Programming Paradigms for Concurrency
Lecture 10 – The Actor Paradigm

Based on a course on
Principles of Reactive Programming
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Limitations of Shared Memory Concurrency

- locks are the "goto statements" of concurrency

  locks do not compose;
  reasoning about programs becomes (even more) difficult

- shared memory typically implies physically shared memory

  programs do not *scale out* to distributed architectures

- OS threads are resource-hungry and context-switching is expensive

number of threads	=	number of available cores
	≠	number of logical tasks

Message Passing Concurrency

- no shared memory (in its pure form)
  + some classes of concurrency errors avoided by design
  + natural programming model for distributed architectures
  - sometimes less efficient on shared-memory architectures: data must be copied before sending
- all synchronization between processes is explicit
  + reasoning about program behavior is simplified
  - "it's harder to parallelize a sequential program using MP"
- higher level of abstraction
  + decouple computation tasks from physical threads
    -> event-driven programming

Message Passing Paradigms

Two important categories of MP paradigms:

1. Actor or agent-based paradigms
   - unique receivers: messages are sent directly from one process to another

2. Channel-based paradigms
   - multiple receivers: messages are sent to channels that are shared between processes

We will focus on the actor paradigm.

The Actor Paradigm

Actors are the object-oriented approach to concurrency

"everything is an actor"

actor = object + logical thread

A Brief History of Actors

- Hewitt, Bishop, Steiger 1973: actor model
- Agha 1986: actor languages and semantics
- Armstrong et al. 1990s: Erlang language
- Haller, Odersky 2006: Scala actors
- Boner 2009: Akka actors

The Akka Actor Trait

```
type Receive = PartialFunction[Any,Unit]

trait Actor {
  def receive: Receive
  ...
}
```

The `Actor` type describes the behavior of an actor, i.e., how it reacts to received messages.

A Simple Actor

```
class Counter extends Actor {
  var count = 0
  def receive = {
    case "incr" => count += 1
  }
}
```

Use pattern matching to dispatch incoming messages

Sending Messages

```
class Counter extends Actor {
  var count = 0
  def receive = {
    case "incr" => count += 1
    case ("get", customer: ActorRef) =>
      customer ! count
  }
}
```

Senders are Implicit

```scala
trait Actor {
  implicit val self: ActorRef
  def sender: ActorRef
  ...
}

abstract class ActorRef {
  def !(msg: Any)(implicit sender: ActorRef = Actor.noSender):
    Unit
  def tell(msg: Any, sender: ActorRef) = this.!(msg)(sender)
  ...
}
```

Using sender

```
class Counter extends Actor {
  var count = 0
  def receive = {
    case "incr" => count += 1
    case "get" => sender ! count
  }
}
```

Changing an Actor's Behavior

```
class ActorContext {
  def become(behavior: Receive, discardOld: Boolean = true): Unit
  def unbecome(): Unit
  ...
}

trait Actor {
  implicit val context: ActorContext
  ...
}
```

Changing an Actor's Behavior

```
class Counter extends Actor {
  def counter(n: Int) = {
    case "incr" => context.become(counter(n + 1))
    case "get" => sender ! n
  }
  def receive = counter(0)
}
```

Important Lessons to Remember

- Prefer `context.become` for different behaviors, with data local to each behavior

Creating and Stopping Actors

```
class ActorContext {
  def actorOf(p: Props, name: String): ActorRef
  def stop(a: ActorRef): Unit
  ...
}

trait Actor {
  val self: ActorRef
  ...
}
```

Actors are created by other actors.

Typically, `stop` is called with `self` as argument.

