CSYE 7215: Parallel & Multithreaded Programming

Textbook:

Brian Goetz et al. "Java Concurrency in Practice."

Lecture 14: Akka: Actors, Java Programming

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Lecture 20
The Actor Framework

Recall

- Concurrency

  Several operations may be in progress at the same time
- Parallelism

  Several operations may be executing simultaneously
- “Distributed-ness”

  Several machines may be working at the same time for the same application

So Far We Have Concentrated On:

- Concurrency in Java
  - Threads
  - Locks
  - Etc.
- Parallelism in Java
  - Performance tuning
  - Fork/Join
  - Etc.
- Focus has been on threaded applications running inside a *single process* (= single instance of JVM)

Recall Threads vs. Processes

- Threads
  - Independent control flows, stacks
  - Shared heap
- Processes
  - Independent flows, stacks
  - *Independent heaps*

Distributed Computing

- Distributed systems have multiple processes
  - No shared memory
  - So, no data races!
  - But, need explicit IPC (Inter-Process Communication) mechanisms
- In case of distributed computing, network communication is typically used

Some Distributed System Terminology

- Host

  Computer running in a distributed environment
- Port

  Communication channel used by hosts to exchange messages
- Network

  System consisting of hosts, equipment used to connect hosts
- IP address

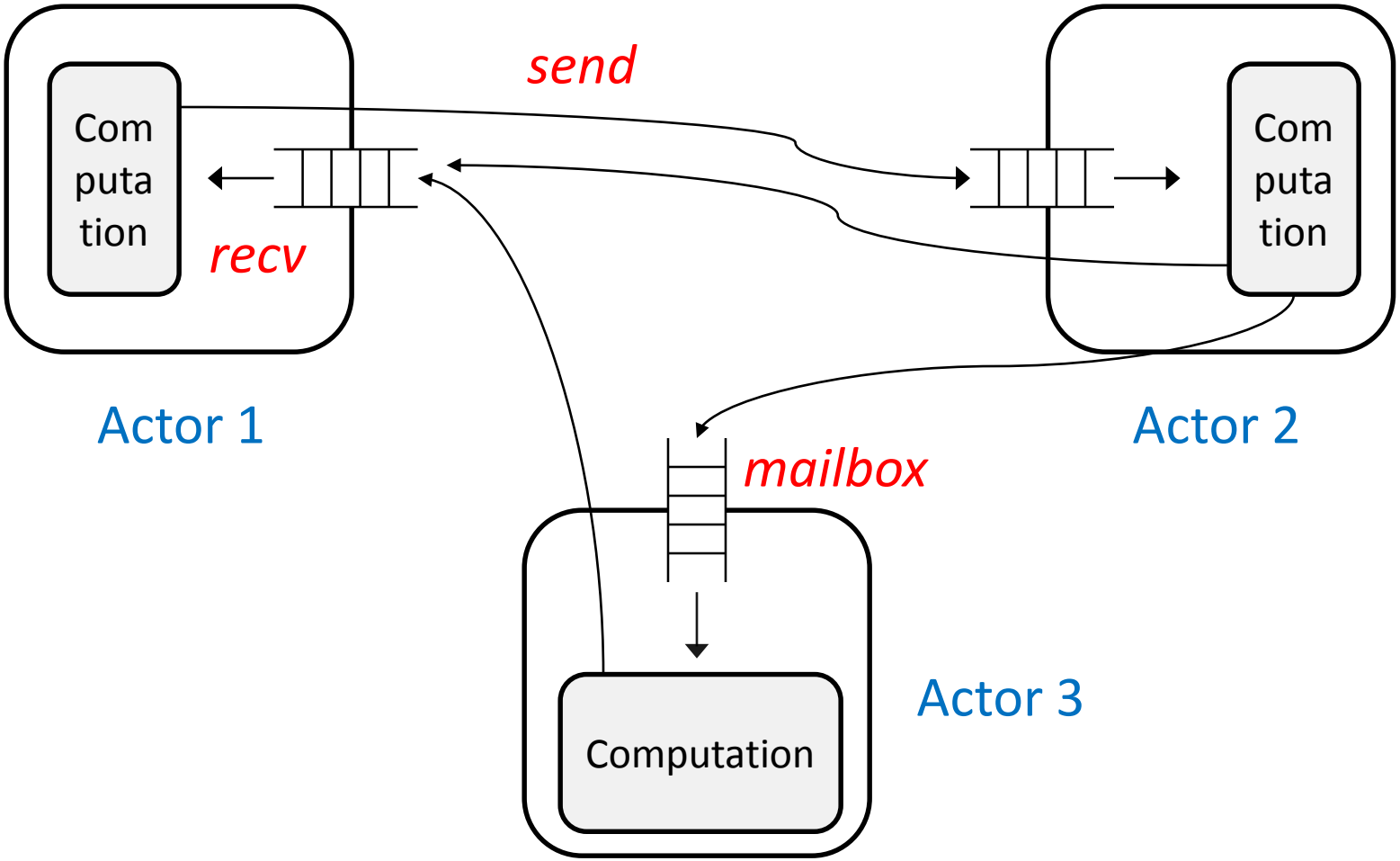
  Internet Protocol address: number assigned to a host connected to the internet so that other hosts may communicate with it
- MAC address

  Media Access Control address: number assigned to a host on a local-area network (LAN) so that other hosts on LAN may communicate with it.

