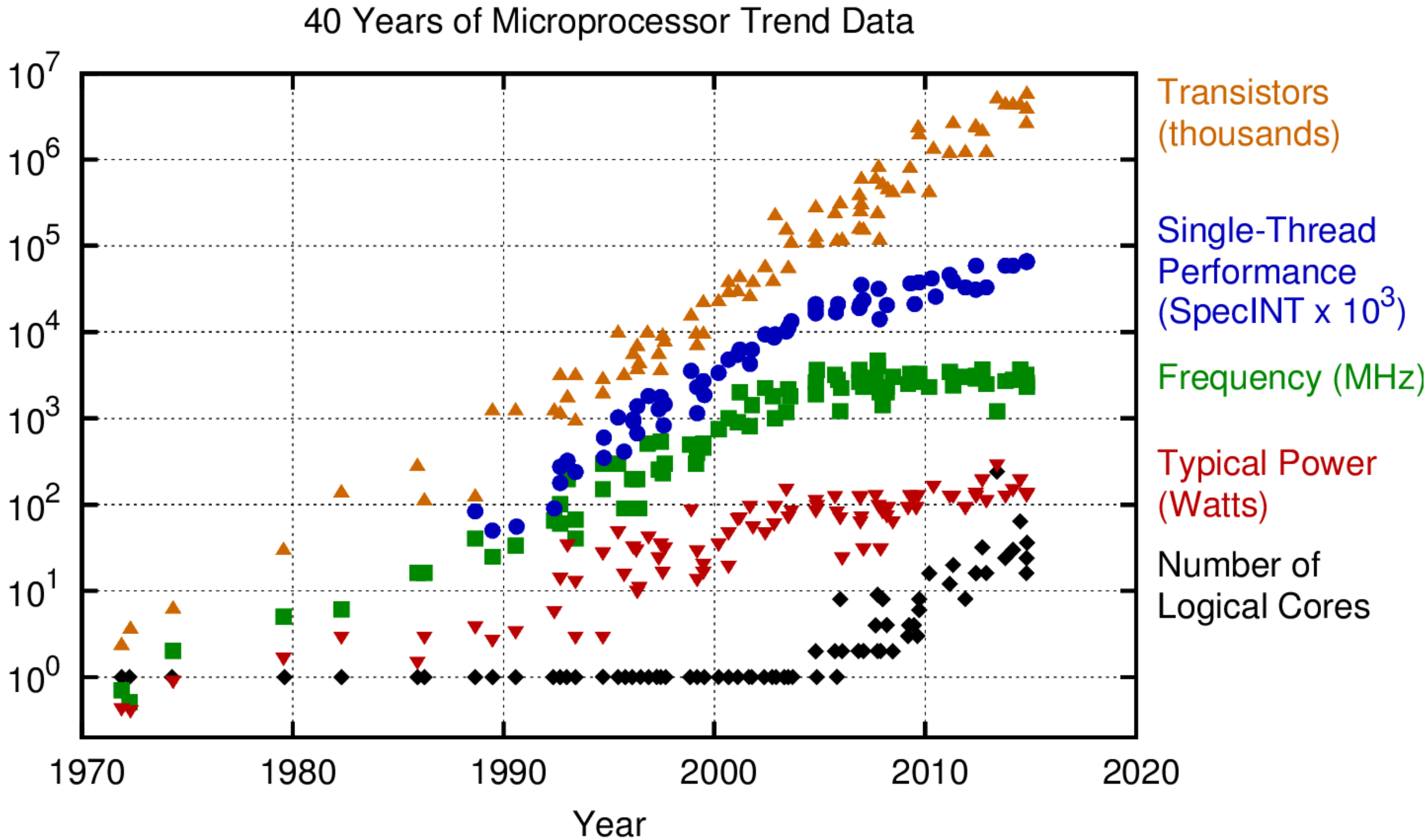
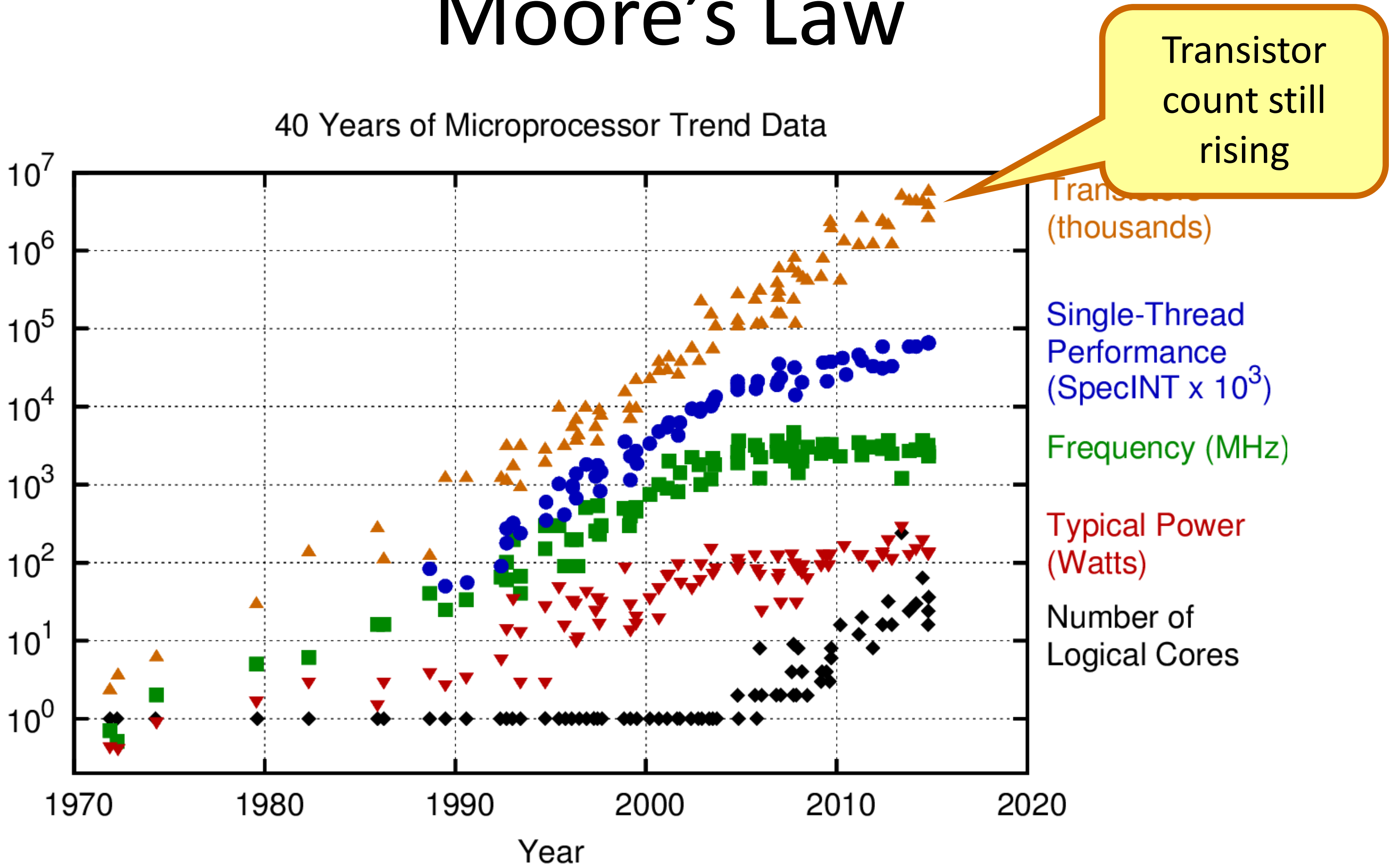
Moore’s Law