A Simple Actor Application

```
class Main extends Actor {
  val counter = context.actorOf(Props[Counter], “counter”)

  counter ! “incr”
  counter ! “incr”
  counter ! “incr”
  counter ! “get”

  def receive = {
    case count: Int =>
        println(s“count was $count”)
        context.stop(self)
  }
}
```

Internal Computation of Actors

- actors can
  - react to incoming messages
  - dynamically create other actors
  - send messages to other actors
  - dynamically change behavior

Evaluation Order of Actor Computations

- Actor-internal computation is single-threaded
  - messages are received sequentially
  - behavior change is effective before next message is processed
  - processing one message is an atomic operation
- Sending a message is similar to calling a synchronized method, except that it is non-blocking

Actors Encapsulate State

- no direct access to an actor's internal state
- state is accessed indirectly through message passing
- message passing is
  - asynchronous
  - buffered (FIFO)
  - over unique-receiver channels (mailboxes)
  - restricted to "known" actor references
    - `self`
    - actors `this` created
    - references `this` received in messages

The Bank Account (revisited)

```scala
object BankAccount {
  case class Deposit(amount: BigInt) {
    require(amount > 0)
  }
  case class Withdraw(amount: BigInt) {
    require(amount > 0)
  }
  case object Done
  case object Failed
}
```

Good practice:

- use case classes as messages
- declare message types in actor's companion object

The Bank Account (revisited)

```scala
class BankAccount extends Actor {
  import BankAccount._

  var balance = BigInt(0)

  def receive = {
    case Deposit(amount) =>
       balance += amount; sender ! Done
    case Withdraw(amount) if amount <= balance =>
      balance -= amount; sender ! Done
    case _ => sender ! Failed
  }
}
```

Wire Transfer

```
object WireTransfer {
  case class Transfer(from: ActorRef,
                      to: ActorRef, amount: BigInt)
  case object Done
  case object Failed
}
```

Wire Transfer

```
class WireTransfer extends Actor {
  import WireTransfer._

  def receive = {
    case Transfer(from, to, amount) =>
      from ! BankAccount.Withdraw(amount)
      context.become(awaitWithdraw(to, amount, sender))
  }

  def awaitWithdraw ...
}
```

Wire Transfer

```
class WireTransfer extends Actor {
  ...

  def awaitWithdraw(to: ActorRef, amount: BigInt,
                    client: ActorRef): Receive = {
    case BankAccount.Done =>
      to ! BankAccount.Deposit(amount)
      context.become(awaitDeposit(client))
    case BankAccount.Failed =>
      client ! Failed
      context.stop(self)
  }

  def awaitDeposit ...
}
```