The Actors Model

- A system model supporting a multi-process programming paradigm
  - Model assumes no shared memory
  - No assumptions about distributed / non-distributed
- Systems consist of multiple *actors*
  - An actor is an independent sequential ("= single-threaded") computation
  - Each actor has a "mailbox" from which it extracts messages that it then processes
  - Actors communicate by sending each other messages

An Actor System



General Actor Behavior

- Actors wait until there is a message in their mailbox
- They remove message from mailbox and process it
- Processing may involve sending of messages to other actors
- When processing is complete, they retrieve next message from mailbox and repeat

Message Passing

- Recall: actors communicate via message passing
- Different actor frameworks provide different guarantees about message delivery.
- Here are the ones we will use (conform to akka)
  - *Asynchronous*: senders do not know when messages are received
  - *At-most-once delivery*: every message sent is eventually received at most once (could be lost, but not duplicated)
  - *Locally FIFO*: messages sent by one actor directly to another are received in the order sent, lost messages excepted

Actor History

- Originally proposed by Carl Hewitt in 1970s as basic model of distributed computing
- Theory studied in 1980s / early 1990s by researchers
- Mid-1990s: first serious language implementation (*Erlang*, Ericsson)
  - Used in implementation of telephone switches
  - Key features: light-weight (more like tasks than threads), high degree of concurrency, resiliency in face of failure
- Mid-2000s: Scala language targeting JVM includes actors
- Late 2000s: akka open-source actor library for Scala, Java

akka Java Library

- Provides implementation of actor model for Java
- Key features
  - Basic actor framework
    - Special actor objects
    - Communication via message-passing methods
  - Lightweight
    - Actors resemble tasks more than threads
    - 300 bytes of overhead per actor
  - Location transparency
    - Actors programmed identically, whether local or remote host
    - Differences captured in configuration file
  - Fault tolerance via hierarchy
    - Actors arranged in parent/child hierarchy
    - Parents handle failures of children

Installing `akka` for Java

- akka libraries need to be downloaded, installed on Java build path
- Eclipse-based directions
  1. Download latest (2.4.2) Standalone Distribution of akka for Java from http://akka.io/downloads/
  2. Extract all files from the downloaded file akka_2.11-2.4.2.zip. This creates a directory akka-2.4.2
  3. For each project in Eclipse using akka, you need to add following from this directory to build path:
     - lib/scala-library-2.11.7.jar
     - lib/akka/akka-actor_2.11-2.4.2.jar
     - lib/akka/config-1.3.0.jar
  4. To add a file to project build path in Eclipse:
     - Right-click on project, then select Build Path → Add External Archives
     - Use resulting file dialog to locate above .jar files and add.

akka Documentation

- General: http://doc.akka.io/
  - There are links for the full documentation of Java version of akka
  - The “snapshot” documentation is also useful
- Javadoc: http://doc.akka.io/japi/akka/snapshot/

  This summarizes the classes and methods in the akka distribution

Basics of akka Java

- akka actors live in an *actor system*
  - Actor system provides actor execution (think "threads"), message-passing infrastructure
  - To create actors, you must first create an actor system
  - The relevant Java class: `ActorSystem`
- So, first line of Hello World `main()` method is:

```
ActorSystem actorSystem =
ActorSystem.create("Message_Printer");
```

  - "Message_Printer" is name of actor system (required)
  - akka actor system names must not have spaces or punctuation other than - or _ !

Creating Actors in akka Java (1/4)

- Actors are objects (of course!)
- Objects are typically in a subclass of the akka library class `UntypedActor`
- **Step 1 in creating actors:** define class of actors
  - In Hello World example, the class of actors is `MessagePrinterActor`
  - Here is the relevant import / class declaration

```
import akka.actor.UntypedActor;
…
public class MessagePrinterActor extends
UntypedActor …
```

Creating Actors in akka Java (2/4)

- **Step 2 in creating actors:** finish implementation of actor class
  - akka `UntypedActor` needs instance method
    `public void onReceive(Object msg)`
  - This method describes how a message object should be processed
- Hello World example

```
@Override
public void onReceive(Object msg) throws Exception {
    if (msg instanceof String) {
        System.out.printf("Message is: %s", msg);
    }
}
```

- Observations
  - Messages are objects!
  - Processing a message requires determining which class to which it belongs
  - More on messages later

Creating Actors in akka Java (3/4)

- In akka, actors can only be created in the context of an `ActorSystem`
  - Relevant instance method in `ActorSystem` is
    `ActorRef actorOf(Props p, String name);` // method of superclass ActorRefFactory
  - Return type `ActorRef` is class of "references to actors" (more later on this notion)
  - `String` parameter is actor name (no spaces or non-alphanumeric characters other than -,_!)
  - "`Props`"?
- In akka, actors have various configuration information
  - Type of mailbox data structure
  - How messages actually get delivered to mailbox ("dispatching")
  - Etc.
- This information is encapsulated in a `Props` object for a given class of actors
- To create actors in a class, a `Props` object for the class must be constructed
- **Step 3 in creating actors:** create `Props` object for actors class.
  - This is done in the Hello World `main()` using a factory method in akka `Props` class
  - This builds `Props` object with reasonable defaults (unbounded queues for mailboxes, etc.)
  - Relevant Hello World code:
    ```
    Props mpProps = Props.create(MessagePrinterActor.class);
    ```

Creating Actors in akka Java (4/4)

- **Step 4 in creating actors:** call `actorOf()` method in relevant `ActorSystem`
- In Hello World example:

```
ActorRef mpNode =
actorSystem.actorOf(mpProps,
"MP_Node");
```

  - This creates and launches a single actor in `actorSystem`
  - Actor is now ready to receive, process messages

Communicating with Actors

- Actors compute by processing messages
- To send a message to an actor, use `ActorRef` instance method `tell(Object msg, ActorRef sender)`
  - `tell()` takes message (payload) and sender as arguments
    - sender parameter allows return communication
    - If no return communication desired, specify null for sender field
  - `tell()` is often said to implement "fire and forget" communication
    - Method call returns as soon as message handed off to infrastructure
    - No waiting to see if recipient actually receives it
- In Hello World example:

```
mpNode.tell("Hello World", null);
```

Shutting Down an ActorSystem

- `ActorSystem` objects use worker threads internally to execute actors
- These threads must be killed off before an actor-based application can terminate
- This is down by shutting down the `ActorSystem` using instance method `terminate()`
- From Hello World example:

```
actorSystem.terminate();
```

Moving Information from ActorSystem to Java

- The `tell()` method permits messages to be sent to actors
  - In Hello World, this was how information was passed from "rest of Java" into actor
  - Actors can also send messages to each other inside an actor system
- How can actors communicate with outside world?

