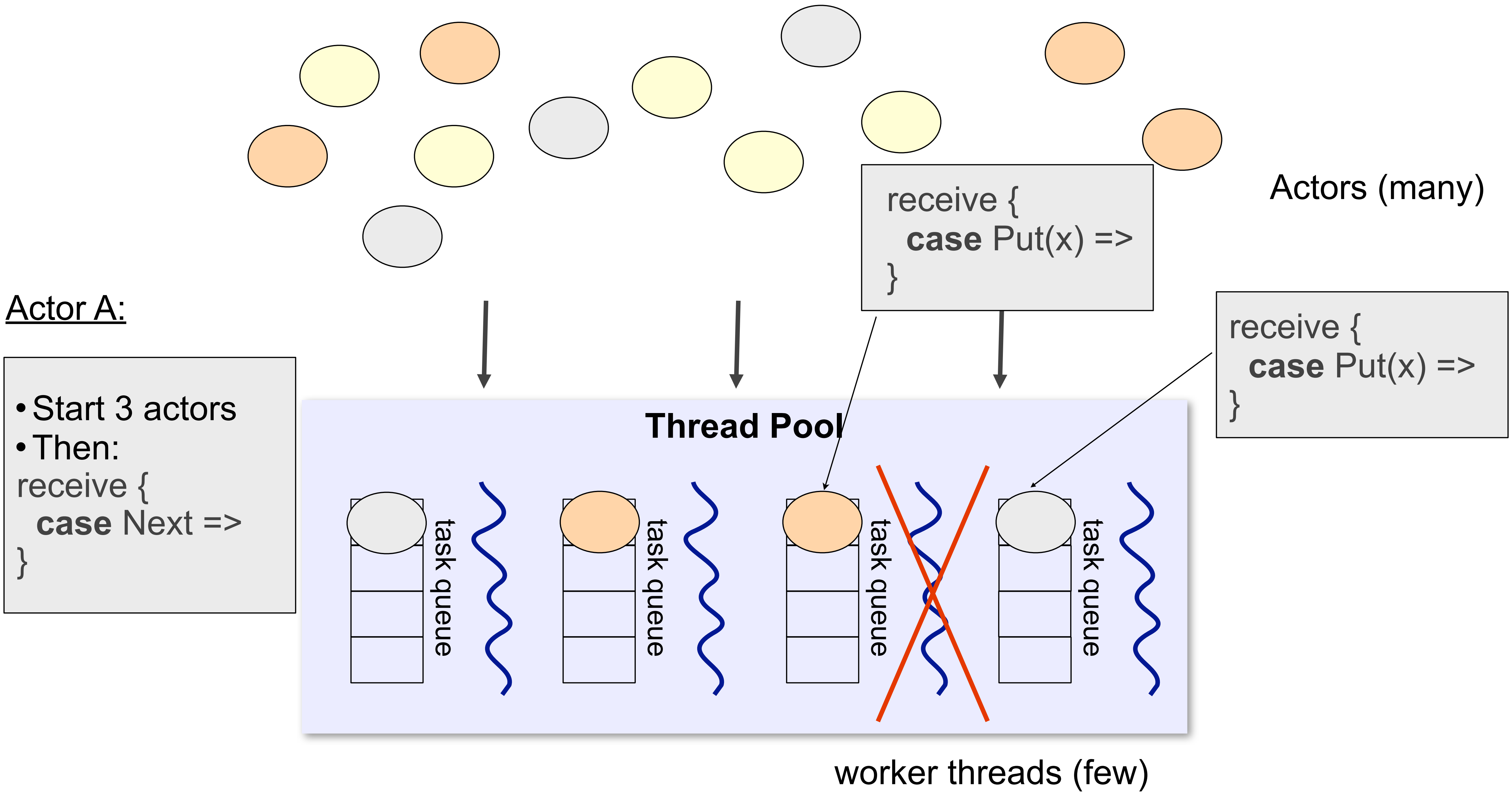

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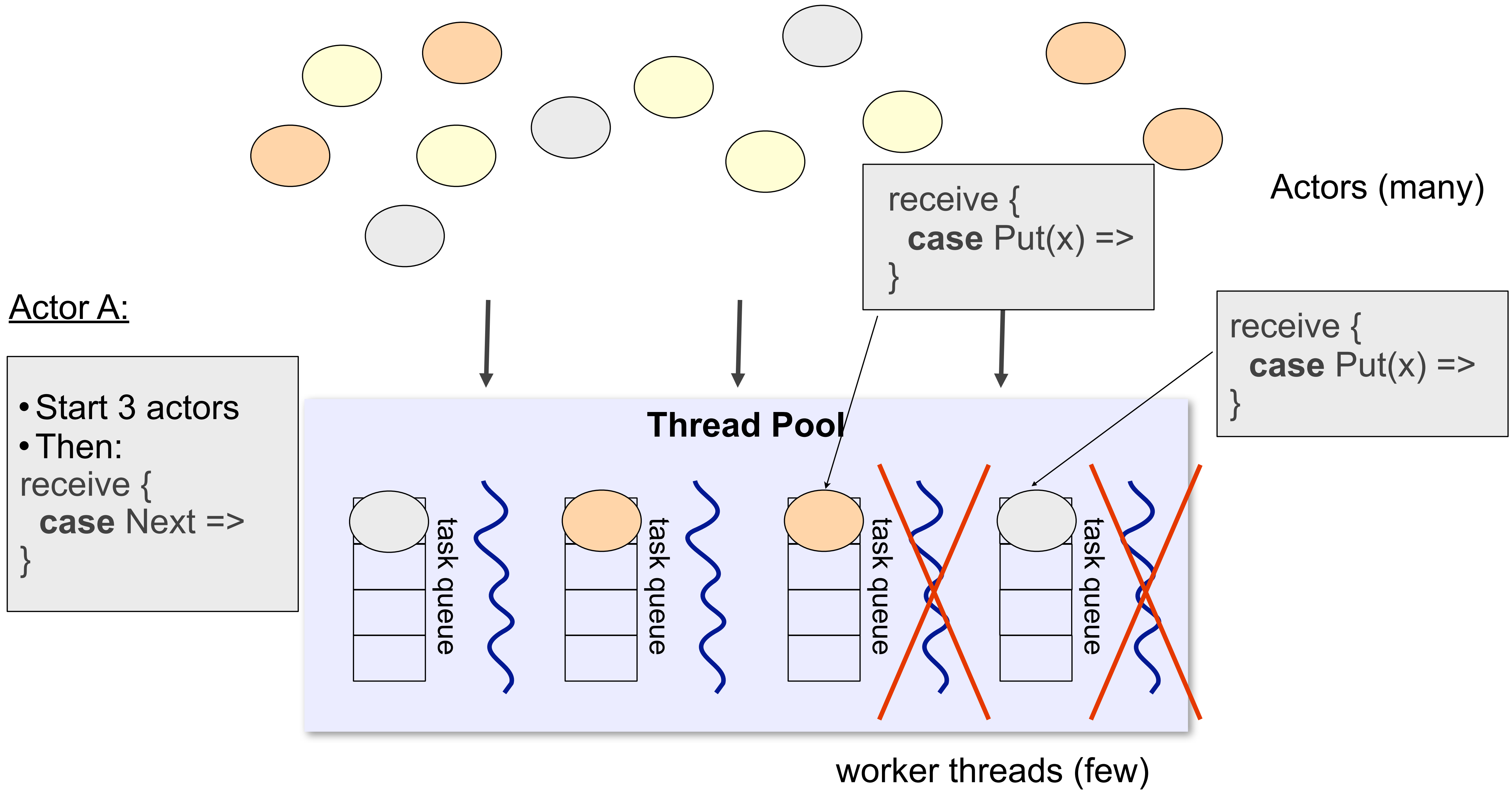

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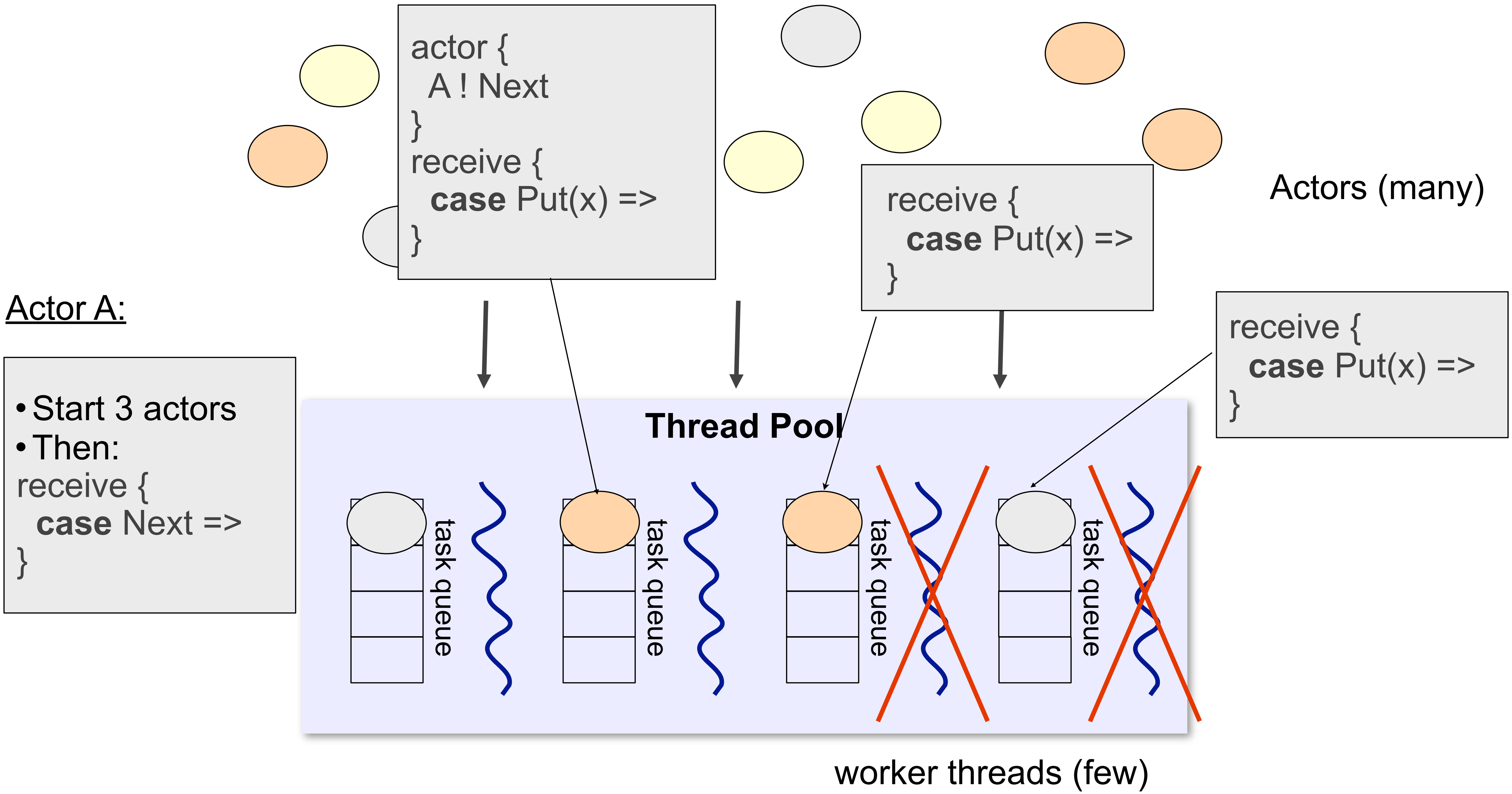

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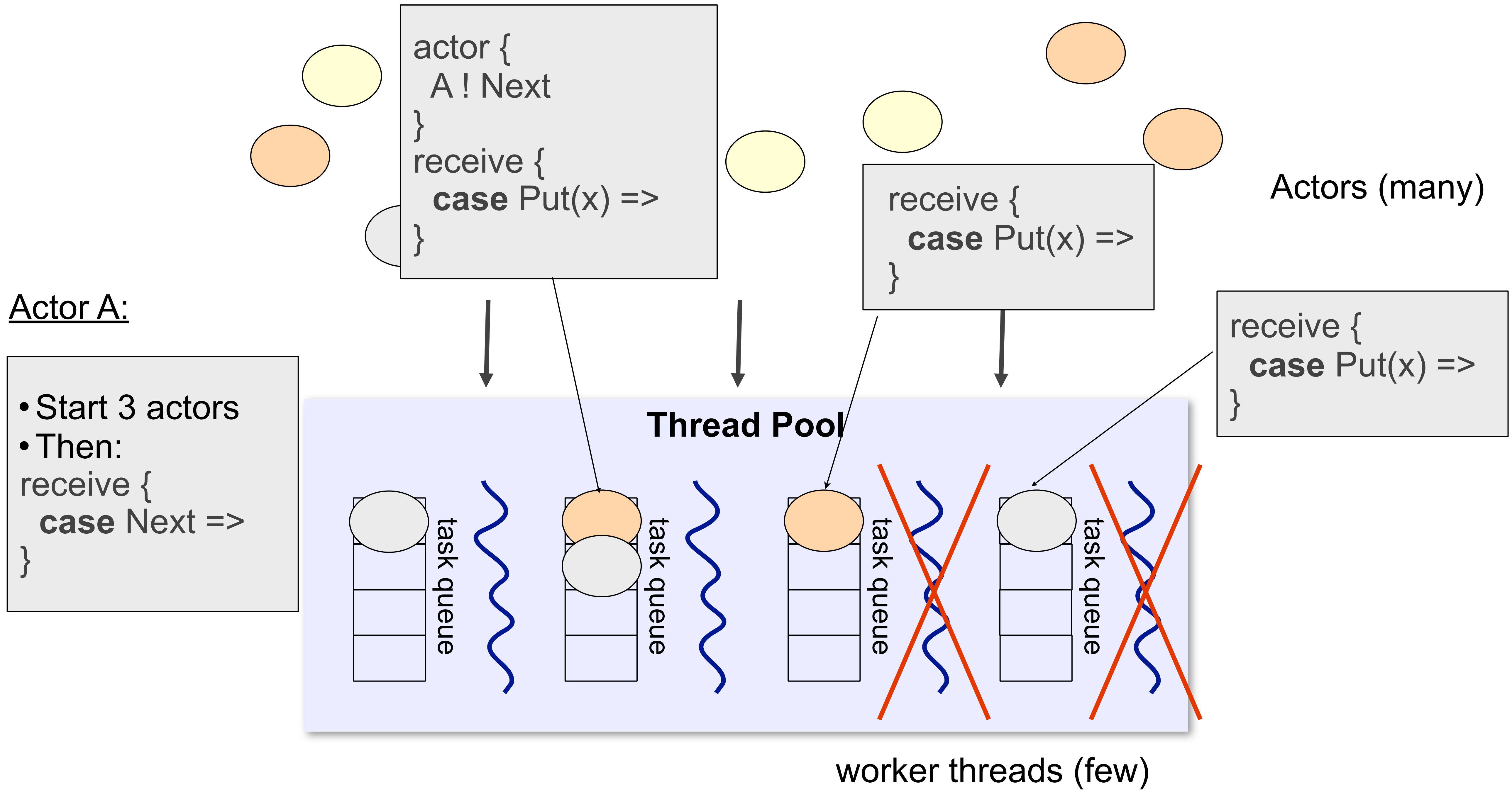