Wire Transfer

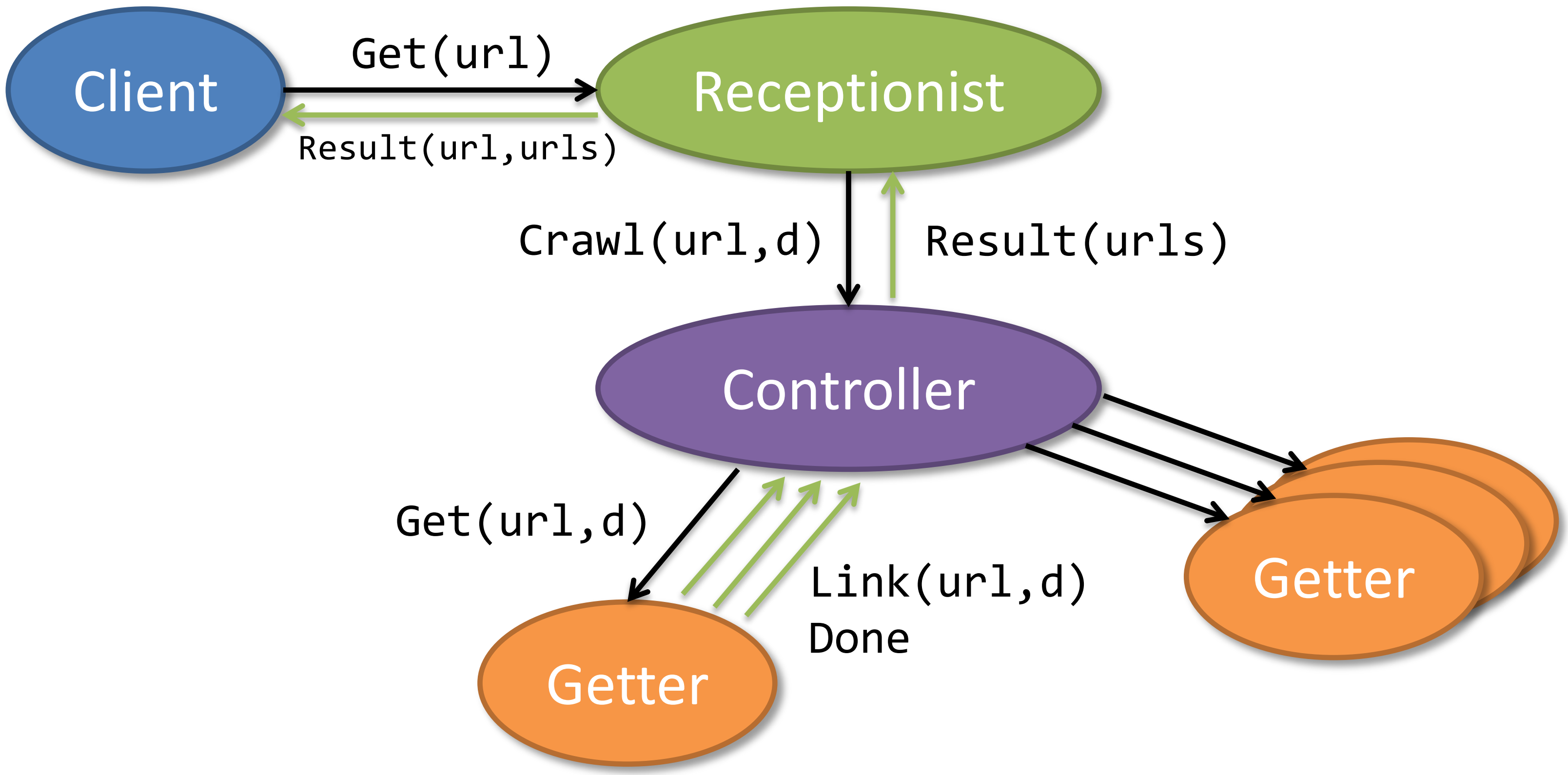
```
class WireTransfer extends Actor {
  ...

  def awaitDeposit(client: ActorRef): Receive = {
    case BankAccount.Done =>
      client ! Done
      context.stop(self)
  }
}
```

A Simple Web Crawler

Goal: write a simple web crawler that

- makes an HTTP request for a given URL
- parses the returned HTTP body to collect all links to other URLs
- recursively follows those links up to a given depth
- all links encountered should be returned.

Basic Design



Plan of Action

- write web client which asynchronously turns a URL into an HTTP body (based on `com.ning.http.client`)
- write a `Getter` actor for processing the body
- write a `Controller` which spawns `Getters` for all links encountered
- write a `Receptionist` managing one `Controller` per request.

The Web Client

```
val client = new AsyncHttpClient
def get(url: String): String = {
  val response = client.prepareGet(url).execute().get
  if (response.getStatusCode < 400)
    response.getResponseBodyExcerpt(131072)
  else throw BadStatus(response.getStatusCode)
}
```

Blocks the caller until the web server has replied
⇒ actor is deaf to other requests, e.g., cancellation
⇒ priority inversion: current thread is blocked

A short Digression to Monads

- Monads allow you to encapsulate side-effects such as
  - state mutation
  - IO
  - exceptions
  - latency
- We look at two of Scala's monads:
  - `Try`: encapsulates exceptions
  - `Future`: encapsulates exceptions and latency

Implicit Exception Handling

```
def divide: Int =
  val dividend =
    Console.readLine("Enter an Int to divide:\n").toInt
  val divisor =
    Console.readLine("Enter an Int to divide by:\n").toInt
  divident/divisor
```

What can go wrong here?