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

Moore's Law



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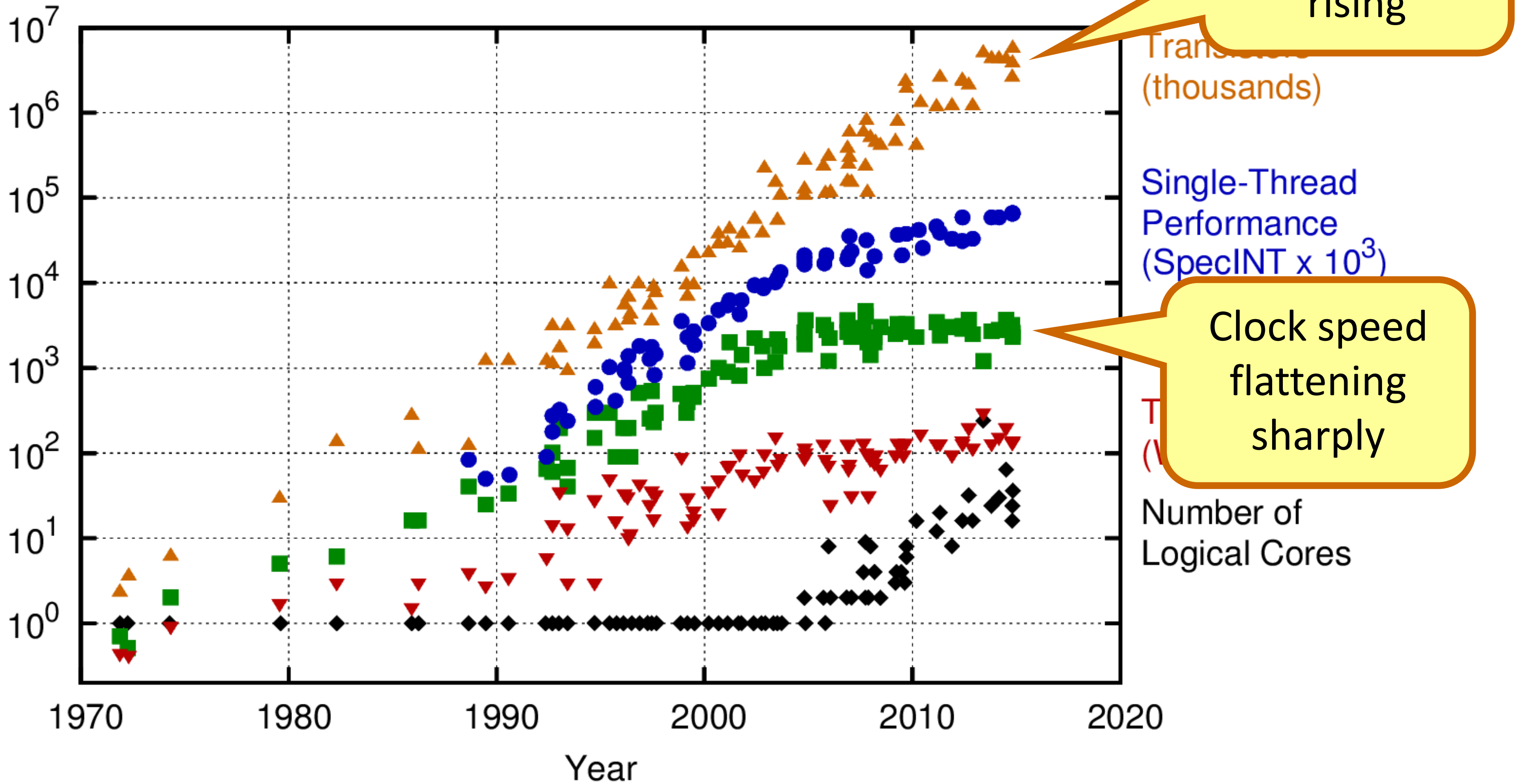
Moore’s Law