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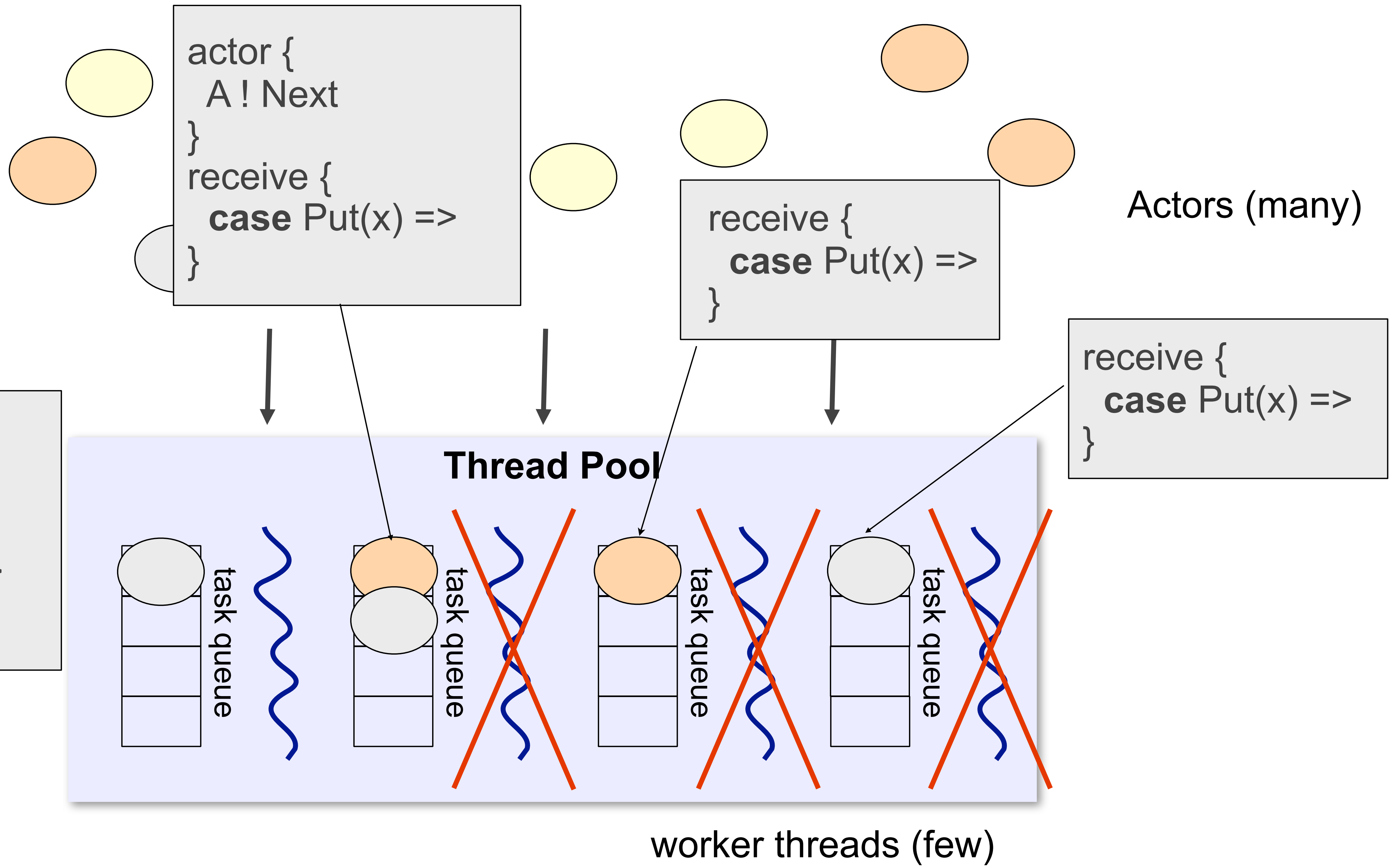

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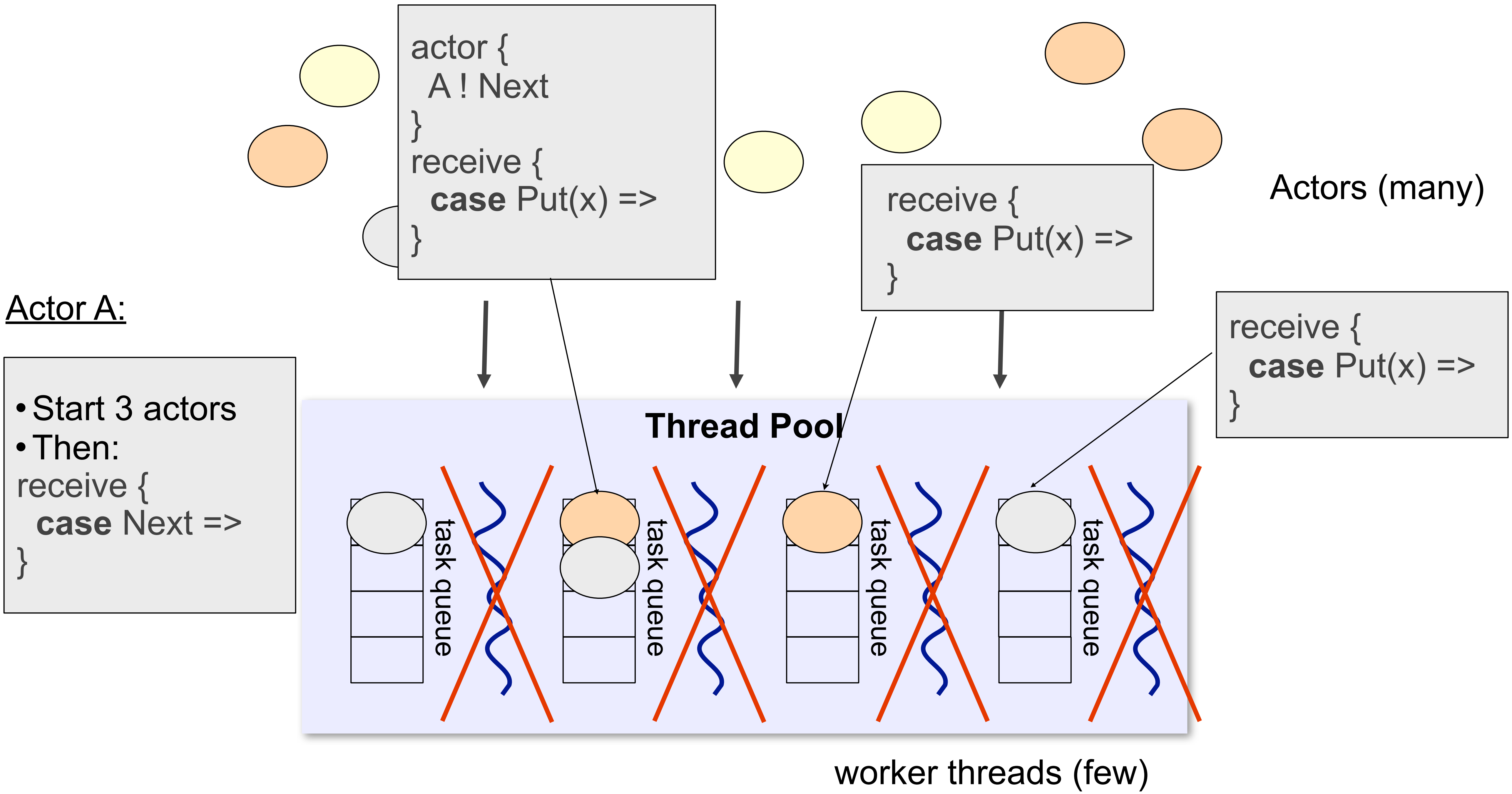

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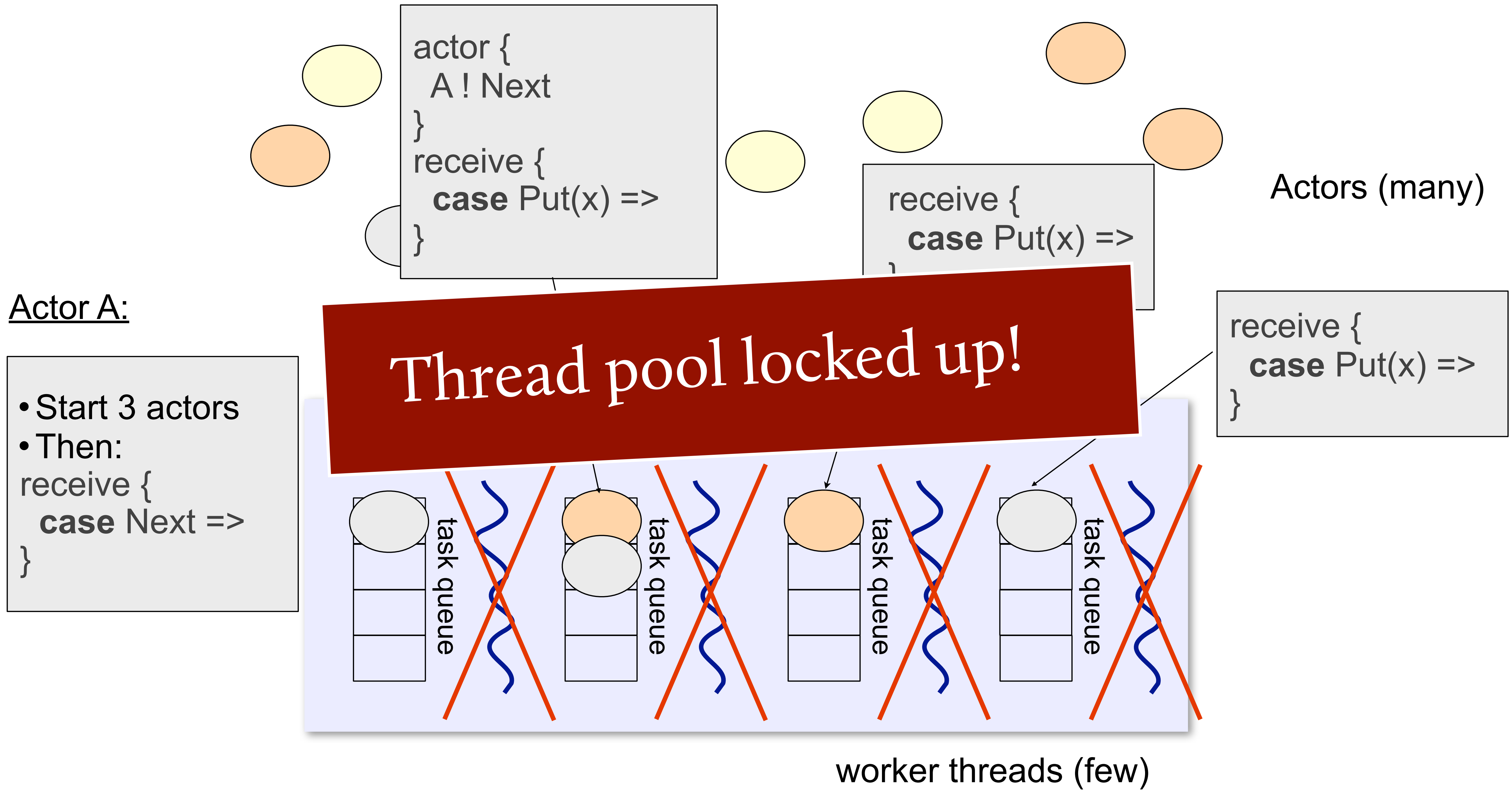
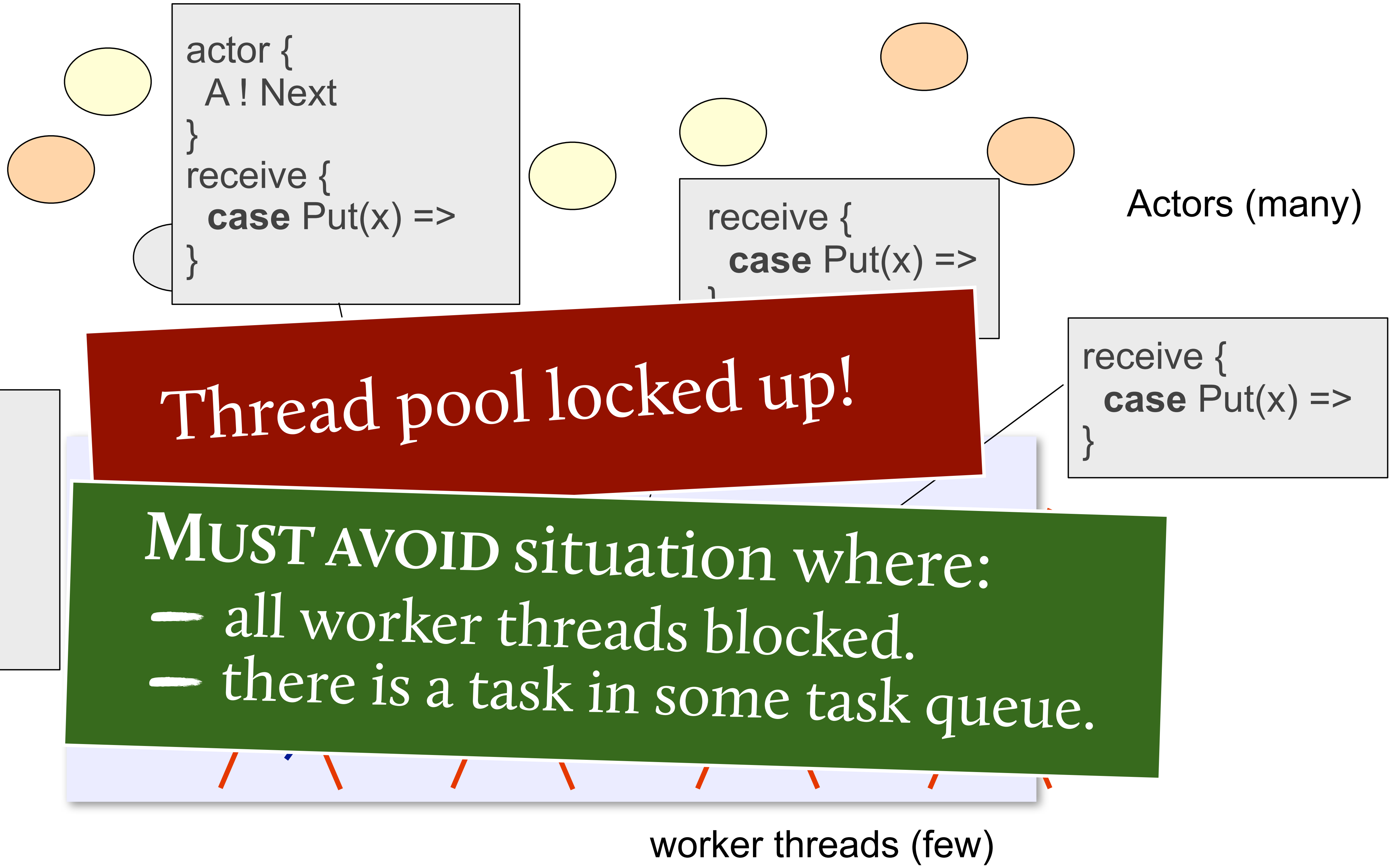


Managing Blocking.