The Try Class

```
sealed abstract class Try[T] {
  abstract def isSuccess: Boolean
  abstract def isFailure: Boolean
  abstract def get: T
  abstract def flatMap[S](f: T => Try[S]): Try[S]
  abstract def map[S](f: T => S): Try[S]
  ...
}
case class Success[T](elem: T) extends Try[T]
case class Failure[T](t: Throwable) extends Try[T]
```

Try's Companion Object

```
object Try {
  def apply[T](body: => T) {
    try { Success(body) }
    catch { t => Failed(t) }
  }
}
```

Now we can wrap the result of a computation in a Try value:

```
val dividend =
  Try(Console.readLine("Enter an Int to divide:\n").toInt)
```

Implicit Exception Handling

```
import scala.util.{Try, Success, Failure}

def divide: Int =
  val dividend =
    Try(Console.readLine("Enter an Int to divide:\n").toInt)
  val divisor =
    Try(Console.readLine("Enter an Int to divide by:\n").toInt)
  val result =
```

Futures

A `Future` is an object holding a value which may become available at some point.

- This value is usually the result of some other computation.
- If the computation has completed with a value or with an exception, then the `Future` is **completed**.
- A `Future` can only be completed once.

Think of a `Future` as an asynchronous version of `Try`

The Future Trait

```
trait Awaitable[T] {
  abstract def ready(atMost: Duration): Unit
  abstract def result(atMost: Duration): T
}

trait Future[T] extends Awaitable[T] {
  abstract def onComplete[U](f: (Try[T]) => U)
    (implicit executor: ExecutionContext): Unit
  abstract def flatMap[S](f: T => Future[S]): Future[S]
  abstract def map[S](f: T => S): Future[S]
  ...
}

object Future {
  def apply[T](body: => T)
    (implicit executor: ExecutionContext): Future[T]
}
```

Using Futures

```scala
import scala.concurrent._
import ExecutionContext.Implicits.global
...
val usdQuote = Future { connection.getCurrentValue(USD) }
val eurQuote = Future { connection.getCurrentValue(EUR) }
val purchase = for {
    usd <- usdQuote
    eur <- eurQuote
    if isProfitable(usd, eur)
} yield connection.buy(amount, eur)

purchase onSuccess {
  case _ => println(s"Purchased EUR $amount")
}
```

Promises

```scala
import scala.concurrent.{Future, Promise}
import scala.concurrent.ExecutionContext.Implicits.global

val p = promise[T]
val producer = Future {
  val r = produceSomething()
  p.success(r)
  continueDoingSomethingUnrelated()
}
val f = p.future
val consumer = Future {
  startDoingSomething()
  f onSuccess {
    case r => doSomethingWithResult(r)
  }
}
```

The Web Client

```
val client = new AsyncHttpClient
def get(url: String): String = {
  val response = client.prepareGet(url).execute().get
  if (response.getStatusCode < 400)
    response.getResponseBodyExcerpt(131072)
  else throw BadStatus(response.getStatusCode)
}
```

Blocks the caller until the web server has replied
⇒ actor is deaf to other requests, e.g., cancellation
⇒ priority inversion: current thread is blocked

The Web Client

```
val client = new AsyncHttpClient
def get(url: String)(implicit exec: Executor):
  Future[String] = {
  val f = client.prepareGet(url).execute()
  val p = Promise[String]()
  f.addListener(new Runnable {
    def run = {
      val response = f.get
      if (response.getStatusCode < 400)
        p.success(response.getResponseBodyExcerpt(131072))
      else p.failure(BadStatus(response.getStatusCode))
    }
  }, exec)
  p.future
}
```

Important Lessons to Remember

- Prefer `context.become` for different behaviors, with data local to each behavior
- An actor application is non-blocking – event-driven from top to bottom

Finding Links

```
val A_TAG = “(?i)<a ([^>]+)>.+?</a>”.r
val HREF_ATTR =
”””\s*(?i)href\s*=\s*(?:”([^”]*)”|’([^’]*)’|([^’”>\s]+))”””.r

def findLinks(body: String): Iterator[String] = {
  for {
    anchor <- A_TAG.findAllMatchIn(body)
    HREF_ATTR(dquot, quot, bare) <- anchor.subgroups
  } yield
    if (dquot != null) dquot
    else if (quot != null) quot
    else bare
}
```

```
<html>
 <head> ... </head>
 <body>
  ...
  <a href=“http://cs.nyu.edu”></a>
  ...
 </body>
</html>
```