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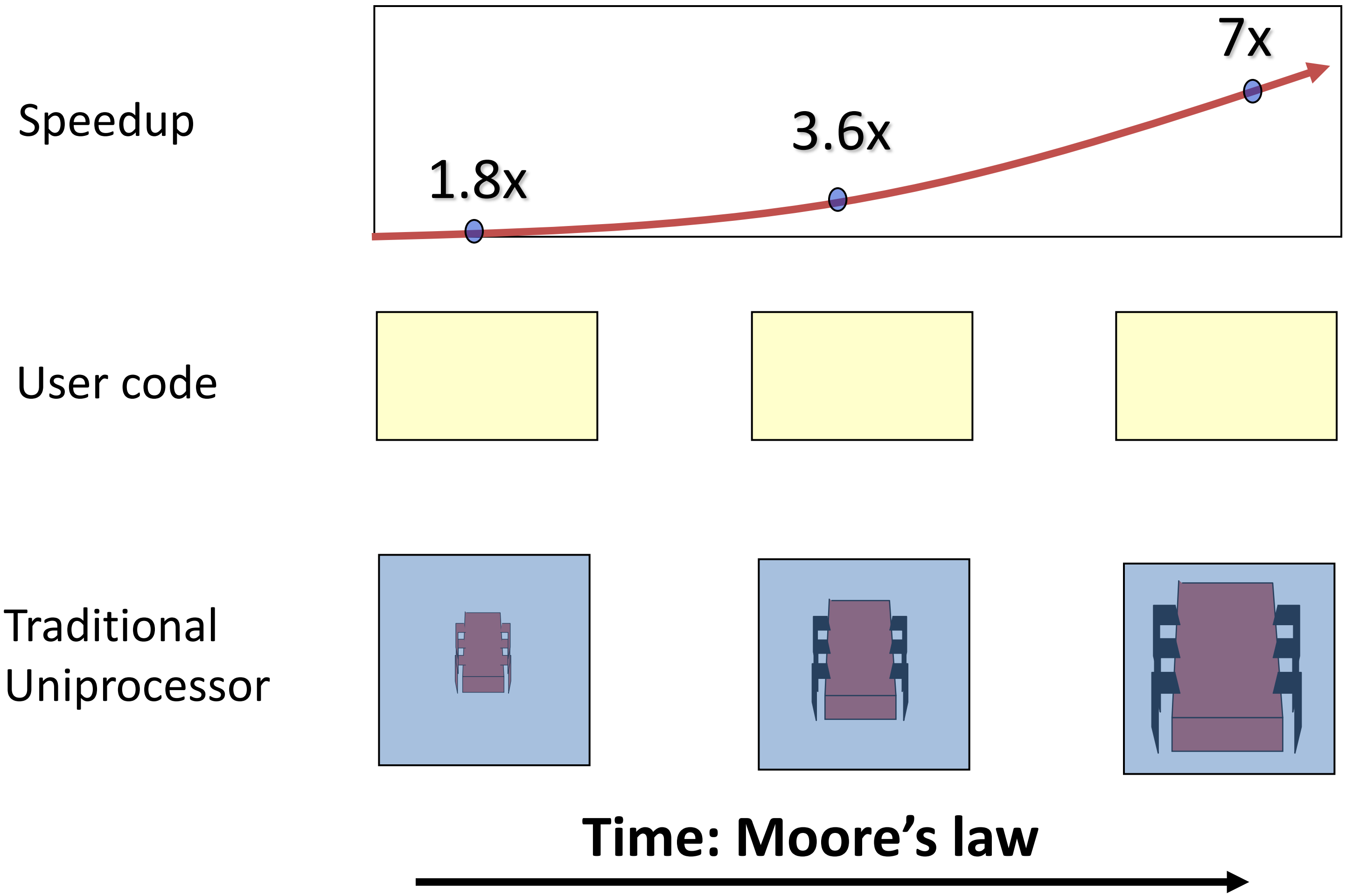
New plot and data collected for 2010-2015 by K. Rupp

Moore’s Law (in practice)