Actor A:

- Start 3 actors
- Then:

```
receive {
  case Next =>
}
```

Thread pool locked up!

MUST AVOID situation where:

- all worker threads blocked.
- there is a task in some task queue.

Under the Hood.

```
def receive[R](f: PartialFunction[Any, R]): R = {
  ...
  val elem = mailbox.extractFirst(msg => f.isDefinedAt(msg))
  if (elem == null) {
    synchronized {
      waitingFor = f
      isSuspended = true
      scheduler.managedBlock(blocker)
    }
  }
  else {
    // process message...
  }
  ...
}
```

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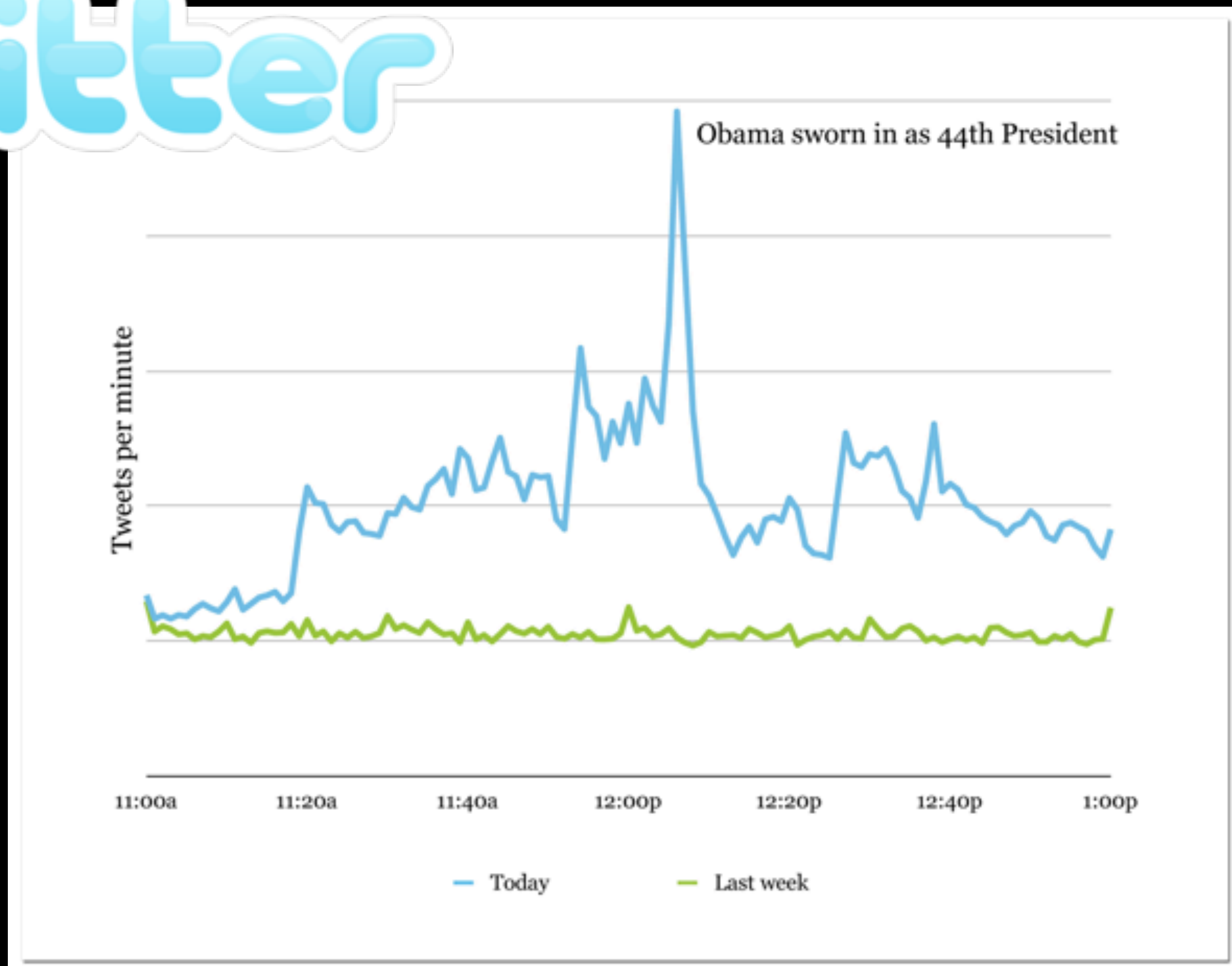
      scheduler.managedBlock(blocker)
    }
  }
  else {
    // process message...
  }
  ...
}
```

```scala
object blocker extends ManagedBlocker {
  def block() = {
    Actor.this.suspendActor()
    true
  }
  def isReleasable =
    !Actor.this.isSuspended
}
```

Inauguration 2.0



"We saw 5x normal tweets-per-second and about 4x tweets-per-minute as this chart illustrates. Overall, Twitter sailed smoothly through the inauguration [...]"

Goal of Scala Actors?

REVISITED.

Programming system for Erlang-style actors that:

- offers high scalability on mainstream platforms;
- integrates with thread-based code;
- provides safe and efficient message passing.

UNIFIED actors

Goal of Scala Actors? Revisited.

Programming system for Erlang-style actors that:

- offers high scalability on mainstream platforms;
- integrates with thread-based code;
- provides safe and efficient message passing.

Event-based actors
- no inversion of control
- no changes to the JVM
- no CPS transform

[Haller and Odersky. **Event-based programming without inversion of control,** ***Proc. JMLC,*** **2006**]

Goal of Scala Actors?

REVISITED.

Programming system for Erlang-style actors that:

- offers high scalability on mainstream platforms;
- integrates with thread-based code;
- provides safe and efficient message passing.

- Temporarily & safely monopolize thread
- Interact with thread-based code

[Haller and Odersky. **Event-based programming without inversion of control, *Proc. JMLC,* 2006**]

[Haller and Odersky. **Scala Actors: Unifying thread-based and event based programming, *Theor. Comput. Sci,* 2009**]

Safe and Efficient Message Passing.

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- (Deep) copying messages upon sending is safe but inefficient

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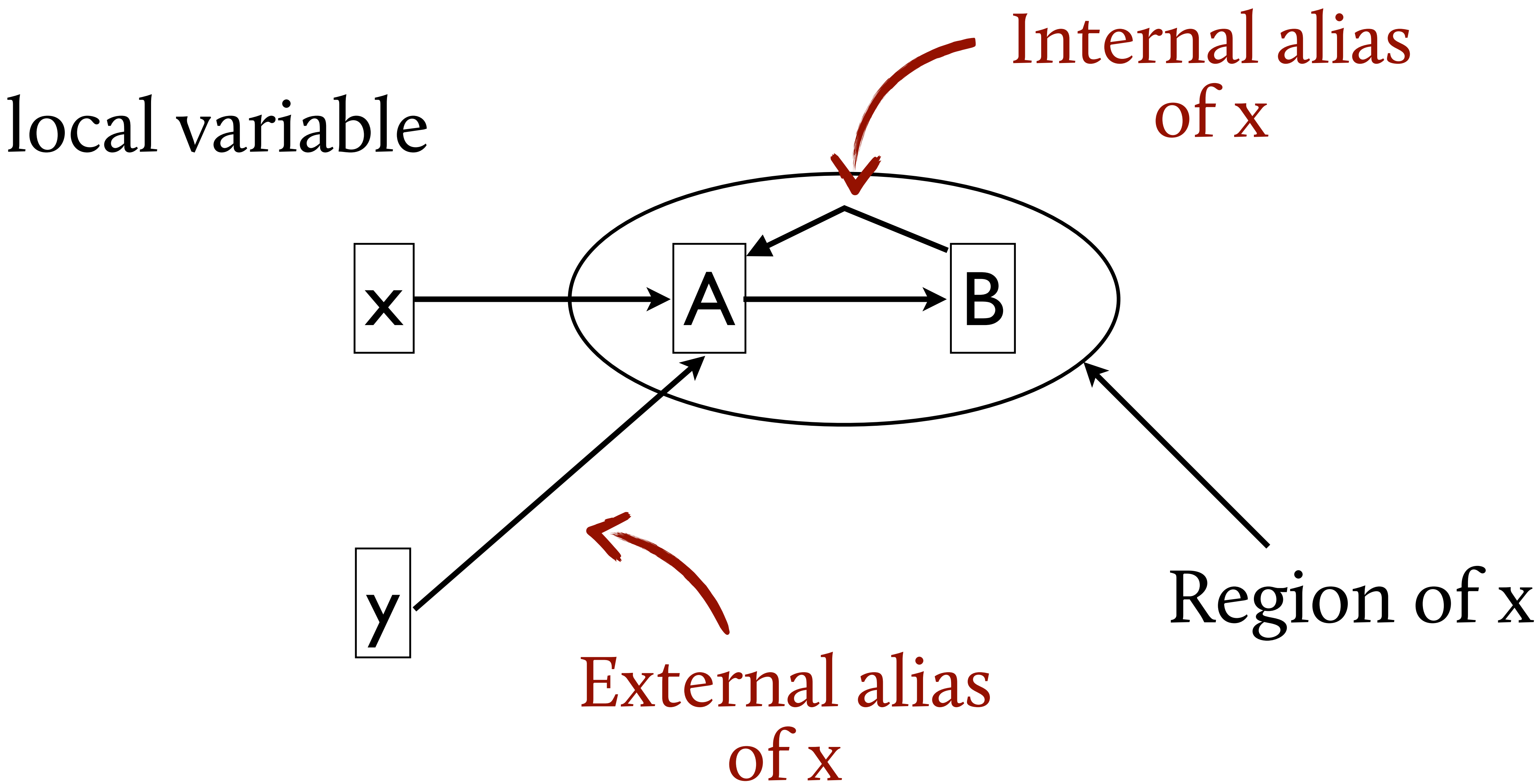
Safe and Efficient Message Passing.

- (Sending mutable objects by reference may lead to data races.)
- (Deep) copying messages upon sending is safe but inefficient
- ✔ Use **unique references** to enable efficient by-reference message passing without races
- ✔ Lightweight type-based approach to enforce uniqueness

Internal vs. External Aliases



Separate Uniqueness.

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- A reference is unique if it is the only reference pointing into some region
- Unique references may only have temporary external aliases
- A region may be transferred between actors using a unique reference; transferring invalidates the unique reference

Annotation System

`@unique`	Unique variable/parameter/result
`@transient`	Non-consumable (borrowed) unique parameter
`@peer(x)`	Parameter/result in the same region as x
`x capturedBy y`	Alias of x in region of y; consumes x
`swap(x.f, y)`	Return unique x.f and replace with unique y

No explicit regions/owners
No static alias analysis
Supports closures and nested classes

Unique Variables and Regions

```
val logList: LogList @unique = new
LogList
for (test <- tests) {
  val logFile: LogFile @unique =
    createLogFile(test, kind)
  // run test...
  logList.add(logFile)
}
report(logList)

def report(logList: LogList @unique) {
  master ! new Results(logList)
}
```

logFile in disjoint region of logList

Mutating Unique Objects.

```
class LogList {
  var elem: LogFile = null
  var next: LogList = this
  @transient def add(file: LogFile @peer(this)) =
    if (isEmpty) {
      elem = file; next = new LogList
    } else next.add(file)
}
```

- Receiver must remain unique after adding file
- `@transient` is equivalent to `@unique` except it does not consume the receiver
- file must point into the same region as the receiver, expressed using `@peer(this)`

Transferring Unique Objects.

How can we transfer a separately-unique object from one region to another?

```
val logList: LogList @unique = new LogList
for (test <- tests) {
  val logFile: LogFile @unique =
    createLogFile(test)
  // run test...
  logList.add(logFile capturedBy logList)
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Returns alias of `logFile` in region of `logList`
Consumes `logFile`