  Outside world (i.e. "rest of Java") is not an actor, so `tell()` cannot be used!
- Solution: `Patterns.ask()`

Patterns.ask()

- `Patterns`: a class in akka supporting the creation of different communication patterns
- `ask()` is a static method in Patterns that supports "call-response" communication
  - Header

    ```
    public static scala.concurrent.Future<java.lang.Object>
    ask(ActorRef actor, Object msg, long timeoutMillis)
    ```
  - Behavior
    - `ask(actor, msg, timeout)` sends `msg` to `actor`, just like `tell()`
    - It returns a (Scala, not Java!) `Future` holding return message from actor
    - If return message not available by `timeout`, `AskTimeoutException` thrown
    - To get return message from Future `f`, need to do Scala equivalent of `f.get()`:

      ```
      Await.result(f, timeout.duration())
      ```
      - `Await` is Scala class of static blocking methods
      - `timeout` is object in Scala Timeout class; `duration()` is instance method for this class
- `ask()` can be used between actors, or between a non-actor and an actor

`ask()` Example: ToAndFrom

- Goal: have simple "call-response" involving `main()`, actor
  - `main()` sends message to actor
  - Actor prints message, sends response
  - `main()` prints response
- Key classes
  - `MessageAcknowledgerActor`
  - `ToAndFrom` (has `main()`)

MessageAcknowledgerActor.java

```
public class MessageAcknowledgerActor extends UntypedActor {
  …
  public void onReceive(Object msg) throws Exception {
    if (msg instanceof String) {
      ActorRef sender = getSender();
      String payload = (String)msg;
      System.out.printf("Message is:  %s%n", payload);
      sender.tell(payload + " message received", sender);
    }
  }
}
```

`getSender()`?

- Instance method in `ActorRef`
- Returns `ActorRef` for sender of current message being processed in `onReceive()`
  - The sender is the second parameter of the tell() method call corresponding to the current message
  - A more accurate characterization: rather than thinking of this as message sender (it may not be!) think of it as "Reply-To", as in e-mail

Actor Communication

- Actor(Ref)s communicate by sending each other messages
- To send a message to recipient `r`, a sender `s` needs to invoke `r.tell()`
- This means the sender needs to know `r`!
- Different ways to do this
  - Send a message to `s` containing `r` as payload
  - Send message to `s` with `r` as sender
  - In constructor associated with `s`, include `r` as parameter

PingPong Example

- Goal: have actor system containing two actors that send message back and forth
  - One prints “Ping … “ when it gets message
  - Other prints “Pong”
- They stop after a set number of exchanges

PongActor.java

```
public class PongActor extends UntypedActor {

  @Override
  public void onReceive(Object msg) throws Exception {
    if (msg instanceof String) {
      String payload = (String)msg;
      if (payload.equals("stop")) { // Game over
        System.out.println(getSelf().path().name() +  ": OK");
      }
      else if (payload.equals("start")) {
        System.out.println(getSelf().path().name() +  ": Let's do it.");
        getSender().tell("go", getSelf());
      }
      else { // Next stroke
        System.out.println("Pong");
        getSender().tell("go", getSelf());
      }
    }
  }
}
```

- `getSelf()` obtains `ActorRef` that `PongActor` is associated with at run time
- `getSelf().path().name()` obtains name assigned to ActorRef at run time

PingActor.java

```
public class PingActor extends UntypedActor {

  private int numHitsLeft;
  private ActorRef partner;

  public PingActor(int numHits) {       // Ping will check numHits, will stop if  == 0
    this.numHitsLeft = numHits;
  }

  @Override
  public void onReceive(Object msg) throws Exception {
    if (msg instanceof ActorRef) {
      partner = (ActorRef)msg;
      System.out.println(getSelf().path().name() +  ": Game on!");
      partner.tell("start", getSelf());
    }
    else if (msg instanceof String) {
    …
    }
  }
}
```

- If `msg` is an `ActorRef`, this is assigned to the `partner` field
- This is how `PingActor` knows to whom to send messages!

PingPong.java

```
public class PingPong {

  public static void main(String[] args) {
    ActorSystem actorSystem = ActorSystem.create("Ping_Pong");
    Props pingProps = Props.create(PingActor.class, 5);
    Props pongProps = Props.create(PongActor.class);
    ActorRef pingNode = actorSystem.actorOf(pingProps, "Ping_Node");
    ActorRef pongNode = actorSystem.actorOf(pongProps, "Pong_Node");
    pingNode.tell(pongNode, null);
    actorSystem.terminate();
  }

}
```

- In `pingProps` definition, the "5" is the argument to the PingActor constructor that will be used
- Note that `main()` is sending `pongNode` to `pingNode` to start system off!

Messages

- Messages are objects
- Valid classes of messages must match `Serializable` interface
  - Serializable objects can be converted into bytes
  - This is needed for actors to communicate over communication networks, which just transmit bytes
- They should also be *immutable* (because Akka cannot enforce immutability, yet)
  - Objects are properly constructed
  - Fields are private, final
  - State never changes

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Lecture 21
akka Java in Detail

Recall akka

- Open-source implementation of actors model
  - Originally developed for Scala language
  - Ported also to Java
- Key concepts
  - `ActorSystem`
  - `UntypedActor`
  - `onReceive()`
  - `tell()`
  - `Patterns.ask()`

Dynamic Actor Creation

- In Java we saw that tasks can create other tasks
- In akka Java, actors can also create other actors!
  - Actor creation so far has been done using calls to `actorOf()` method of `ActorSystem` object
  - It may also be done by calling `actorOf()` method of `ActorContext` object
    - An `ActorContext` object is the environment surrounding an actor
    - To get the `ActorContext` of an `UntypedActor` actor, call `getContext()` instance method