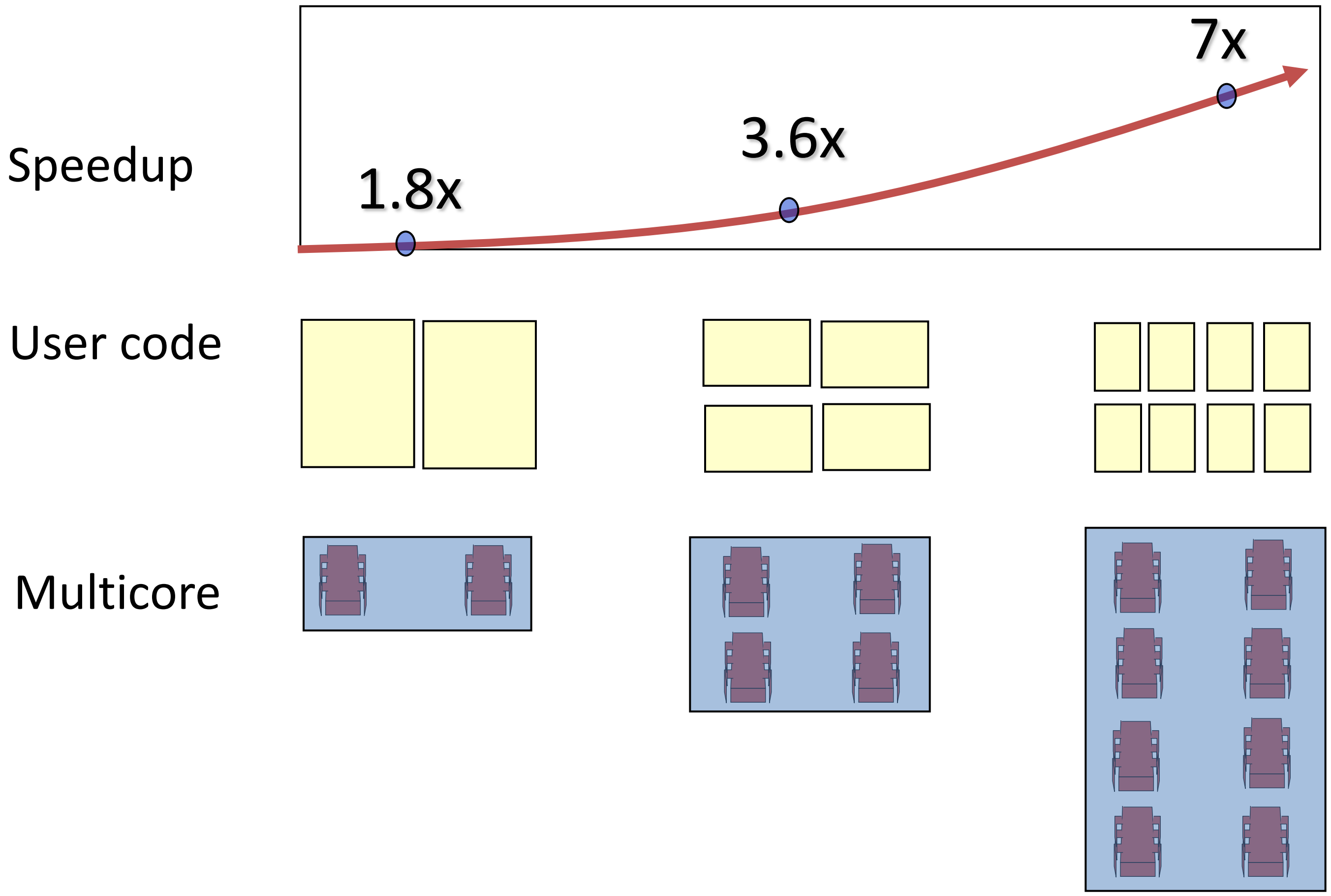
Why do we care?

- Time no longer cures software bloat
  - The “free ride” is over
- When you double your program’s path length
  - You can’t just wait 6 months
  - Your software must somehow exploit twice as much concurrency