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}
```

- Returns alias of `logFile` in region of `logList`
- Consumes `logFile`

Alias Invariant

Two variables x, y are separate (in heap H) *iff* there is no object reachable from both x and y.

Definition (Separate Uniqueness):

A variable x is **separately-unique** in heap H *iff* for all y != x. y is live => separate (H, x, y)

Definition (Alias Invariant):

Unique parameters are separately-unique

Formal Type System

- Class-based object calculus with capabilities and `capturedBy/swap`
- A unique variable has type $\rho \triangleright C$
- Capability ρ = access permission to a region in heap

Definition (Capability Type Invariant):

Let x: $\rho \triangleright C$ and x': $\rho' \triangleright C'$ be local variables (ρ != ρ'). If there is a heap H at program point P such that both x and y are live at P, then separate(H, x, y)

Type Checking

- Typing judgment: $\Gamma ; \Delta \boxtimes t : T ; \Delta'$
- Type rules consume capability set Δ and produce capability set Δ'
- Capabilities in Δ grant access to variables in t
  - A variable of type $\rho \triangleright C$ can only be accessed if ρ is contained in Δ
- Capabilities in Δ' available after type checking t

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Capability Creation/ Consumption

Instance creation:

$$\frac{\Gamma\ ;\ \Delta \vdash \overline{y : \rho \triangleright D} \qquad \Delta = \Delta' \oplus \overline{\rho} \qquad fields(C) = \overline{\alpha\, l : D} \qquad \rho' \text{ fresh}}{\Gamma\ ;\ \Delta \vdash \mathsf{new}\ C(\overline{y}) : \rho' \triangleright C\ ;\ \Delta' \oplus \rho'}$$

Separation and Internal Aliasing

Field assignment:

$$\frac{\Gamma\,;\,\Delta \vdash y : \rho \triangleright C \qquad \Gamma\,;\,\Delta \vdash z : \rho \triangleright D_i \qquad fields(C) = \overline{\alpha\; l : D} \qquad \alpha_i \neq \texttt{unique}}{\Gamma\,;\,\Delta \vdash y.l_i := z : \rho \triangleright C\,;\,\Delta}$$

Separate Uniqueness

- Assume x has type $\rho \triangleright C$
- *Capability type invariant:* if there is a heap H where ¬separate(H, x, y), then y has type $\rho \triangleright D$
- Consuming ρ makes all variables of type $\rho \triangleright D$ unusable
- Consuming ρ makes **all external aliases of x unusable**
- Invoking a method consumes capabilities of unique arguments

Soundness

- Small-step operational semantics
- Soundness established using syntactic Wright-Felleisen Technique
  - *Preservation:* Reduction preserves uniqueness and separation invariants
  - *Progress:* Well-typed programs do not get stuck because of missing capabilities

Immutable Types

- Instances of ***immutable classes*** are deeply immutable
- Allow immutable objects to be reachable from two different regions
- Capabilities guarding ***immutable instances are not consumed***

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Actors and Concurrency

Add !, receive, and actor creation expressions

REDUCTION

- Actor = sequential execution state + mailbox
- Rules for reducing a set of actors in the context of a shared heap

TYPING

- Actors are instances of `Actor` subclasses
- `Send` consumes non-immutable arguments
- `Receive` returns unique references

Actor Isolation

Isolation theorem:

Variables accessible by different actors are separate up to immutable objects

→ *Corollary (with progress):*
only immutable objects are accessed concurrently

Implementation and Experience

Plug in for Scala compiler

- Erases capabilities and `capturedBy` for code generation

Practical experience:

	size [LOC]	changes [LOC]	property checked
mutable collections	2046	60	collections self-contained
partest	4182	61	actor isolation
ray tracer	414	18	actor isolation

Implementation and Experience

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ray tracer	41[illegible]	[illegible]	[illegible]

TYPES: `DoubleLinkedList`, `ListBuffer`, and `HashMap`
Including all transitively extended traits

External vs. Separate Uniqueness

External Uniqueness

- No external aliases
- No unique method receivers
- Deep/full encapsulation

[*Clarke, Wrigstad 2003; Müller, Rudich 2007; Clarke et al. 2008*]

Separate Uniqueness

This talk.

- Local external aliases
- Unique method receivers (self transfer)
- Full encapsulation

Goal of Scala Actors?

REVISITED. (AGAIN)

Programming system for Erlang-style actors that:

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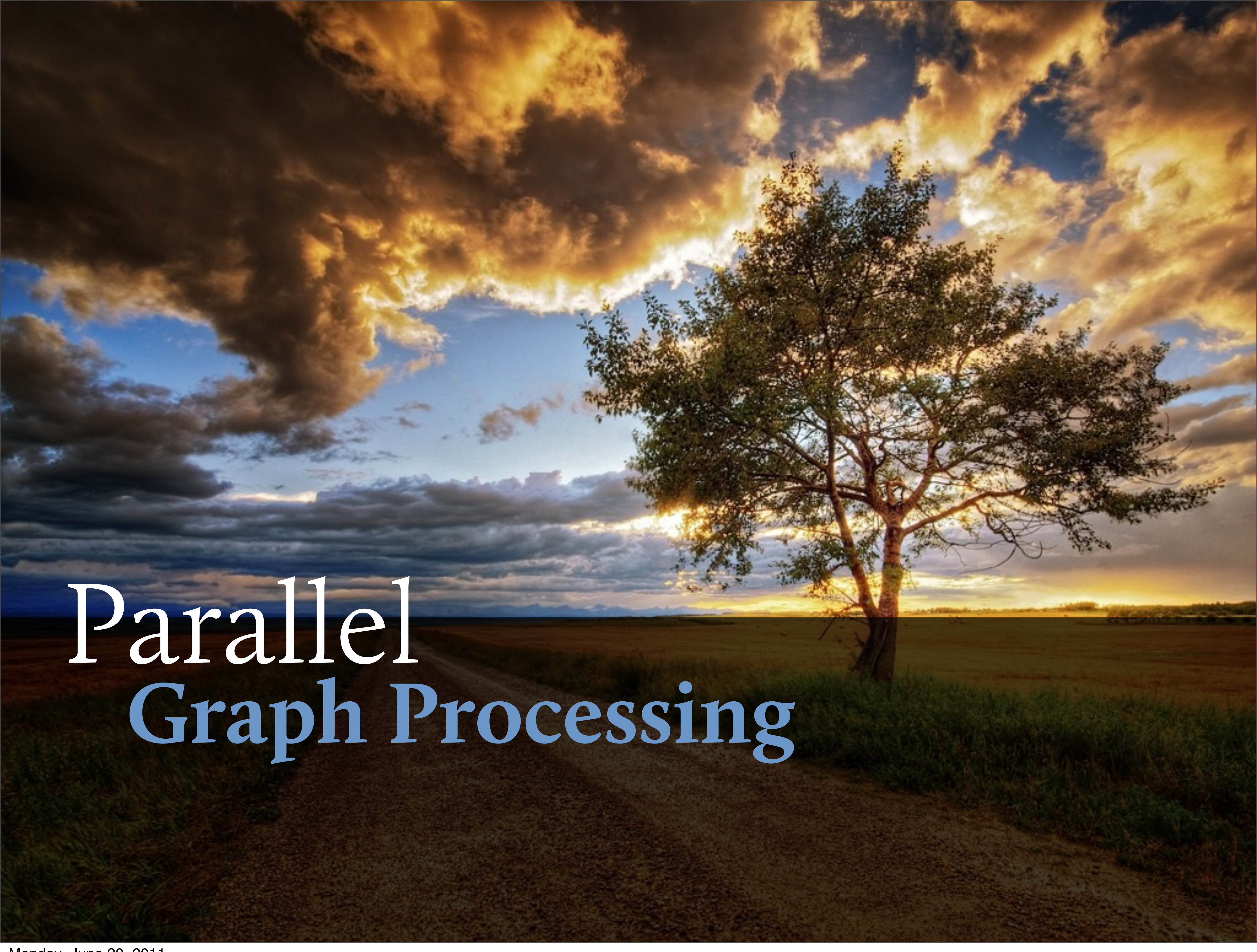
CAPABILITIES FOR UNIQUENESS

- Lightweight pluggable type system.
- Race-freedom through actor isolation.

[Haller and Odersky. **Capabilities for uniqueness and borrowing,** ***Proc. ECOOP, 2010***]

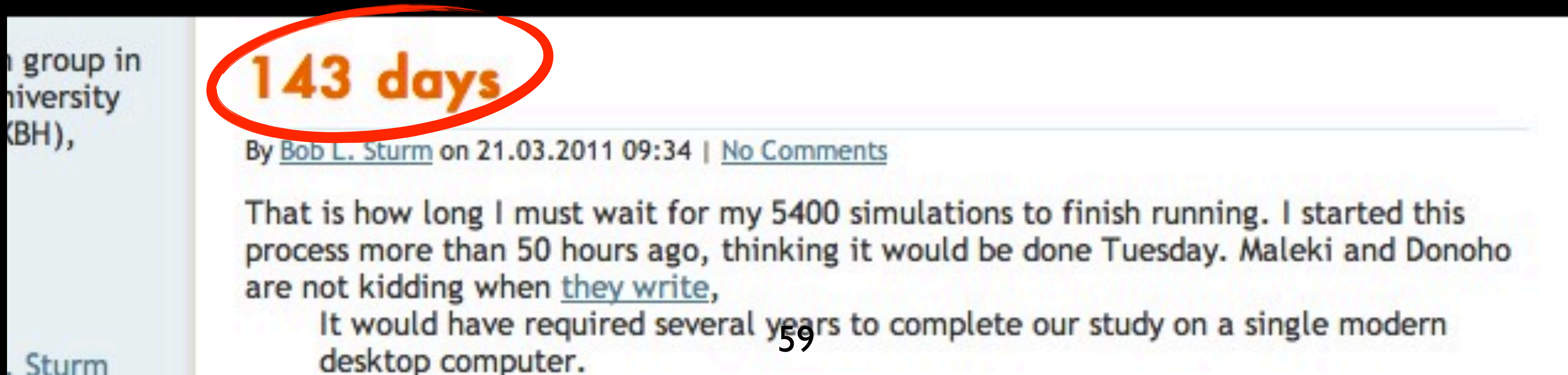
Summary: Actors

- Scalable Erlang-style actors
- Integration of thread-based and event-based programming
- Used in large-scale production systems
- Lightweight uniqueness types for actor isolation
  - No explicit regions/owners
  - Soundness and actor isolation proofs


Parallel
Graph Processing

Data is growing.

At the same time,
there is a growing desire
to ***do* MORE *with that data.***



143 days

By Bob L. Sturm on 21.03.2011 09:34 | No Comments

That is how long I must wait for my 5400 simulations to finish running. I started this process more than 50 hours ago, thinking it would be done Tuesday. Maleki and Donoho are not kidding when they write,

> It would have required several years to complete our study on a single modern desktop computer.

As an example,

MACHINE LEARNING (ML)

- has provided elegant and sophisticated solutions to many complex problems on a small scale,

As an example,

Machine Learning (ML)

- has provided elegant and sophisticated solutions to many complex problems on a small scale,

could open up New Applications + New Avenues of Research if ported to a larger scale

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typically focus on optimizing sequential algorithms when faced with scaling problems.

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described as,

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typically foc… …hen faced with scaling…

need to make it easier to experiment with parallelism

What about MapReduce?

What about MapReduce?

Poor support for iteration.

MapReduce instances must be chained together in order to achieve iteration.

- Not always straightforward.
  Even building non-cyclic pipelines is hard (e.g., FlumeJava, PLDI'10).
- Overhead is significant.
  Communication, serialization (e.g., Phoenix, IISWC'09).

Menthor...

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- is a framework for parallel graph processing.
  (But it is not limited to graphs.)

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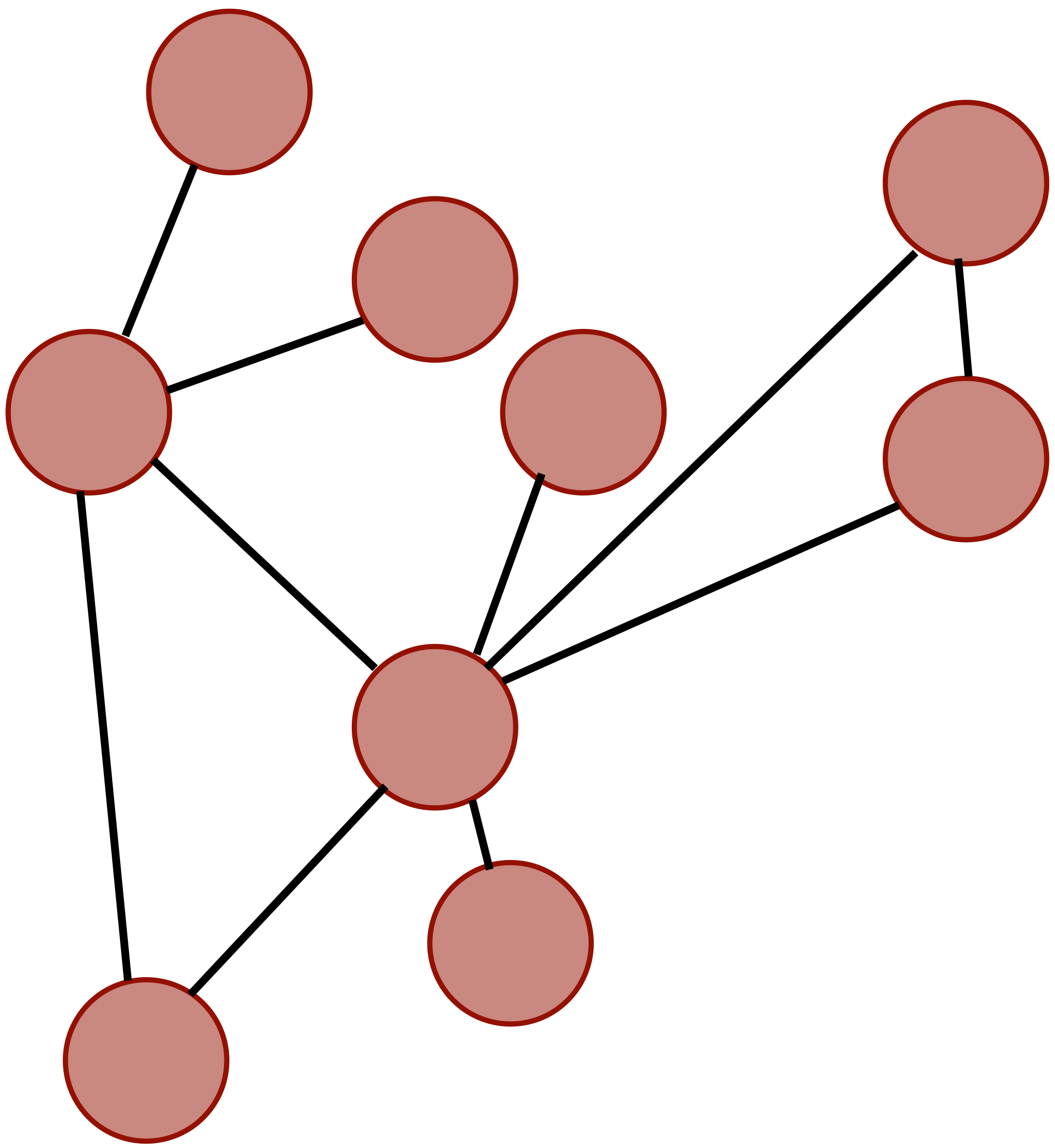
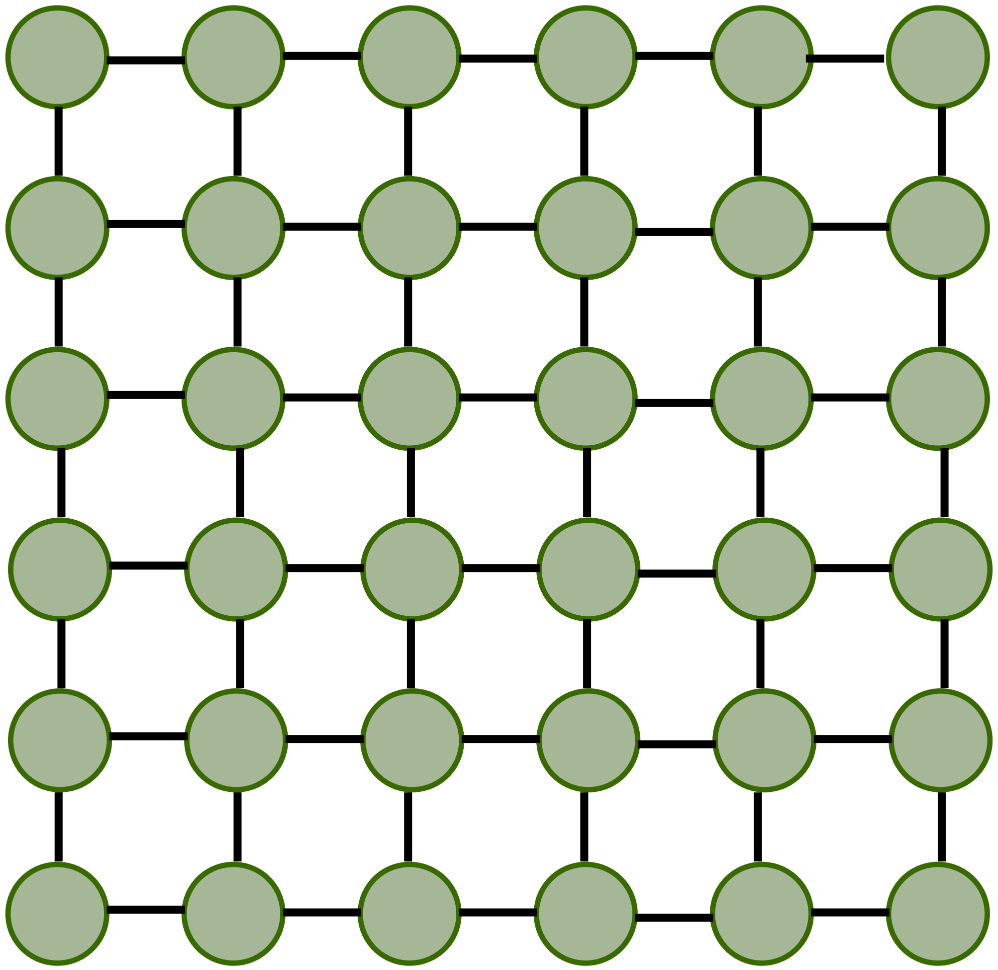
- is a framework for parallel graph processing.
  (But it is not limited to graphs.)
- is inspired by BSP.
  With functional reduction/aggregation mechanisms.
- avoids an inversion of control
  of other BSP-inspired graph-processing frameworks.
- is implemented in Scala,
  and there is a preliminary experimental evaluation.

Menthor's

Model of Computation.

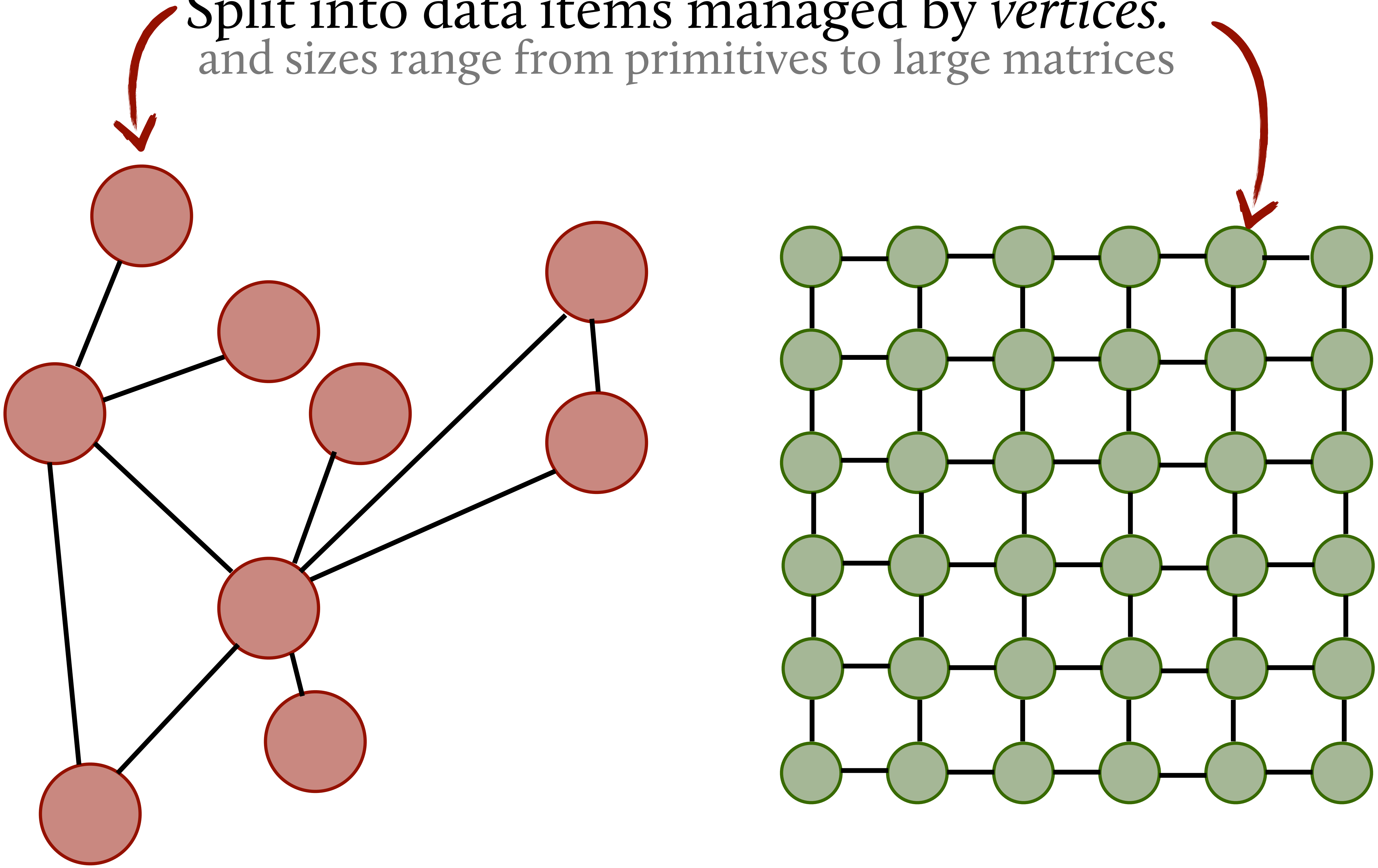
Data.





Data.

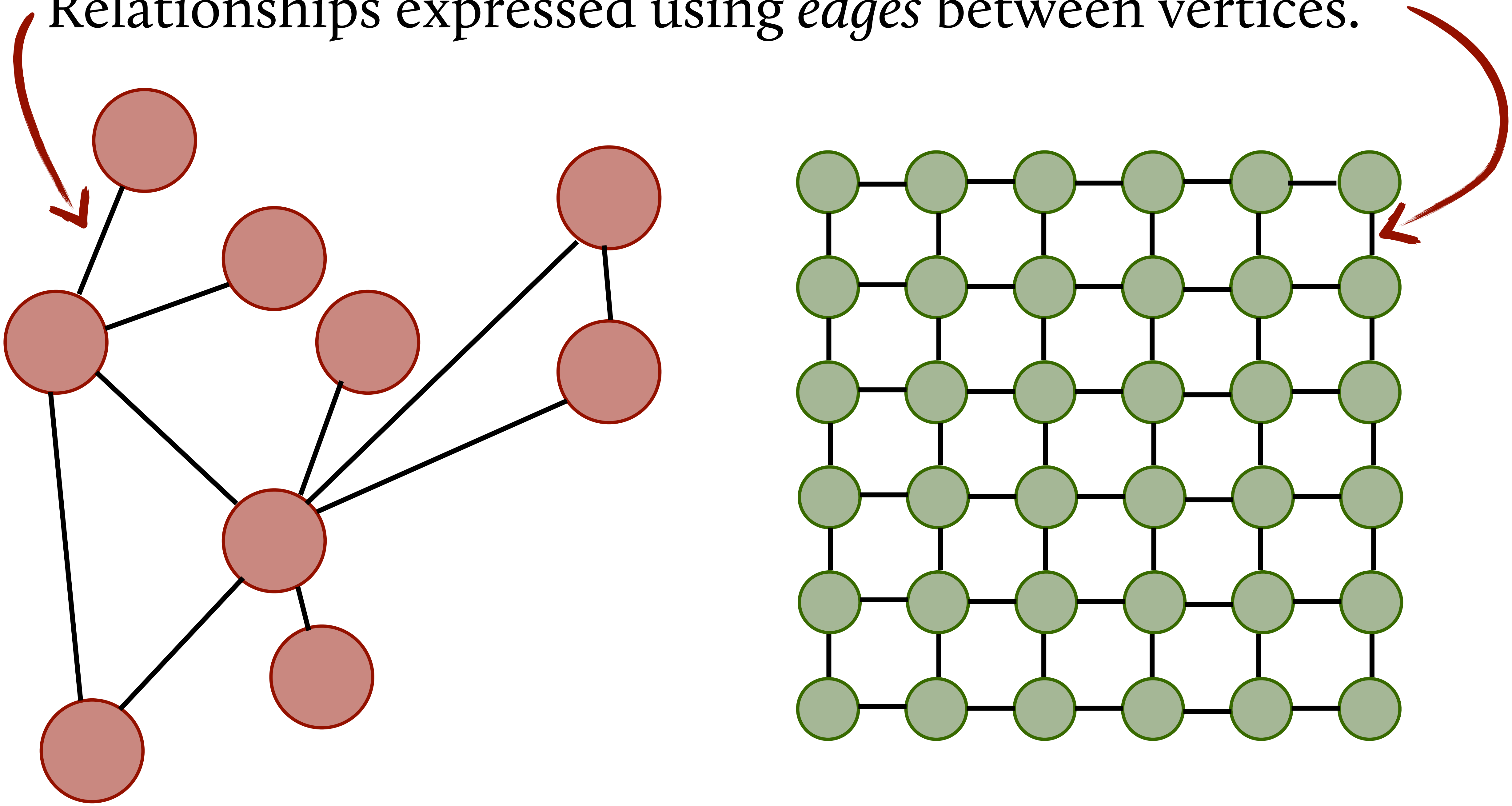
Split into data items managed by *vertices.*
and sizes range from primitives to large matrices



Data.

Split into data items managed by *vertices.*

Relationships expressed using *edges* between vertices.



Algorithms.

Algorithms.

* Data items stored inside of vertices *iterative*ly updated.

Algorithms.

- Data items stored inside of vertices *iteratively* updated.
- Iterations happen as **SYNCHRONIZED SUPERSTEPS.**

(inspired by the BSP model)

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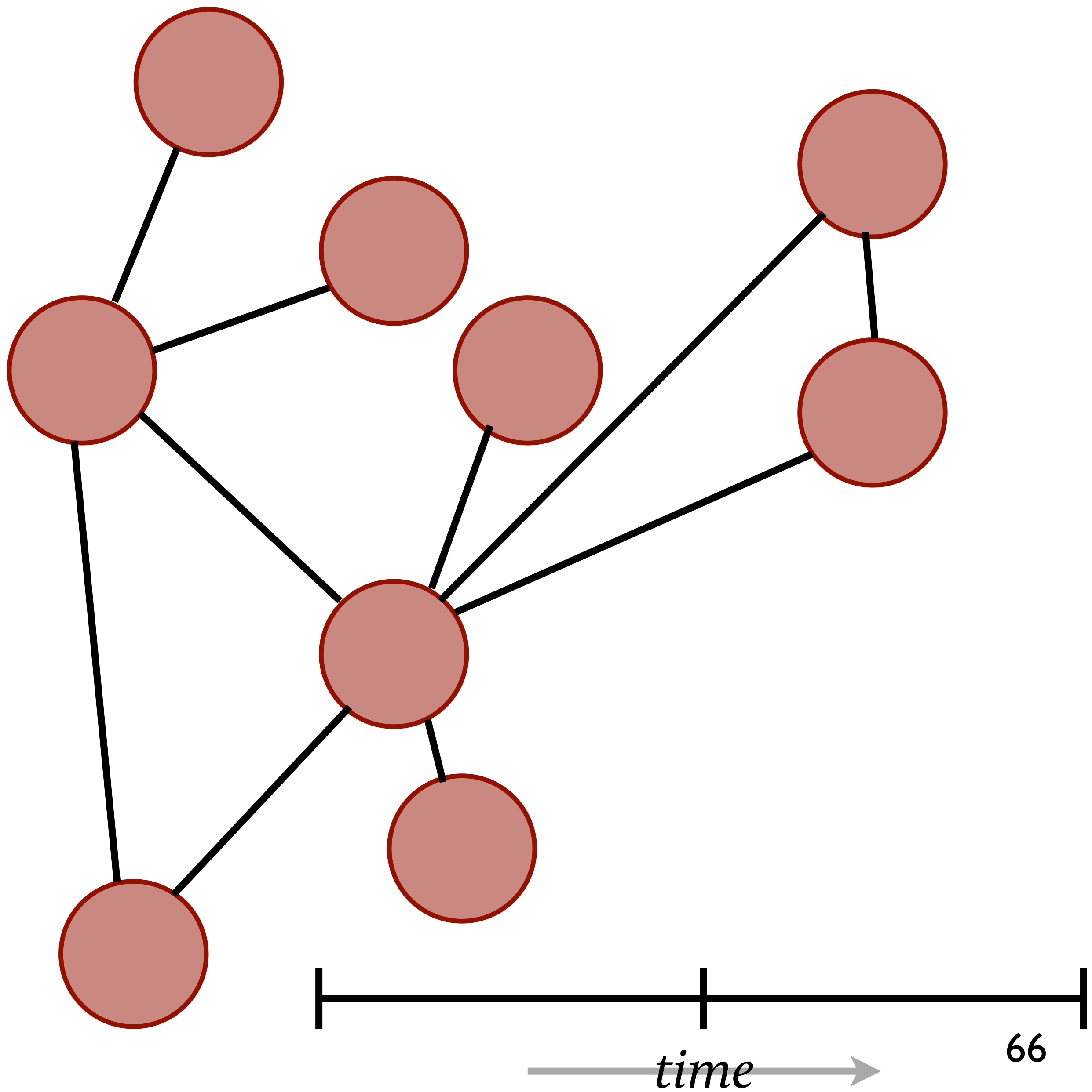

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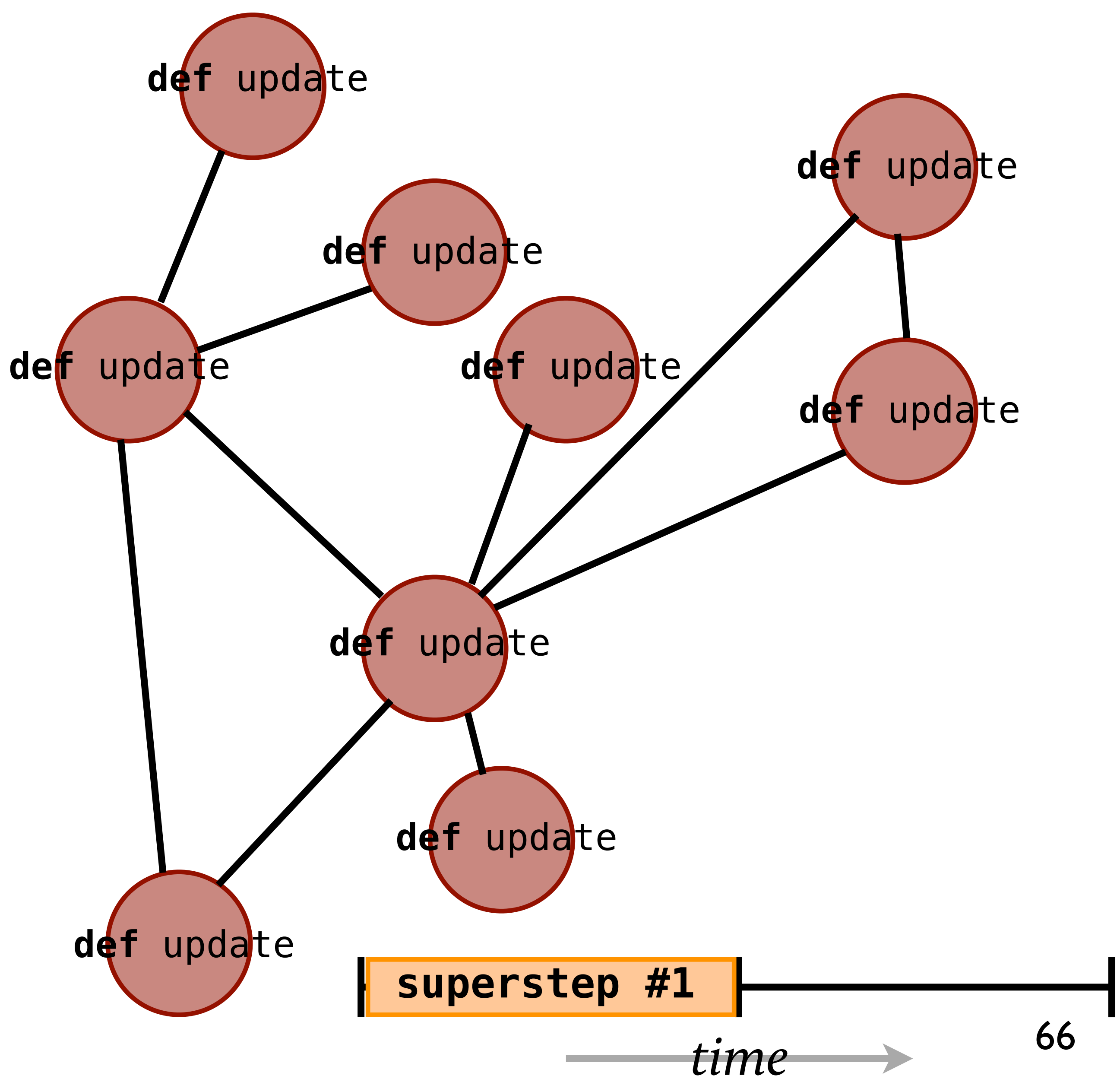

I. update each vertex in *parallel.*

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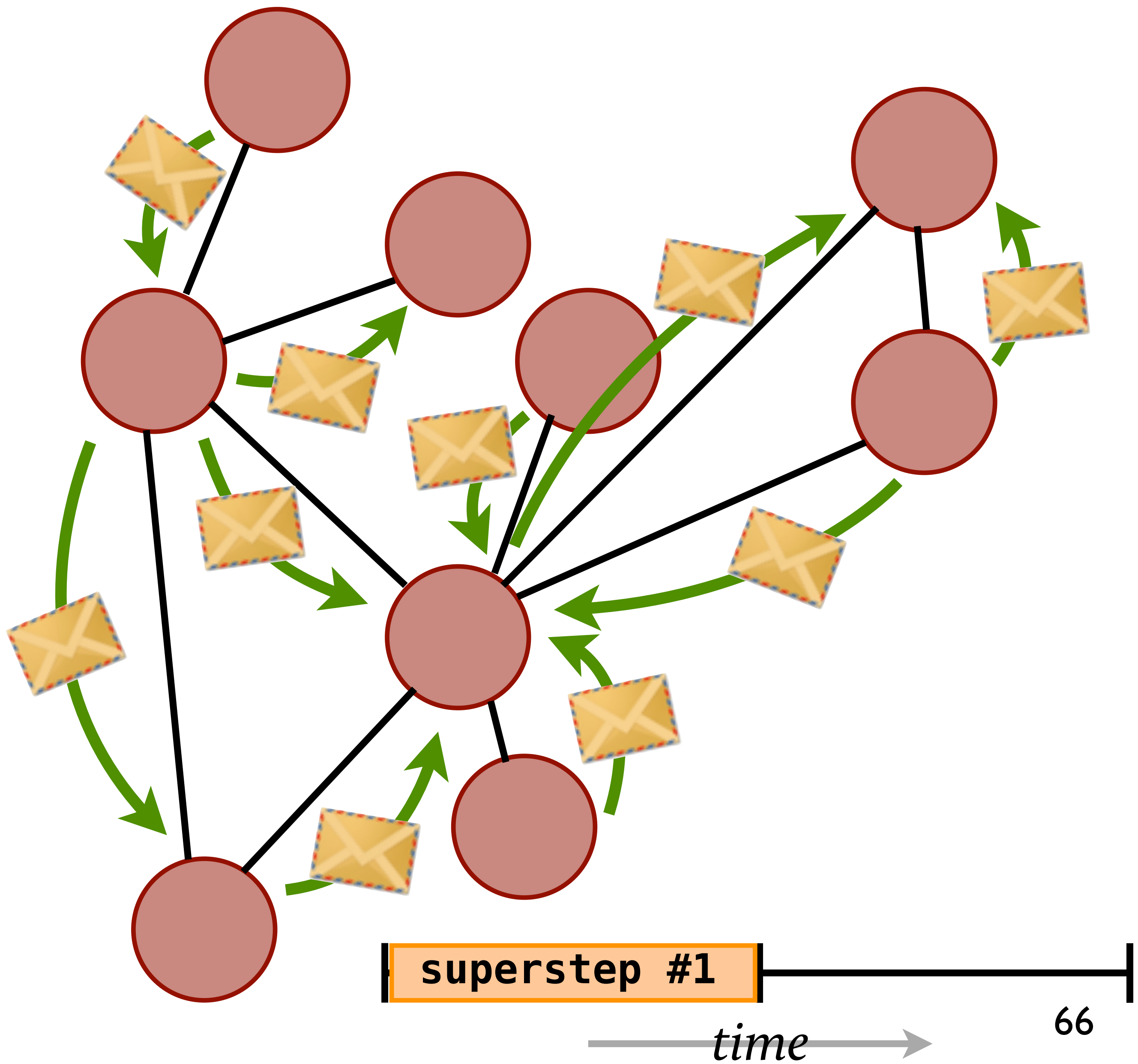

1. update each vertex in *parallel.*
2. `update` produces *outgoing* messages to other vertices

Algorithms.

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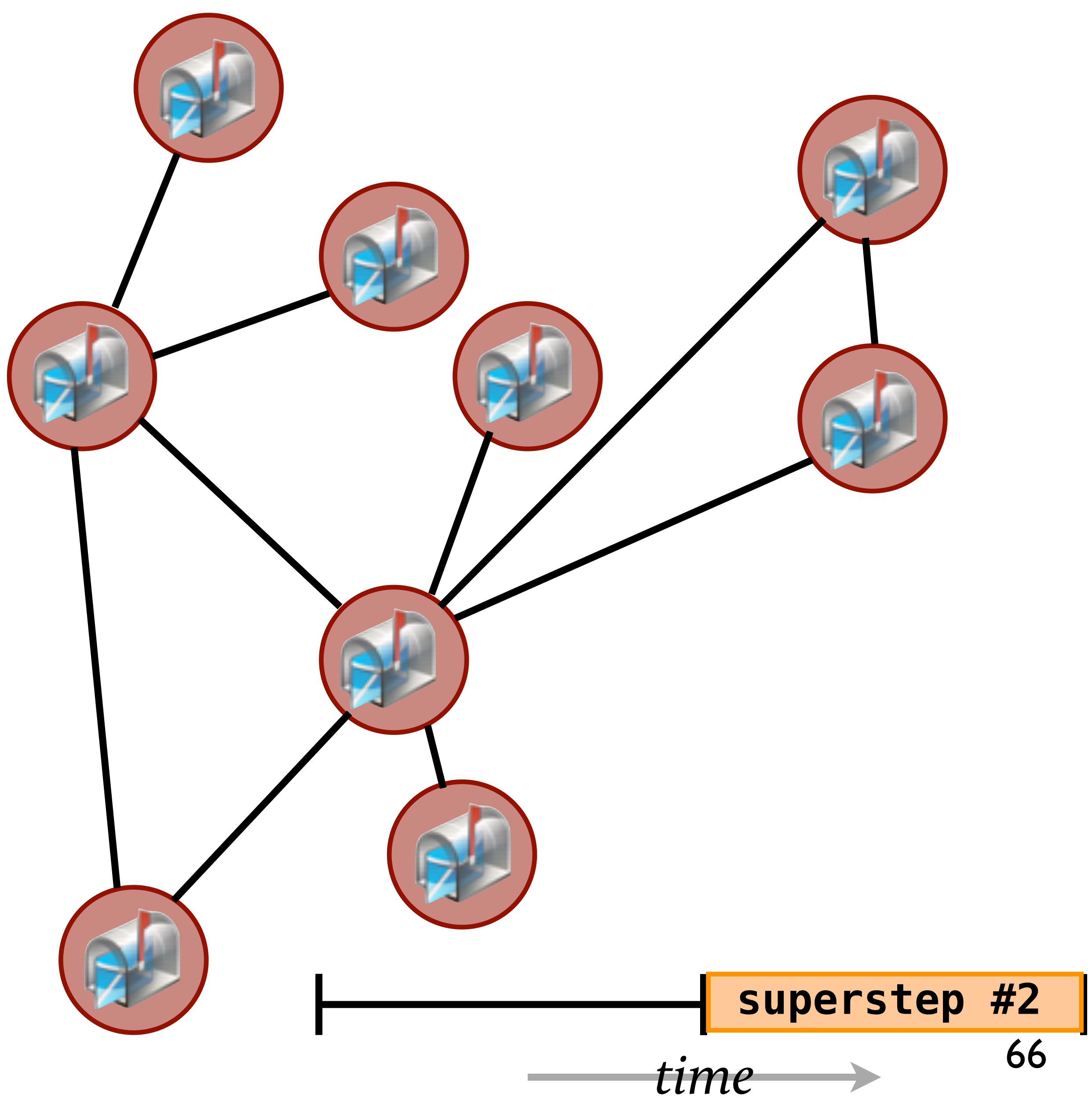

1. update each vertex in *parallel.*
2. `update` produces *outgoing* messages to other vertices
3. incoming messages available at the beginning of the next **SUPERSTEP.**

Substeps. (and Messages)

SUBSTEPS are computations that,

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2. return a list of messages:

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case class Message[Data](source: Vertex[Data],
  dest: Vertex[Data], value: Data)
```