Supervision

- Every actor has exactly one supervising actor
  - When one actor creates another using first actor's context, first actor is *supervisor* of second
    - First actor often also called *parent*
    - Second usually called *child* or *subordinate*
  - What about actors created via ActorSystem actorOf()?
    - Every actor system three top-level actors (called *guardians*) that are started automatically
      - / The root guardian
      - /system The System guardian (child of /)
      - /user The Guardian Actor (child of /)
    - When an object is created using actorOf() in ActorSystem, it is by default made a child of /user
- What supervisors do
  - Delegate tasks to children
  - Take remedial action when children fail
- Supervision is basis of *fault tolerance* in akka

Getting Supervisory Information

- `ActorContext` has methods for retrieving parent, child information
  - `ActorRef parent()`

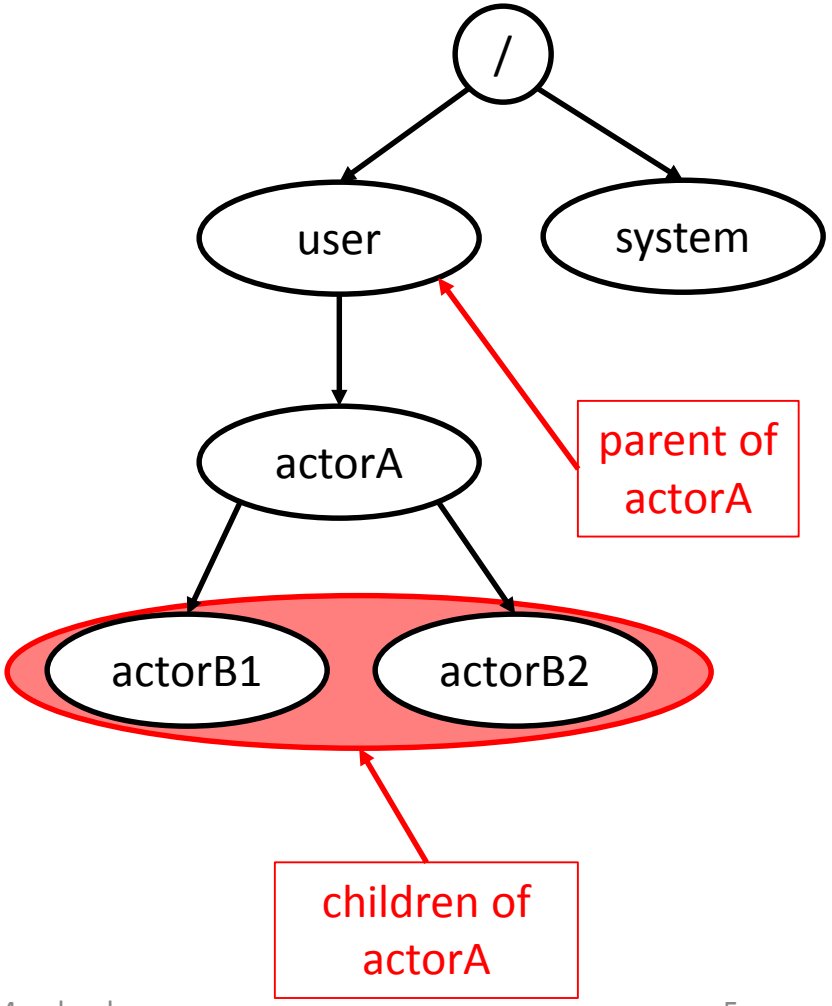
    Return parent of actor associated with context
  - `java.lang.Iterable<ActorRef> getChildren()`

    Return children as a Java Iterable
  - `ActorRef getChild(String name)`

    Return child having given name, or null if there is no such child
- To find parent of given actor, invoke following in body of actor definition:
  `getContext().parent()`

Supervisory Hierarchy

- Supervision relationship induces a tree
  - Every actor (except /) has exactly one parent
  - Every actor has ≥ 0 children
- Every actor can be identified via path (`ActorPath`) in tree
- To get path of `ActorRef`, use `path()` instance method
- For actorA
  - Parent: user
  - Children: actorB1, actorB2
  - Path: /user/actorA



How an Actor Can Find Its Name

- `getName()`? `name()`? No
  No such instance methods in `UntypedActor`
- `getSelf().getName()`? `getSelf().name()`? No
  No such instance methods in `ActorRef`
- `getContext().getName()`?
  `getContext().name()`? No
  No such instance methods in `ActorContext`
- Solution: go through `ActorPath`
  - `ActorPath` objects have `name()` method returning name (`String`) of actor at that path
  - So, `getSelf().path().name()` returns name of yourself

Supervision in Detail

- When an actor fails (i.e. throws an exception) a special system message is sent to its parent
  - Systems messages have their own message queue; they are not handled by `onReceive()`
  - No guarantees about precedence of system messages over regular messages
- Parent actor has four choices in akka
  1. *Resume* the failed child in child's accumulated internal state
  2. *Restart* the failed child in its initial state
  3. *Stop* the failed child permanently
  4. *Escalate* (i.e. fail itself, handing off responsibility to its own parent)
- Communication associated with these choices is via system messages that are handled by special system-message queue