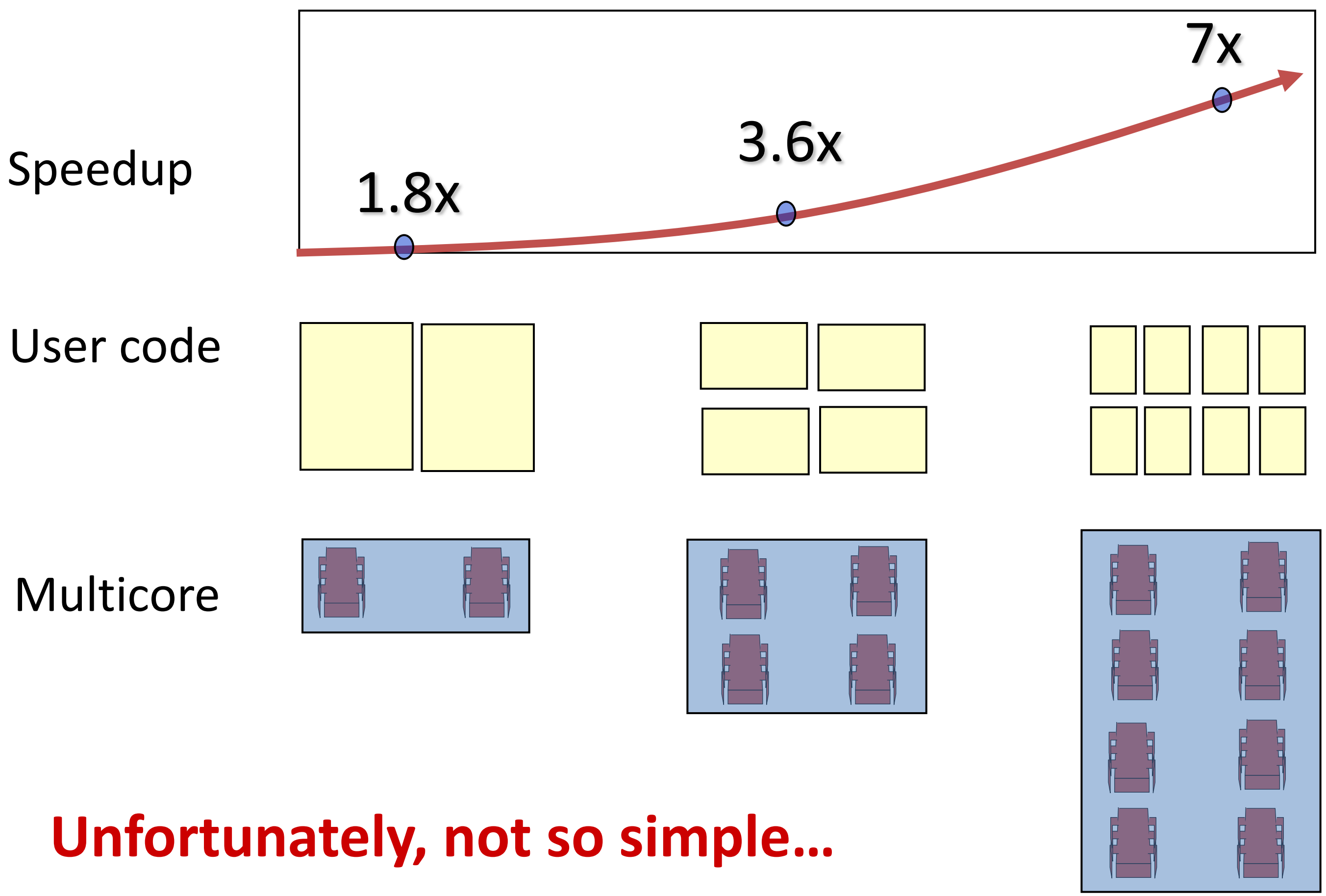
Traditional Scaling Process



Ideal Scaling Process

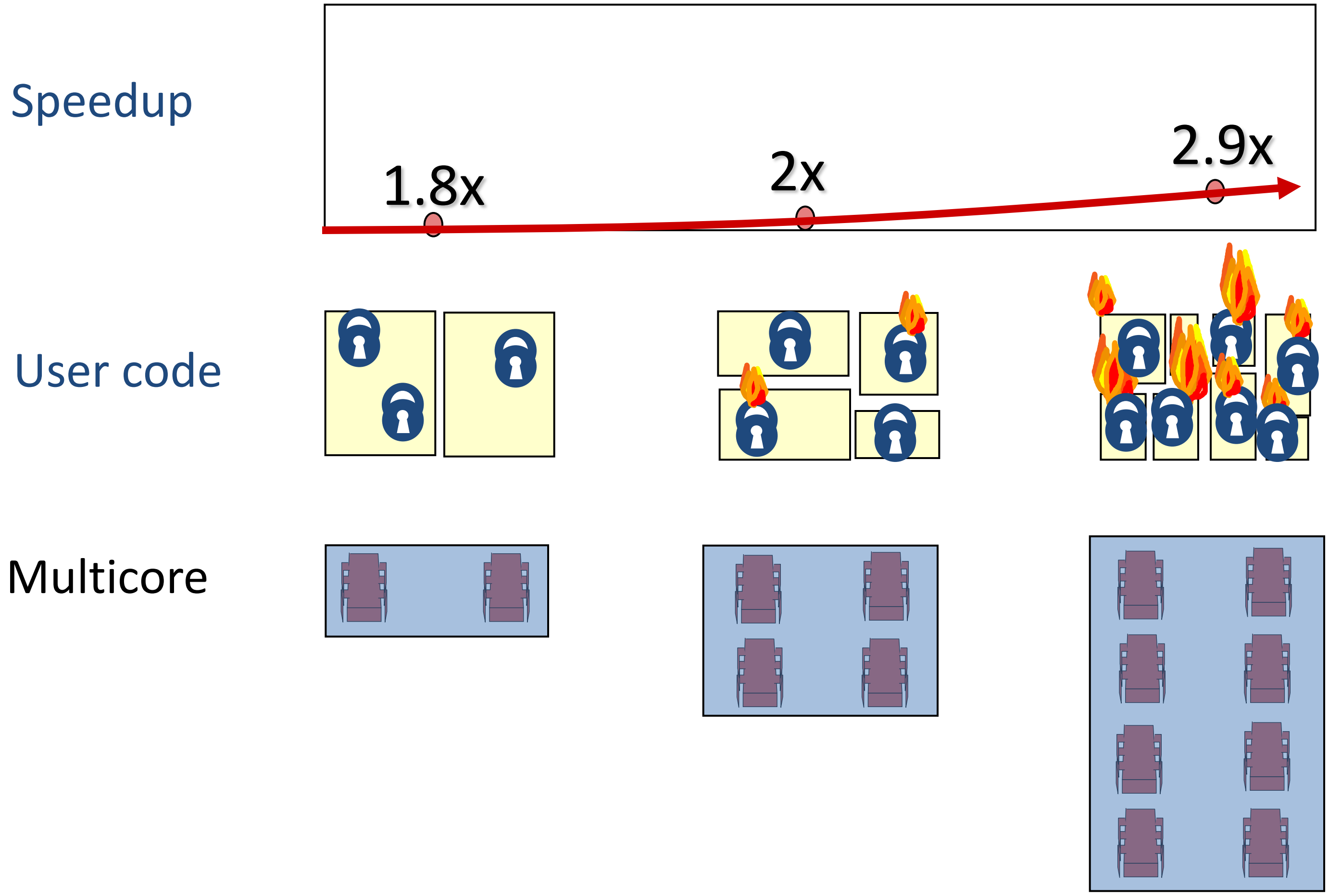


Ideal Scaling Process

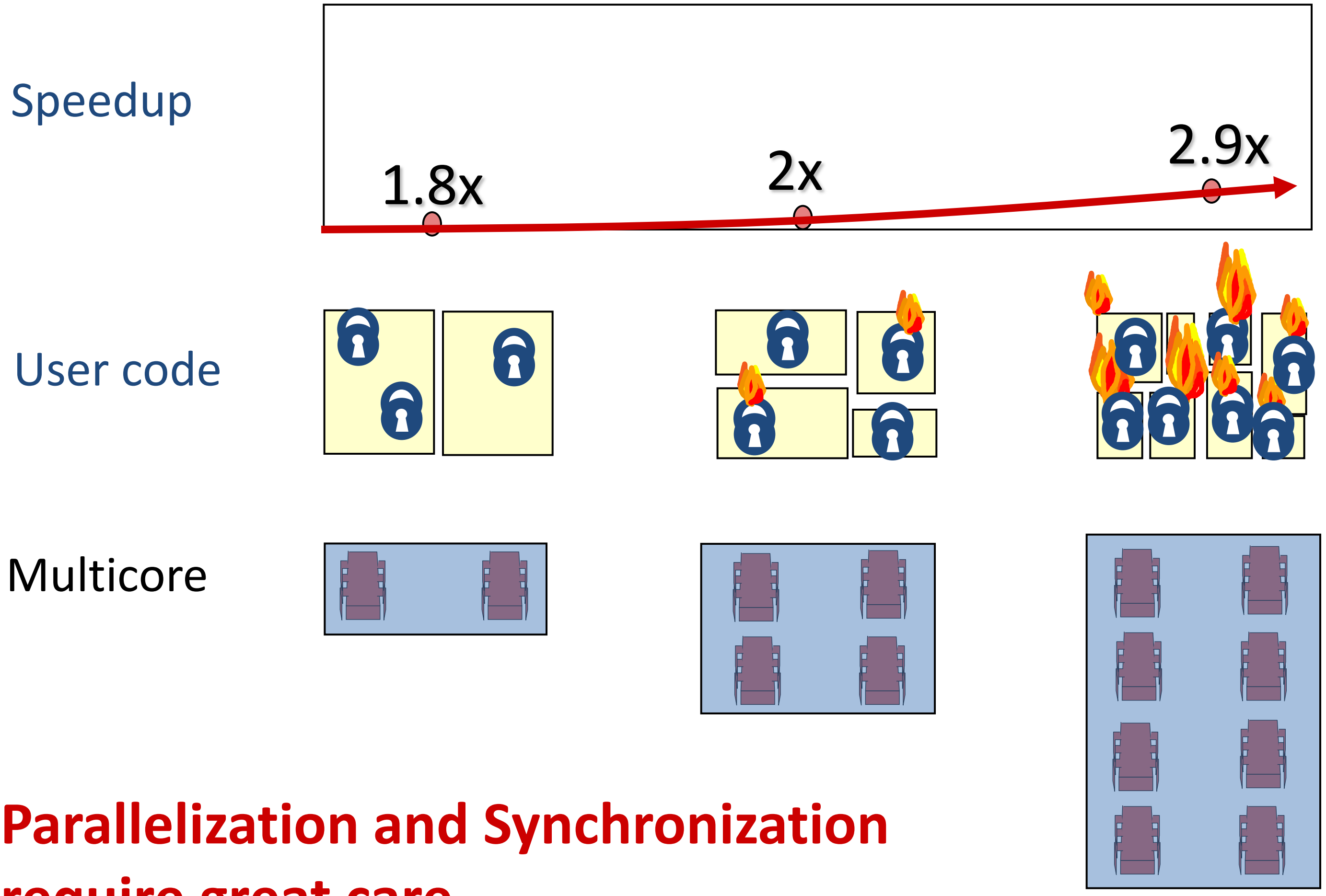


Unfortunately, not so simple…

Actual Scaling Process



Actual Scaling Process



Parallelization and Synchronization require great care…

Concurrent Programming

- In order to keep scaling, programs now need to take advantage of parallelism
  - multi-core programming
  - distributed programming (aka cloud computing)
- What are good programming language abstractions for dealing with concurrency?
  - this is still an active area of research
  - let's look at some of the issues and some of the contenders