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EXAMPLES...

```
{
  value = ...
  List()
}
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EXAMPLES...

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  value = ...
  List()
}
```

```
{
  ...
  for (nb <- neighbors)
    yield Message(this, nb, value)
}
```

Substeps. (and Messages)

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2. return a list of messages:

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```

EXAMPLES...

```
{
```

```
{
  yield Message(this, nb, value)
}
```

Each is *implicitly* converted to a `Substep[Data]`

Some Examples...

PageRank.

```
class PageRankVertex extends Vertex[Double](0.0d) {
  def update() = {
    var sum = incoming.foldLeft(0)(_ + _.value)
    value = (0.15 / numVertices) + 0.85 * sum

    if (superstep < 30) {
      for (nb <- neighbors) yield
        Message(this, nb, value / neighbors.size)
    } else
      List()
  }
}
```

Another Example.

```
class PhasedVertex extends Vertex[MyData] {
  var phase = 1

  def update() = {
    if (phase == 1) {
      ...
      if (condition)
        phase = 2
    } else if (phase == 2) {
      ...
    }
  }
}
```

Another Example.

```
class PhasedVertex extends Vertex[MyData] {
  var phase = 1
      if (condition)
        phase = 2
    } else if (phase == 2) {
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    }
  }
}
```

INVERSION OF CONTROL!!

Thus, manual stack management...

Inverting the Inversion.

- Use high-level combinators to build expressions of type `Substep[Data]`

```
class PhasedVertex extends Vertex[MyData] {

  def update() = {
    thenUntil(condition) {
      ...
    } then {
      ...
    }
  }
}
```

Inverting the Inversion.

- Use high-level combinators to build expressions of type `Substep[Data]`

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Inverting the Inversion.

- Use high-level combinators to build expressions of type `Substep[Data]`
- Thus avoiding manual stack management.

```
class PhasedVertex extends Vertex[MyData] {

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    }
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```

Reduction Combinators: `crunch` steps.

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- Reduction operations important.
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- Reduction operations important.
  - Replacement for shared data.
  - Global decisions.
- Provided as just another kind of `Substep[Data]`

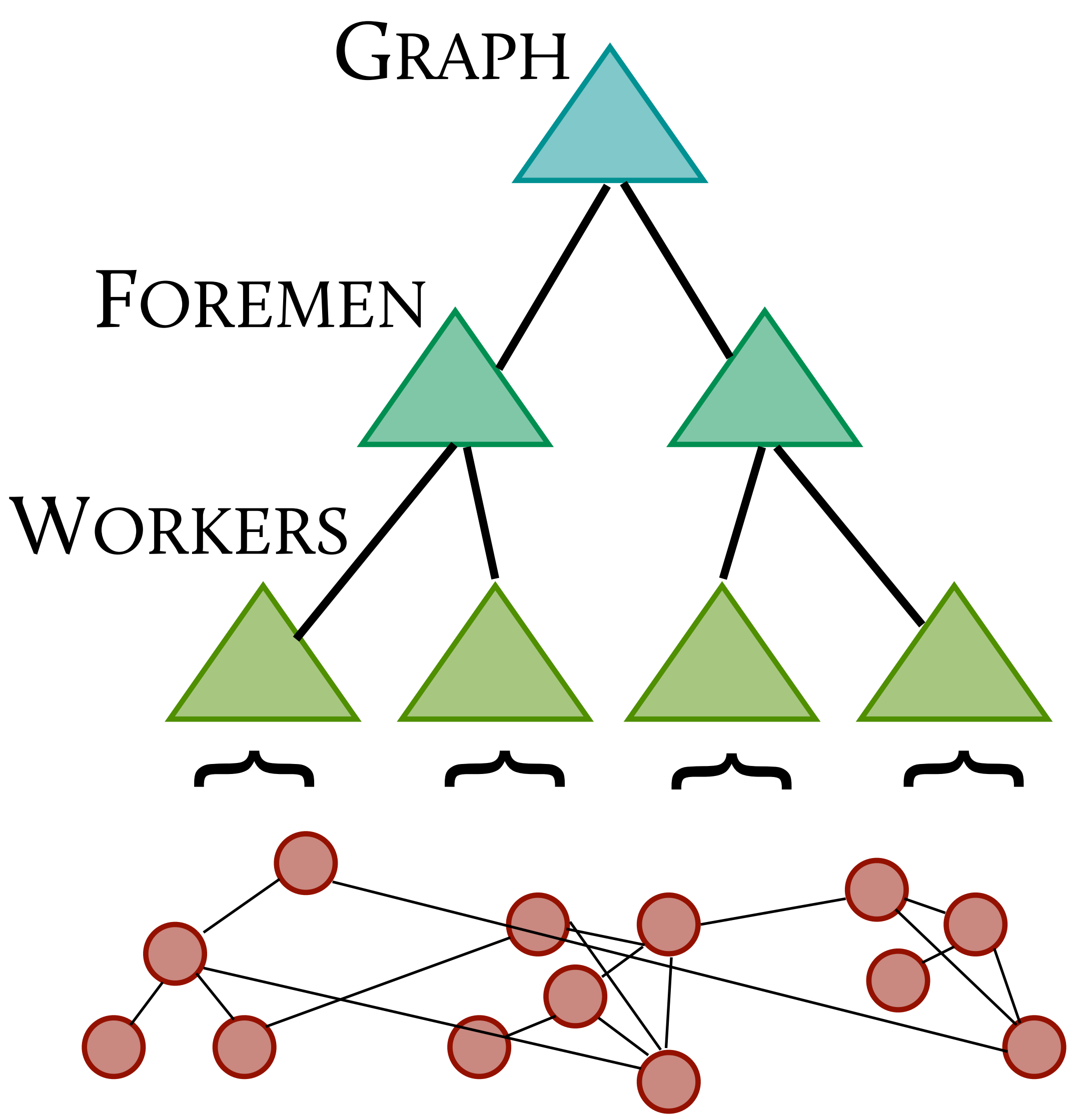
Reduction Combinators: crunch steps.