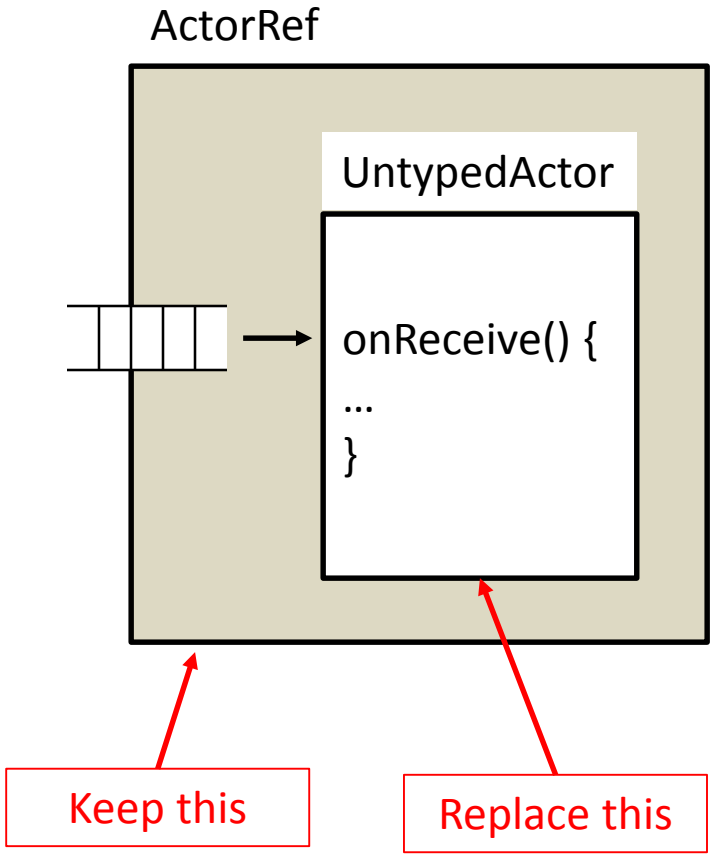
  This queue is only used for supervision (i.e. parent-child) communication

Resumption of Failed Child

- `onReceive()` method in child is re-invoked
  - Message being processed when failure occurred is lost
  - Processing of messages in child's message queue resumes
- When to do this?
  - Maybe if transient system fault caused failure
  - Maybe if there is a bug in child that doesn't affect its ability to process future messages

Restarting a Failed Child

- Idea
  - Create new actor instance
  - Replace actor instance in ActorRef for failed child with new instance
    - Path unchanged
    - So is name
  - Invoke onReceive() method of new actor instance to start processing messages in message queue
- Message processed during failure is lost, but no pending messages in failed child's mailbox are



Stopping an Actor

- Stopping a child during supervision involves a general actor-stopping technique
- `ActorContext` objects include following method

  `void stop(ActorRef actor)`
  - Stops actor
  - Processing of current message completes first, however
- What about messages in mailbox when actor is stopped? And those sent to stopped actor?
  - These are called *dead letters*
  - akka uses a special actor (`/deadLetters`) to handle these
  - There are also mechanisms for retrieving them
- What about children?
  - They are stopped also,
  - This percolates downwards through supervision hierarchy, to children's children, children's children's children, etc.

Actors Can Stop Other Actors …

- … even themselves!
- If following is executed in UntypedActor …

```
getContext().stop(getSelf())
```

- … then it stops itself! (And consequently its children, grandchildren, etc.)
  - When an actor is stopped, its supervisor is notified
  - So are other actors that are monitoring this actor
  - akka buzzwords for this: DeathWatch, DeathPact
    - Special `Terminated` messages (these are not system messages, so are delivered to regular mailboxes) are sent to actors that have registered with stopped actor
    - Registration is done via `watch()` method in `ActorContext`
    - De-registration: `unwatch()` method in same class

Failure Escalation

- As name suggests, escalation in response to child failure means that parent fails by throwing same exception as child
- Parent's parent then must handle failure

Details of Supervision

- Each `UntypedActor` object contains a `SupervisorStrategy` object
  - To obtain `SupervisorStrategy` object, execute actor's `supervisorStrategy()` instance method
  - This method may be overridden in order to customize supervision approach
- The `SupervisorStrategy` determines how failures of children will be handled

Two Kinds of `SupervisorStrategy`

- `AllForOneStrategy` (subclass of `SupervisorStrategy`)
  - If one child fails, apply supervision strategy to all of the children, not just the failing one
  - Used if children are tightly coupled
- `OneForOneStrategy` (also subclass of `SupervisorStrategy`)
  - Apply supervision strategy only to failing child; other children left unaffected
  - Used if children are largely independent

Deciders

- Core of a `SupervisionStrategy`: *decider*
  - A decider maps exception classes to directives, which describe which of four mechanisms to use to recover
  - A directive has one of four forms: Escalate, Restart, Resume, Stop
- You may customize a `SupervisionStrategy` by changing the decider
- There is also a default decider

akka and the Java Memory Model

- Actors do not (intentionally) share memory
- In a local application (single JVM), one still needs to worry about visibility
- akka guarantees the following
  - If one actor sends a message to another, then pending writes before the send are guaranteed to be visible after the receipt
  - Pending writes after an actor reads a message are visible when the actor reads the next message

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Lecture 22
Programming in akka Java

Programming in Java

- In single-threaded setting, synchronous!
  - Computation happens via method invocation
  - When a method is called, caller waits until method is done
- In multi-threaded setting, multiple method calls can be active at same time
  - General model is still synchronous within threads, though; threads launch methods, wait for results
  - Futures, etc. give mechanism for separating call, response, however

Programming in akka

- Actors-based programming is sometimes referred to as *reactive programming*
  - Actors compute by reacting to messages
  - Message sending is asynchronous
- Promotes "server-like" programming model
  - Actors are like servers
  - You send messages to servers to get them to do something
  - The server may send a response, or not; it depends on how it is programmed
  - You should be clear about the *communications protocol* in your application
    - Which interactions are "fire-and-forget"
    - Which interactions involve a "request-response" model?
    - Etc.