Issues with Shared Memory Concurrency

- **Data race**: two instructions (at least one of which is a write) access the same memory location concurrently

  variable x shared by two threads T1 and T2

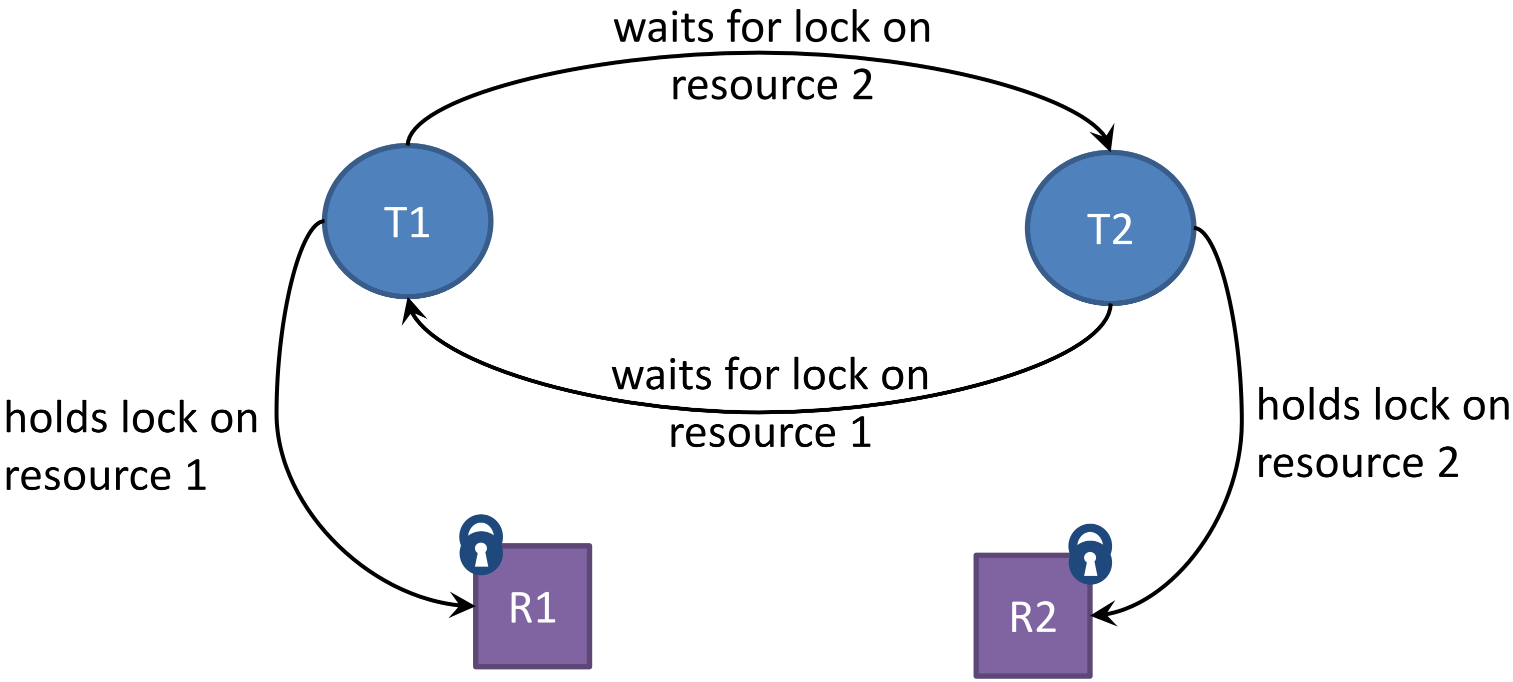
  ```
  T1: x = x + 1    ||    T2: y = x
  ```

- Data races can cause catastrophic software failures
  - Therac-25 radiation overdose
  - 2003 Northeast power blackout

- Need locks or similar synchronization mechanism to avoid data races

Issues with Shared Memory Concurrency

- Deadlock situation



Issues with Shared Memory Concurrency

- Weak memory consistency

```
T1: x = 1     ||  T2: y = 1
    print y   ||      print x
```

Can this program print `00` if the initial state is `x == y == 0`?

Issues with Shared Memory Concurrency

- Weak memory consistency

```
T1: x = 1     ||  T2: y = 1
    print y   ||      print x
```

Can this program print `00` if the initial state is `x == y == 0`?

Yes!

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

```scala
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
  }
}
```

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

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

Senders are Implicit

```
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

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

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

Changing an Actor’s Behavior

```scala
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 on the receiver, 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 that **`this`** created
    - actor references **`this`** received via incoming messages

Bank Account

```
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

Bank Account