```
def update() = {
  then {
    value = ...
  } crunch ((v1: Double, v2: Double) => v1 + v2) then {
    incoming match { case List(reduced) =>
      ...
    }
  }
  ...
}
```

Menthor's
Implementation

Actors.

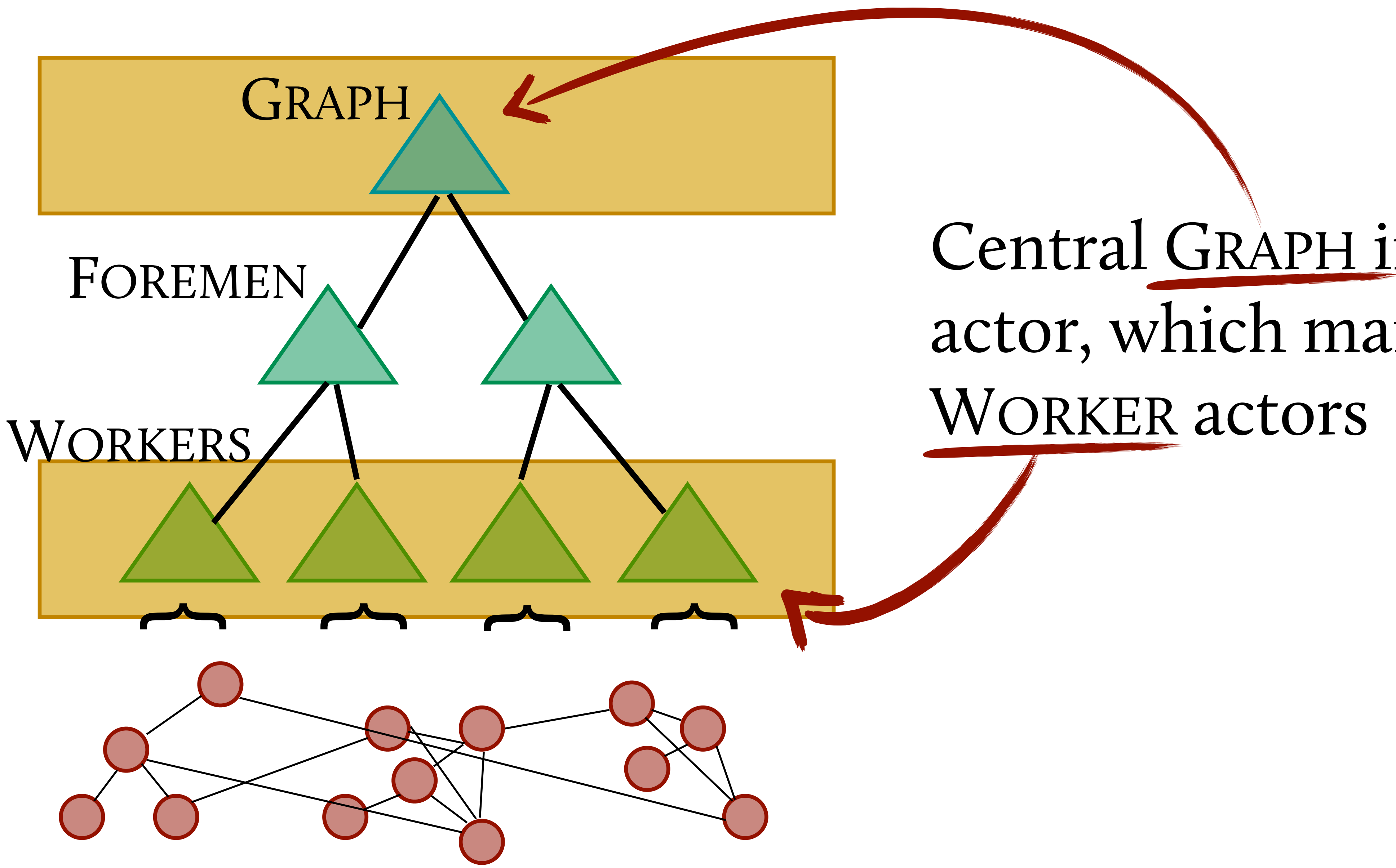
Implementation based upon Actors.



Central GRAPH instance is an actor, which manages a set of WORKER actors

Actors.

Implementation based upon Actors.



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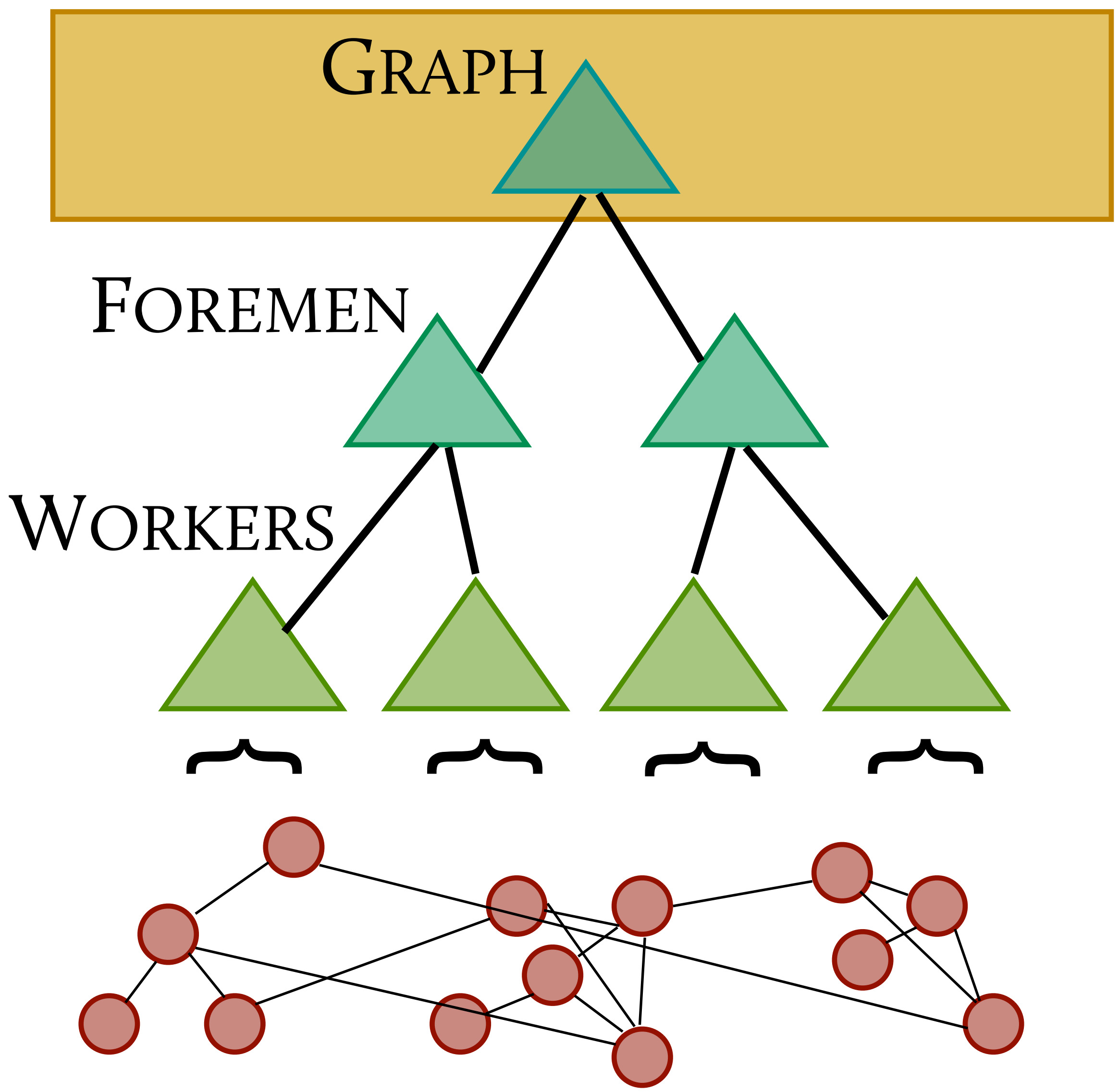
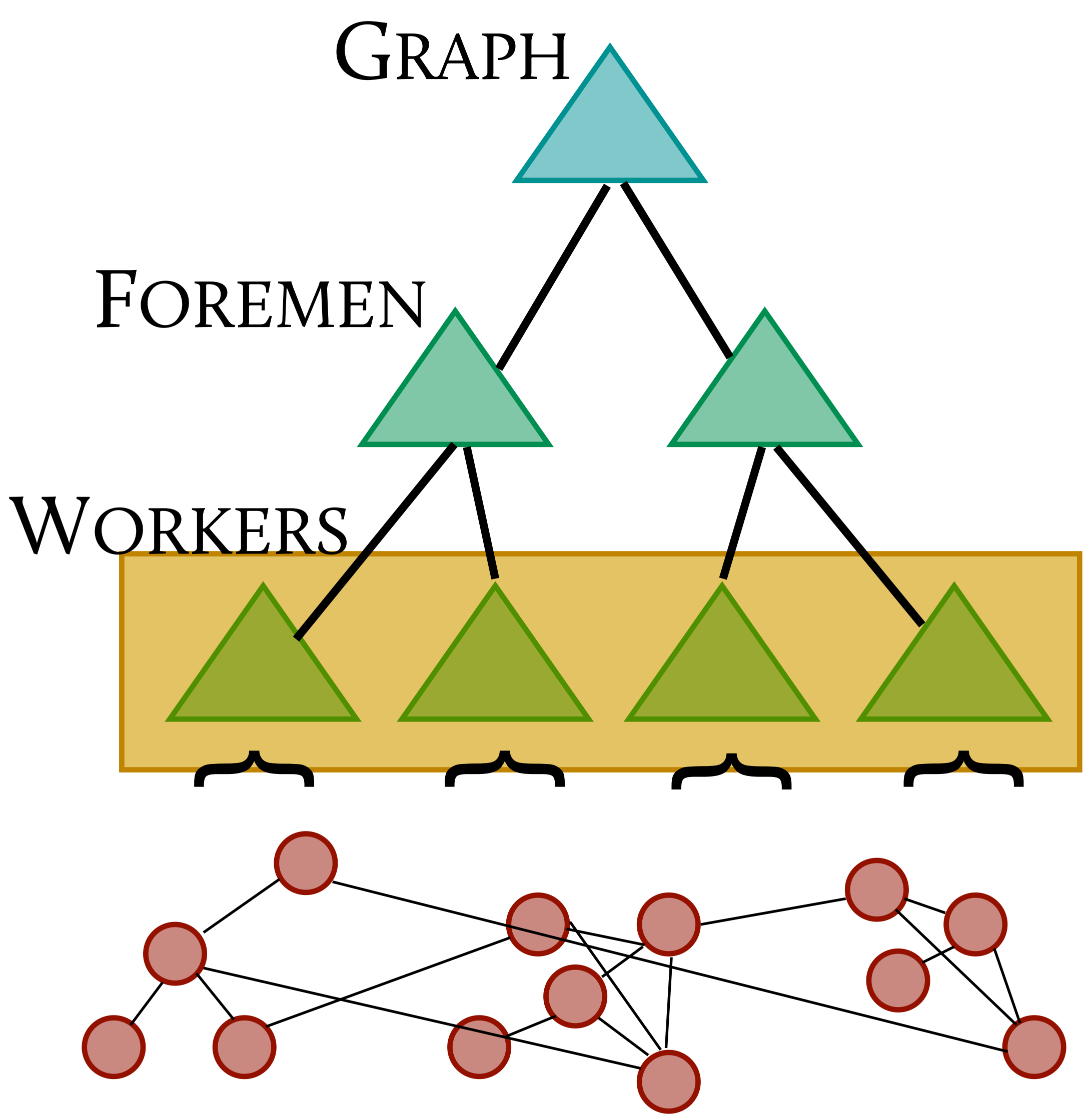


Central GRAPH instance is an actor, which manages a set of WORKER actors

GRAPH synchronizes workers using supersteps.

Actors.

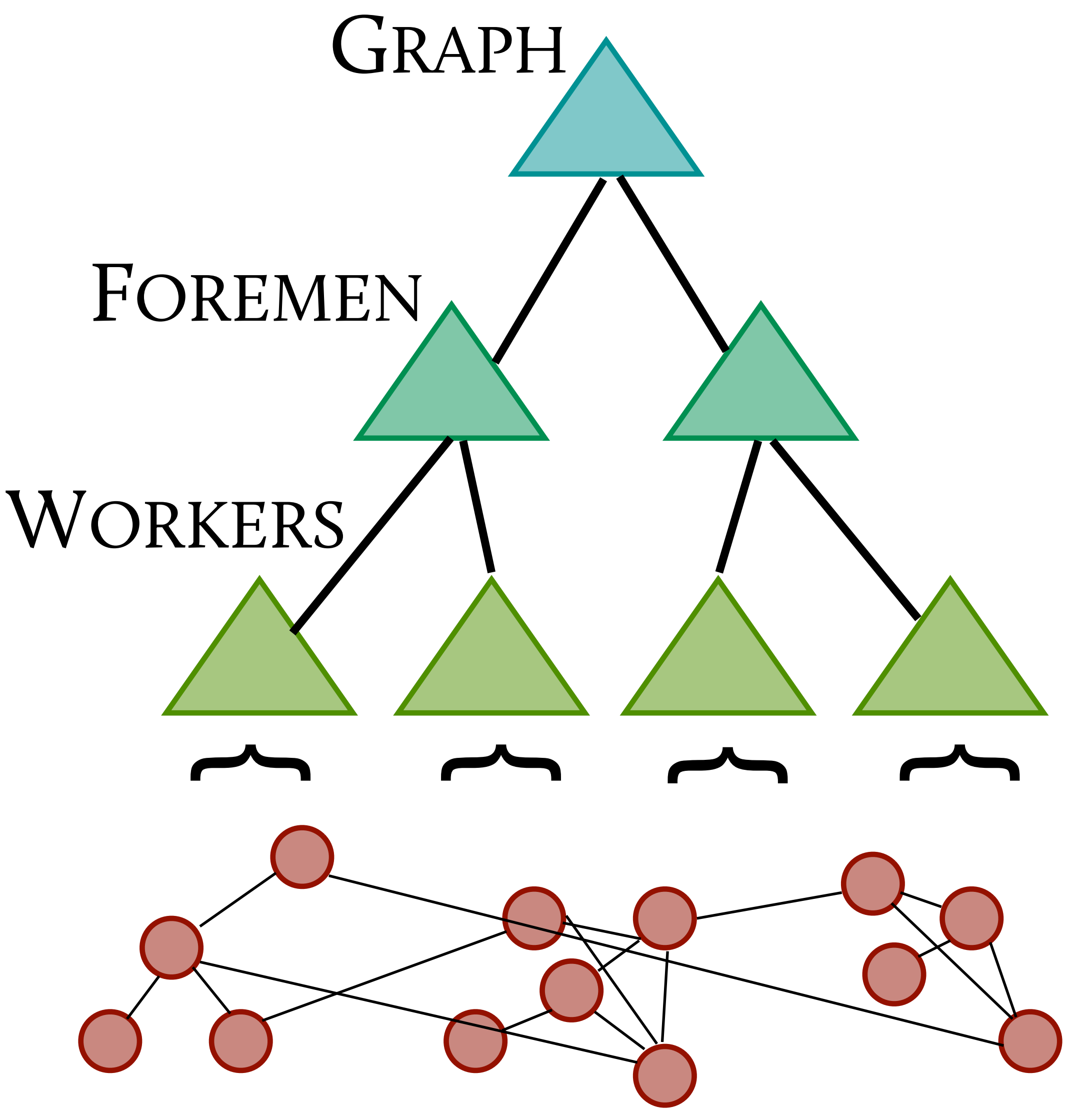
Implementation based upon Actors.



Each WORKER manages a partition of the graph's vertices,

- Deliver incoming messages that were sent in the previous superstep;
- Select and execute `update` step on each vertex in its partition;
- Forward outgoing messages generated by its vertices in the current superstep.

Implementing Reduction.



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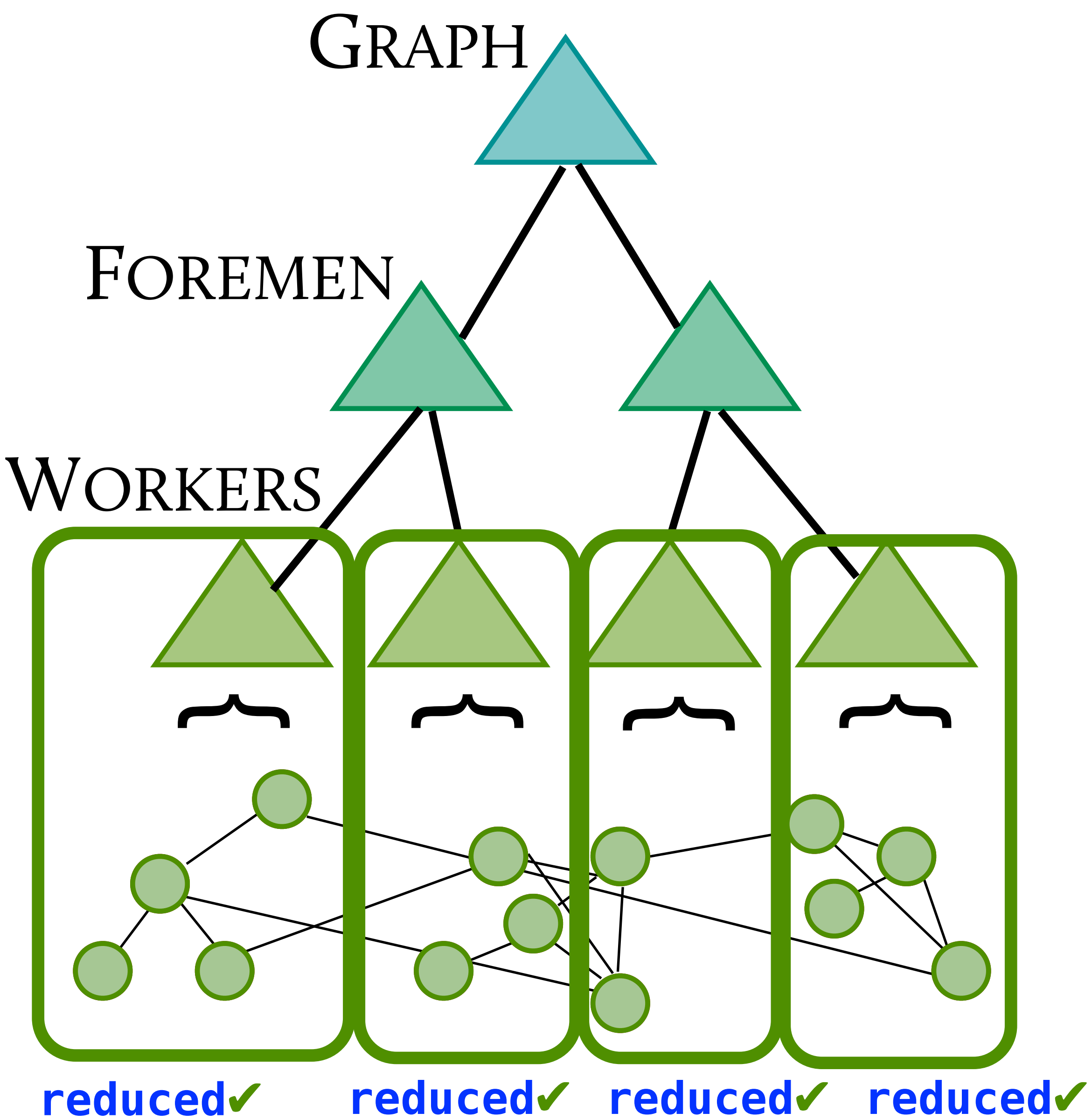

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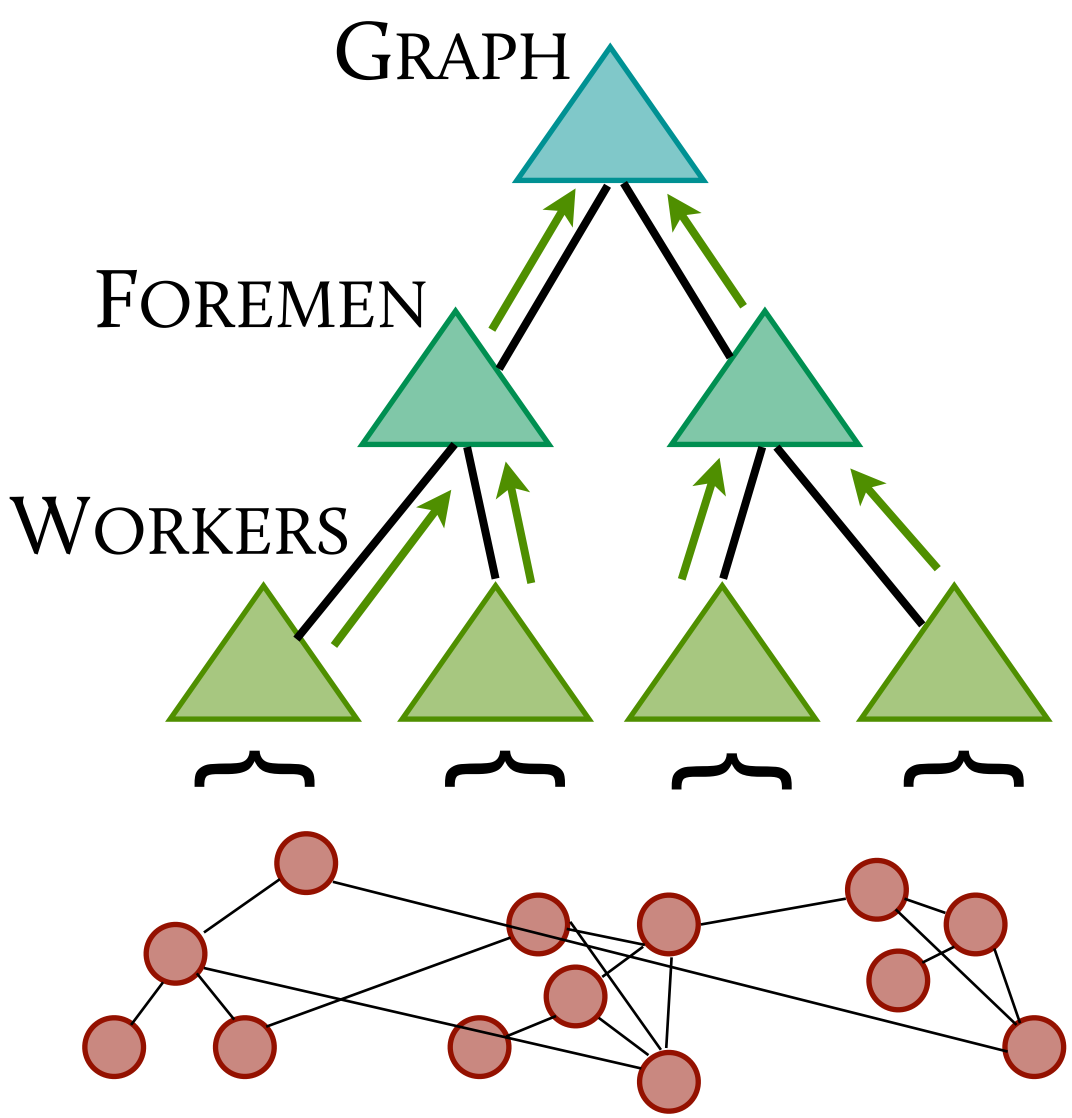

1. WORKER reduces the values of all vertices in its partition.