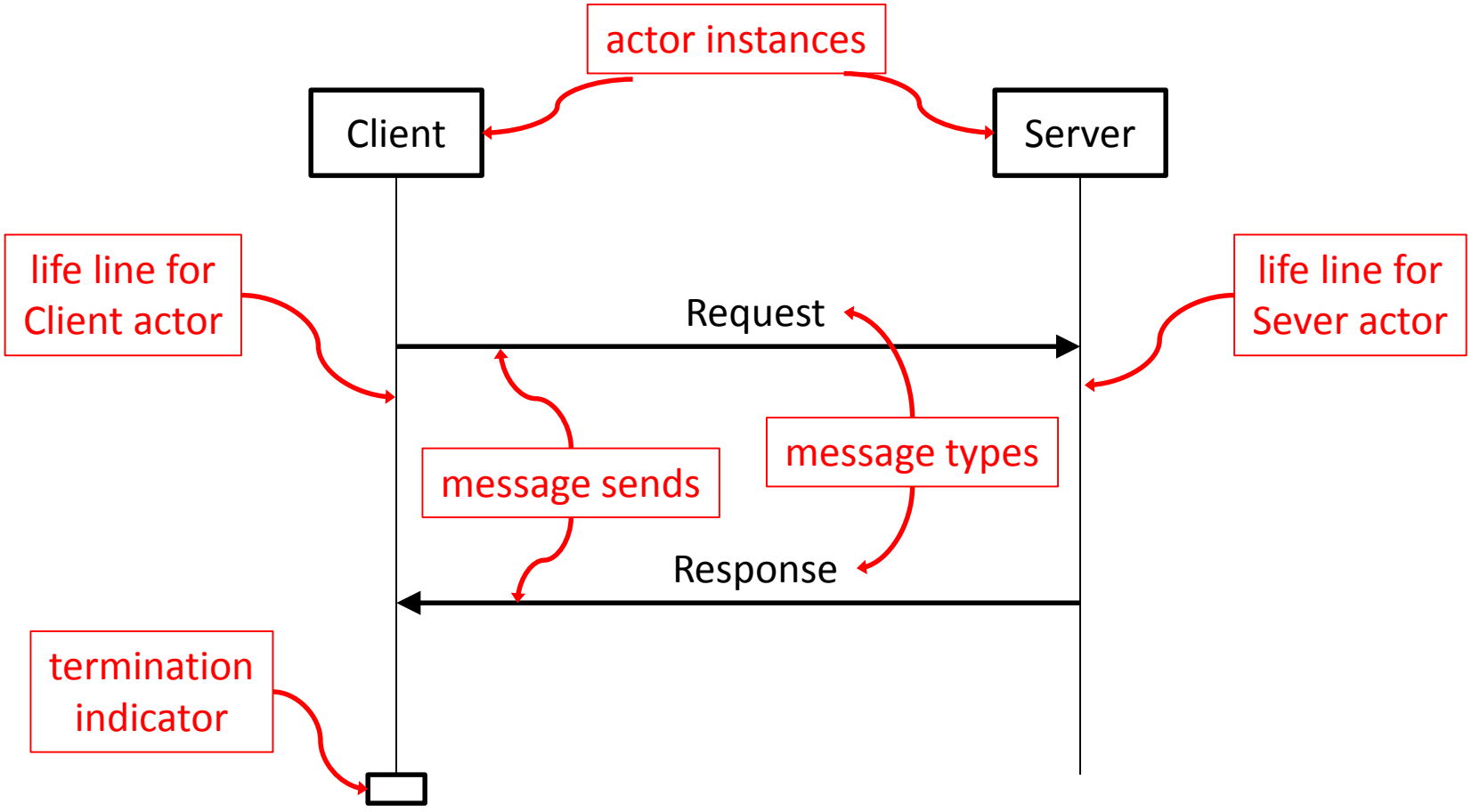
Sample Protocols

- Request-response interaction
  - Like asynchronous method call
  - Messaging
    - Send message to “server”
    - Process return message from method server
    - Since return message can be mixed in with other messages, return message needs some detail to tell recipient what to do
- Trigger interaction
  - Like exec.execute() in Java executors
  - Messaging:
    - Send message to “launch server”
    - Note that assumptions cannot be made about when the interaction is finished

Designing Communications Protocols for Actors

- Two similar graphical notations for representing communications protocols
  - Sequence Diagrams (SDs)
    - Part of Unified Modeling Language (UML)
    - Used for describing interactions among general objects
  - Message Sequence Charts (MSCs)
    - International Telecommunications Union (ITU) standard
    - Used for describing message-passing interactions
- We can use them to write down how we want actors to exchange messages
  - We will refer to the diagrams as sequence diagrams
  - They will not strictly adhere to the UML standard, and will include some MSC-style notation

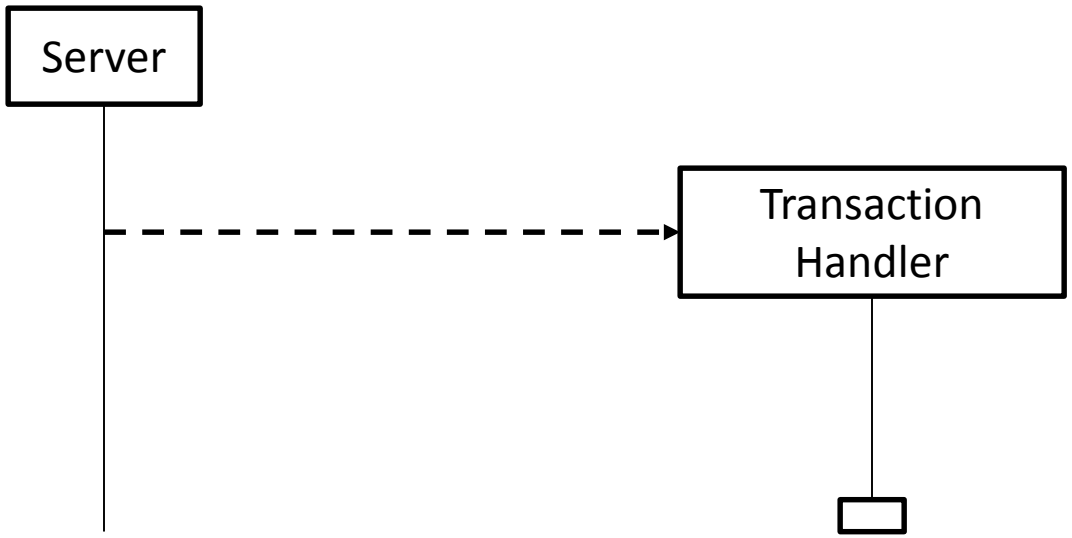
Sample Sequence Diagram



Components of a Sequence Diagram

- Collection of actors, each with a (named) lifeline
  - Name given in box at top of lifeline
  - Lifeline represents execution flow for the given actor
    - Execution starts at top, goes to bottom
    - Execution may terminate (e.g. Client in previous example), or keep going (e.g. Server)
- Message passing arrows
  - Arrows go from lifeline of sender to lifeline of receiver
  - Array labeled by the type of message (i.e. what message is for)