The Getter Actor (1)

```
class Getter(url: String, depth: Int) extends Actor {
  implicit val exec = context.dispatcher.
      asInstanceOf[Executor with ExecutionContext]

  val future = WebClient.get(url)
  future onComplete {
    case Success(body) => self ! body
    case Failure(err) => self ! Status.Failure(err)
  }
  ...
}
```

The Getter Actor (2)

```
class Getter(url: String, depth: Int) extends Actor {
  implicit val exec = context.dispatcher.
      asInstanceOf[Executor with ExecutionContext]

  val future = WebClient.get(url)
  future pipeTo(self)
  ...
}
```

The Getter Actor (3)

```
class Getter(url: String, depth: Int) extends Actor {
  implicit val exec = context.dispatcher.
      asInstanceOf[Executor with ExecutionContext]

  WebClient get url pipeTo self
  ...
}
```

Important Lessons to Remember

- Prefer `context.become` for different behaviors, with data local to each behavior
- An actor application is non-blocking – event-driven from top to bottom
- Actors are run by a dispatcher – potentially shared – which can also run Futures

The Getter Actor (4)

```
class Getter(url: String, depth: Int) extends Actor {
  ...
  def receive = {
    case body: String =>
      for (link <- findLinks(body))
        context.parent ! Controller.Crawl(link, depth)
      stop()
    case _: Status.Failure => stop()
  }
  def stop() = {
    context.parent ! Done
    context.stop(self)
  }
}
```

Actor Logging

- Logging includes IO which can block indefinitely
- Akka's logging delegates this task to dedicated actor
- supports system-wide levels of debug, `info`, `warning`, `error`
- set level, e.g., by using the setting `akka.loglevel=DEBUG`

```
class A extends Actor with ActorLogging {
  def receive = {
    case msg => log.debug("received message: {}", msg)
  }
}
```

The Controller

```
class Controller extends Actor with ActorLogging {
  var cache = Set.empty[String]
  var children = Set.empty[ActorRef]
  def receive = {
    case Crawl(url, depth) =>
      log.debug(“{} crawling {}”, depth, url)
      if (!cache(url) && depth > 0)
        chilren += context.actorOf(
                    Props(new Getter(url, depth – 1)))
      cache += url
    case Getter.Done =>
      children -= sender
      if (children.isEmpty) context.parent ! Result(cache)
  }
}
```

Important Lessons to Remember

- Prefer `context.become` for different behaviors, with data local to each behavior
- An actor application is non-blocking – event-driven from top to bottom
- Actors are run by a dispatcher – potentially shared – which can also run Futures
- Prefer immutable data structures, since they can be shared between actors

Handling Timeouts

```scala
import scala.concurrent.duration._

class Controller extends Actor with ActorLogging {
  context.setReceiveTimeout(10 seconds)
  ...
  def receive = {
    case Crawl(...) => ...
    case Getter.Done => ...
    case ReceiveTimeout => children foreach (_ ! Getter.Abort)
  }
}
```

The receive timeout is reset by every received message.

Handling Abort in the Getter

```
class Getter(url: String, depth: Int) extends Actor {
  ...
  def receive = {
    case body: String =>
      for (link <- findLinks(body)) ...
      stop()
    case _: Status.Failure => stop()
    case Abort => stop()
  }
  def stop() = {
    context.parent ! Done
    context.stop(self)
  }
}
```

The Scheduler

Akka includes a timer service optimized for high volume, short durations, and frequent cancellations of events.

```
trait Scheduler {
  def scheduleOnce(delay: FiniteDuration, target: ActorRef, msg: Any)
                  (implicit ec: ExecutionContext): Cancellable

  def scheduleOnce(delay: FiniteDuration)(block: => Unit)
                  (implicit ec: ExecutionContext): Cancellable

  def scheduleOnce(delay: FiniteDuration, run: Runnable)
                  (implicit ec: ExecutionContext): Cancellable

  // ... the same for repeating timers
}
```

Adding an Overall Timeout (1)

```
class Controller extends Actor with ActorLogging {
  import context.dispatcher
  var children = Set.empty[ActorRef]
  context.system.scheduler.scheduleOnce(10 seconds) {
    children foreach (_ ! Getter.Abort)
  }
  ...
}
```

This is not thread-safe!