2. The result and the closure that was used to compute it is sent to the GRAPH actor, which computes the final reduced value.

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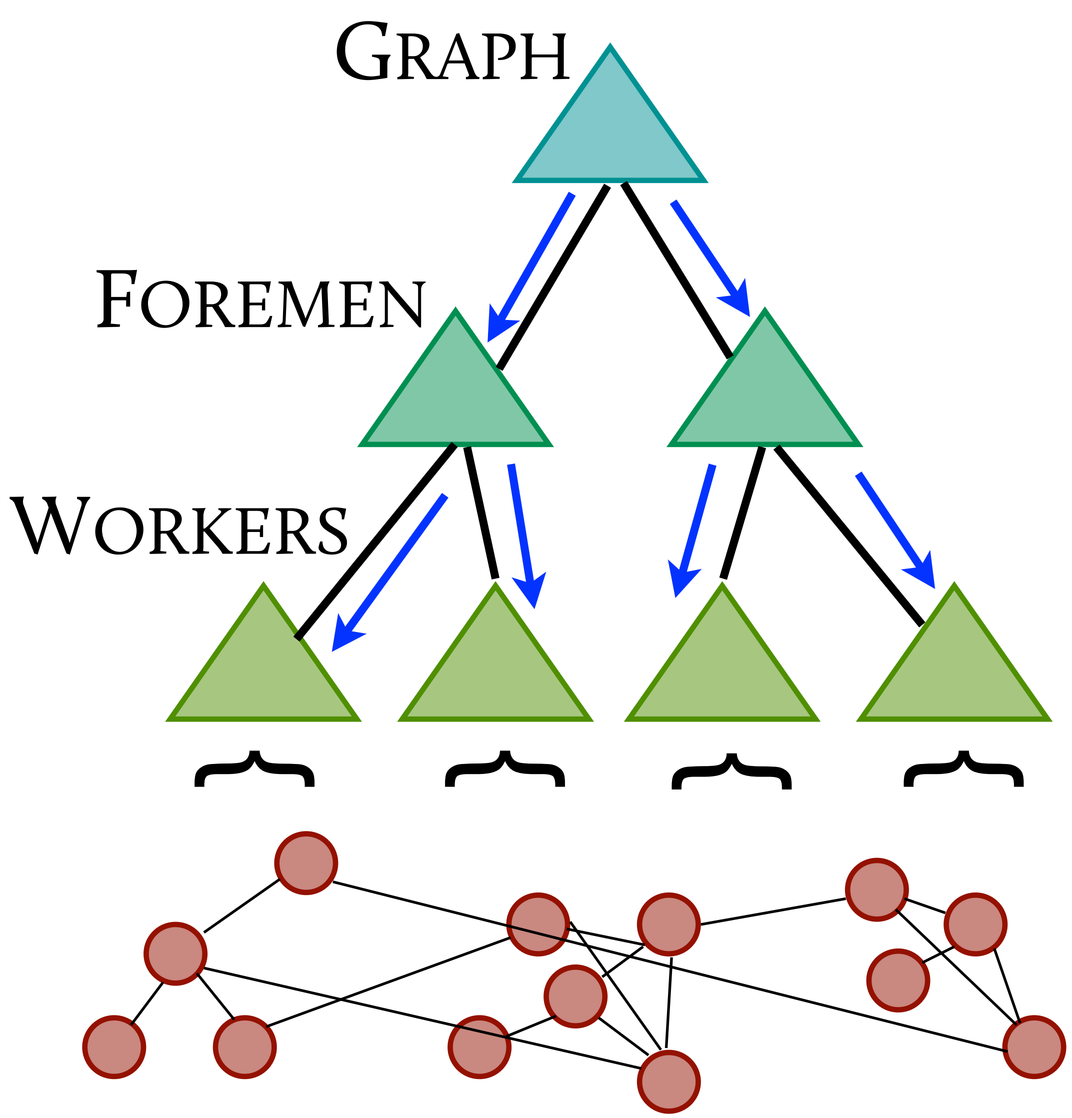

1. WORKER reduces the values of all vertices in its partition.
2. The result and the closure that was used to compute it is sent to the GRAPH actor, which computes the final reduced value.
3. The final result is passed to all WORKERS which make it available to their vertices as incoming messages (at the beginning of the next superstep)

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  - No support for heterogeneous hardware platforms.

Related Work.

Google's Pregel
GraphLab
Signal/Collect

Main Inspiration
Graphs/BSP

Control
Inverted

Async Execution
Non-determinism

OptiML

Aggressive
Optimizations

Requires Staging

Debugging
Not optimal, yet

Spark

Designed for Iteration

Cluster support

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(Many more discussed in a workshop paper.)

Conclusions

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- Higher-order functions useful for reductions, in an imperative model.
- Explicit parallelism feasible if computational model simple (cf. MapReduce)
- The puzzle pieces are there to make analyzing bigger data easier.

http://lamp.epfl.ch/~phaller/menthor/