Actor Creation

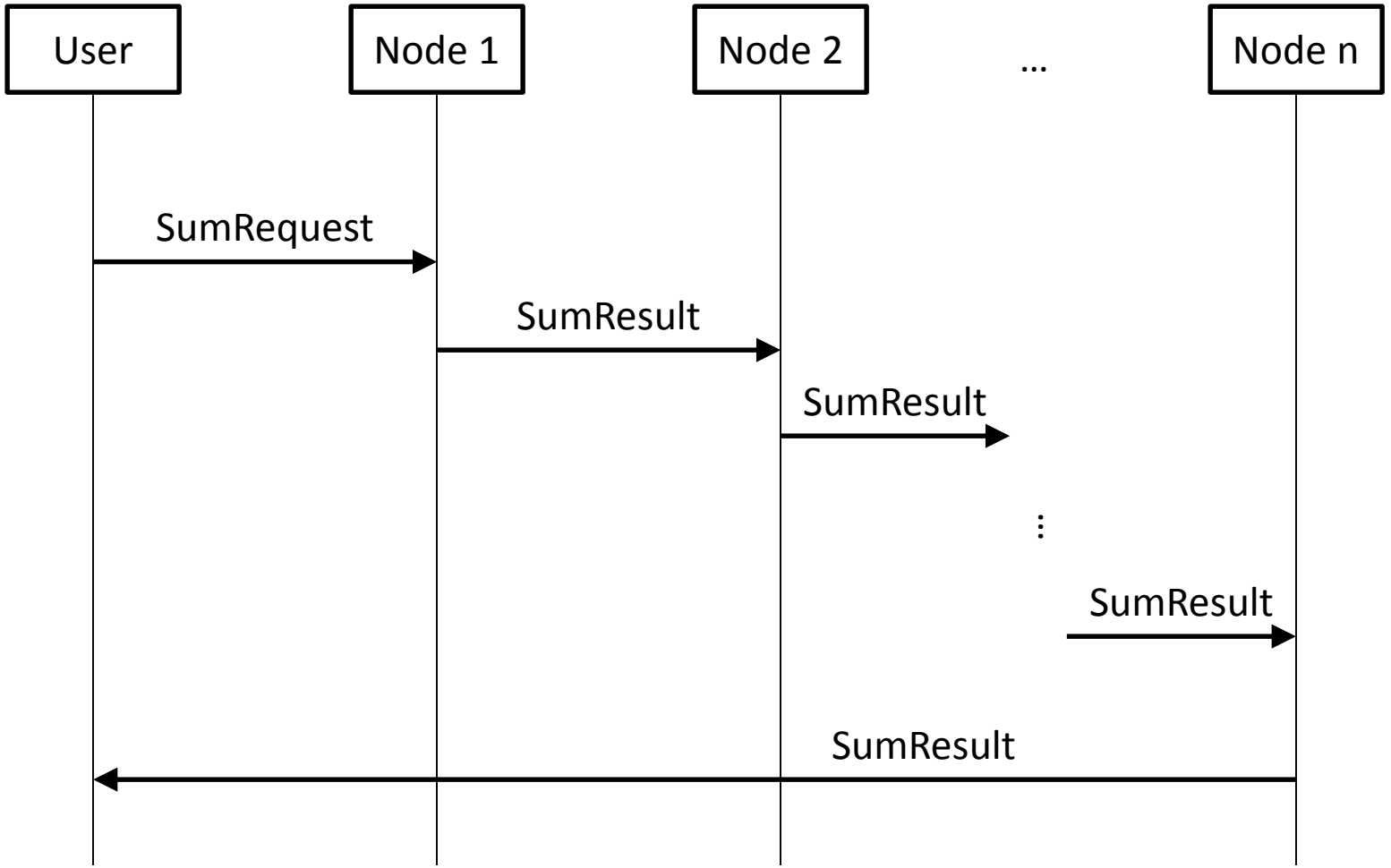


- Dashed line indicates that Server creates an instance of Transaction Handler
- Position of arrow on lifeline of Server indicates when this happens

Example

- Setting
  - We have a system of “integer chains”, i.e. actors that each store an integer and can send messages to their downstream neighbor
  - We would like a message-passing protocol for computing the sum of all integers in a chain
- General solution
  - Node in a chain receives a message from its upstream neighbor with partial sum
  - Node updates partial sum, sends message to its downstream neighbor
  - Final node returns result