- code is run by the scheduler in a different thread
- potential race condition on `children`

Adding an Overall Timeout (2)

```
class Controller extends Actor with ActorLogging {
  import context.dispatcher
  var children = Set.empty[ActorRef]
  context.system.scheduler.scheduleOnce(10 seconds, self,
    Timeout)
  ...
  def receive = {
    ...
    case Timeout => children foreach (_ ! Getter.Abort)
  }
}
```

How Actors and Futures Interact (1)

Future composition methods invite to closing over the actor's state:

```
class Cache extends Actor {
  var cache = Map.empty[String, String]
  def receive = {
    case Get(url) =>
      if (cache contains url) sender ! cache(url)
      else
        WebClient get url foreach { body =>
          cache += url -> body
          sender ! body
        }
  }
}
```

How Actors and Futures Interact (2)

```
class Cache extends Actor {
  var cache = Map.empty[String, String]
  def receive = {
    case Get(url) =>
      if (cache contains url) sender ! cache(url)
      else
        WebClient get url map (Result(sender, url, _))
          pipeTo self
    case Result(client, url, body) =>
          cache += url -> body
          client ! body
        }
  }
}
```

Still leaking state!

How Actors and Futures Interact (3)

```
class Cache extends Actor {
  var cache = Map.empty[String, String]
  def receive = {
    case Get(url) =>
      if (cache contains url) sender ! cache(url)
      else
        val client = sender
        WebClient get url map (Result(client, url, _))
          pipeTo self
    case Result(client, url, body) =>
          cache += url -> body
          client ! body
        }
  }
}
```

Important Lessons to Remember

- Prefer `context.become` for different behaviors, with data local to each behavior
- An actor application is non-blocking – event-driven from top to bottom
- Actors are run by a dispatcher – potentially shared – which can also run Futures
- Prefer immutable data structures, since they can be shared
- Do not refer to actor state from code running asynchronously

The Receptionist (1)

```
class Receptionist extends Actor {
  def receive = waiting

  def waiting: Receive = {
    // upon Get(url) start a crawl and become running
  }

  def running(queue: Vector[Job]): Receive = {
    // upon Get(url) append that to queue and keep running
    // upon Controller.Result(links) ship that to client
    //  and run next job from queue (if any)
  }
}
```

The Receptionist (2)

```
case class Job(client: ActorRef, url: String)
val DEPTH = 2
var reqNo = 0
def runNext(queue: Vector[Job]): Receive = {
  reqNo += 1
  if (queue.isEmpty) waiting
  else {
    val controller = context.actorOf(Props[Controller], s”c$reqNo”)
    controller ! Controller.Crawl(queue.head.url, DEPTH)
    running(queue)
  }
}
```

The Receptionist (3)

```
def enqueueJob(queue: Vector[Job]): Receive = {
  if (queue.size > 3) {
    sender ! Failed(job.url)
    running(queue)
  } else running(queue :+ job)
}
```

The Receptionist (4)

```
def waiting: Receive = {
  case Get(url) =>
    context.become(runNext(Vector(Job(sender, url))))
}

def running(queue: Vector[Job]): Receive = {
  case Controller.Result(links) =>
    val job = queue.head
    job.client ! Result(job.url, links)
    context.stop(sender)
    context.become(runNext(queue.tail))
  case Get(url) =>
    context.become(enqueueJob(queue, Job(sender, url)))
}
```

Important Lessons to Remember

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