Sequence Diagram for Sum Protocol



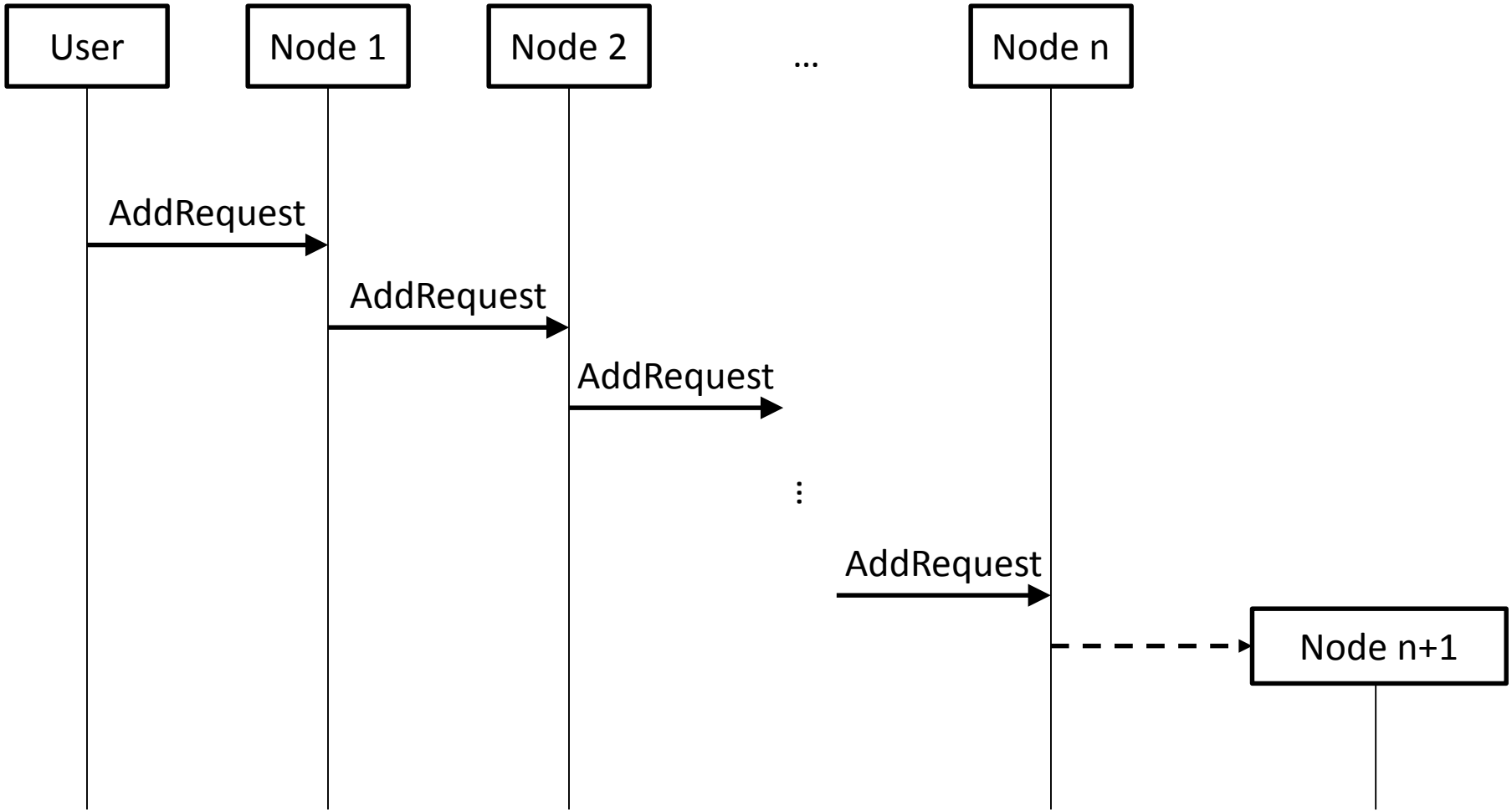
What Sum Sequence Diagram Says

- “User” is the actor who triggers the protocol by sending a SumRequest message to the first node
- First node sends SumResult message (carrying its value, but this is not explicit in the diagram) to the next node
- Each intermediate node, upon receiving a SumResult message, adds in its value and sends the resulting SumResult message to its downstream neighbor
- Final node (Node n) sends SumResult message back to “User”

Another Example

- Another operation on chains: adding a new node at the end of a chain
- How this should work
  - Request message comes in to first node
  - Nodes forward message to neighbors until final node reached
  - Final node creates new node

Sequence Diagram for Add Protocol



What Add Sequence Diagram Says

- “User” is the actor who triggers the protocol by sending an AddRequest message (with value to put in new node, but this is not explicit in diagram) to the first node
- First node sends AddRequest message to the next node
- Each intermediate node, upon receiving an AddRequest message, sends the message to its downstream neighbor
- Final node (Node n) creates the new node (which holds value in AddRequest message, although diagram does not say this explicitly)

Using Sequence Diagrams to Design Actor Systems

- Sequence diagrams make two things clear
  - What types of messages will be exchanged
  - For each actor, what types of incoming messages it needs to be able to process
- In the Integer Chain system example:
  - Three kinds of messages: SumRequest, SumResult, AddRequest
  - Node actors can receive all three kinds of messages
  - Consequently, code for onReceive() method in node actors needs to deal with each of these three kinds of messages

Messages in akka

- Recall header for `onReceive()` in `UntypedActor`

  ```
  void onReceive(Object arg0)
  ```

  - Type of message is `Object`!
  - To do anything useful with message, it must be cast to a type at runtime
  - Messages should also convey information to recipient actors about what they are for
- Good practice: use different classes for different message types
  - Ensure messages are all in message classes
  - Only send messages that are instance of message classes
  - This helps remind you what they are for and makes processing easier
- Tips
  - Put message class files in one package, actors in another
  - Distinguish “Request” and “Reponse” (or “Result”) message types when appropriate
  - Base names of classes on sequence diagrams, if these exist

Designing Actors

- Main control structure of `onReceive()`: if … else if … else if …
  - Do case analysis on message type
  - Final else clause should call unhandled() with message (unhandled() is instance method in UntypedActor)
- Example

// inherited from Actor

```
if (msg instanceof MType1) {      // msg has type MType1
      MType1 payload = (MType1)msg;  // cast needed to get type
      …
}
else if (msg instanceof MType2) {
      MType2 payload = (MType2)msg;
      …
}
else {
      System.out.println …; // Print unhandled message
      unhandled(msg);
}
```

- Tips
  - Put agent implementations in packages separate from messages
  - Include static Props-producing factory method in actor classes to ease production of actors from actor classes

Testing

- Start with single-threaded tests
  - Interact with actor system using messages sent from Java via `Patterns.ask()`
  - Check that correct results are being returned
- Then try doing multiple simultaneous tests
  - This can be done by creating special "test actors" that are run inside the actor system and interact with the "regular actors"
  - You can also create multiple threads in Java and have them each execute single-threaded tests as above
- Point of simultaneous tests: make sure that actors do not get confused when messages involving multiple interactions are being passed around
  - Possibility of multiple simultaneous interactions has implications for message-class design
  - For example, depending on your application:
    - You may want information regarding eventual recipient of data, etc.
    - You may want to include full intermediate results of a computation inside message