```
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)
  }
}
```

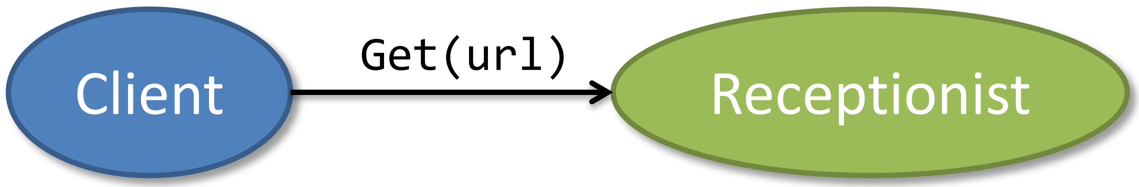
A Simple Web Crawler

Goal: write a simple web crawler that

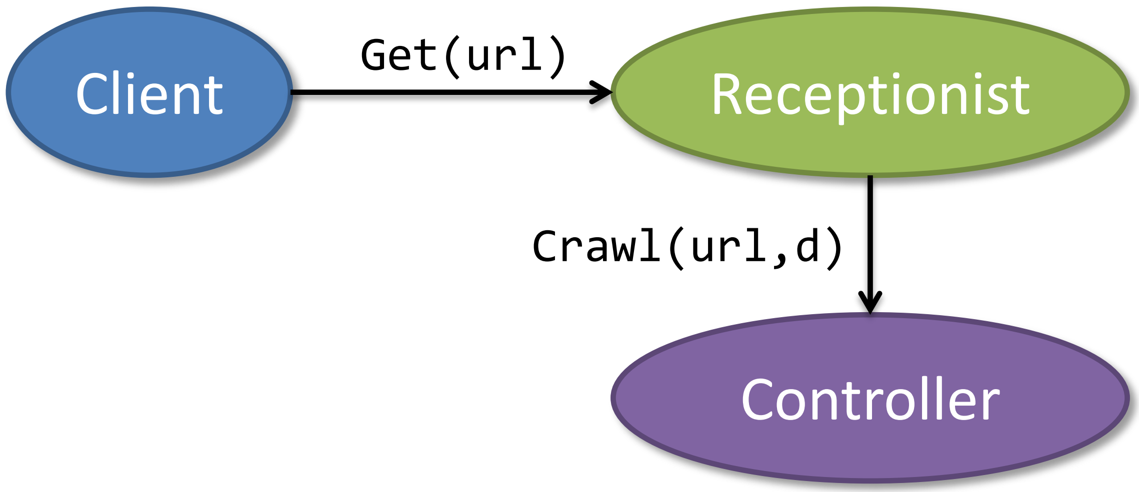
- makes an HTTP request for a given URL
- parses the returned HTTP body to collect all links to other URLs
- recursively follows those links up to a given depth
- all links encountered should be returned.

Basic Design

Basic Design



Basic Design



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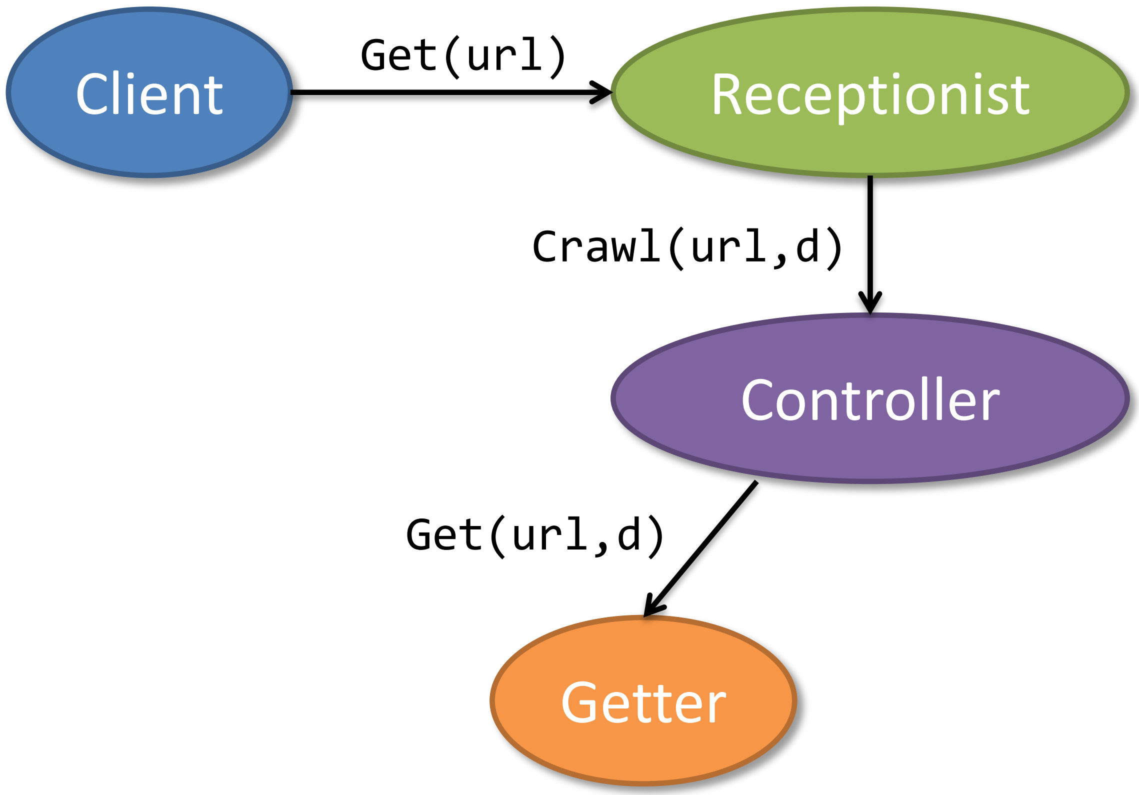

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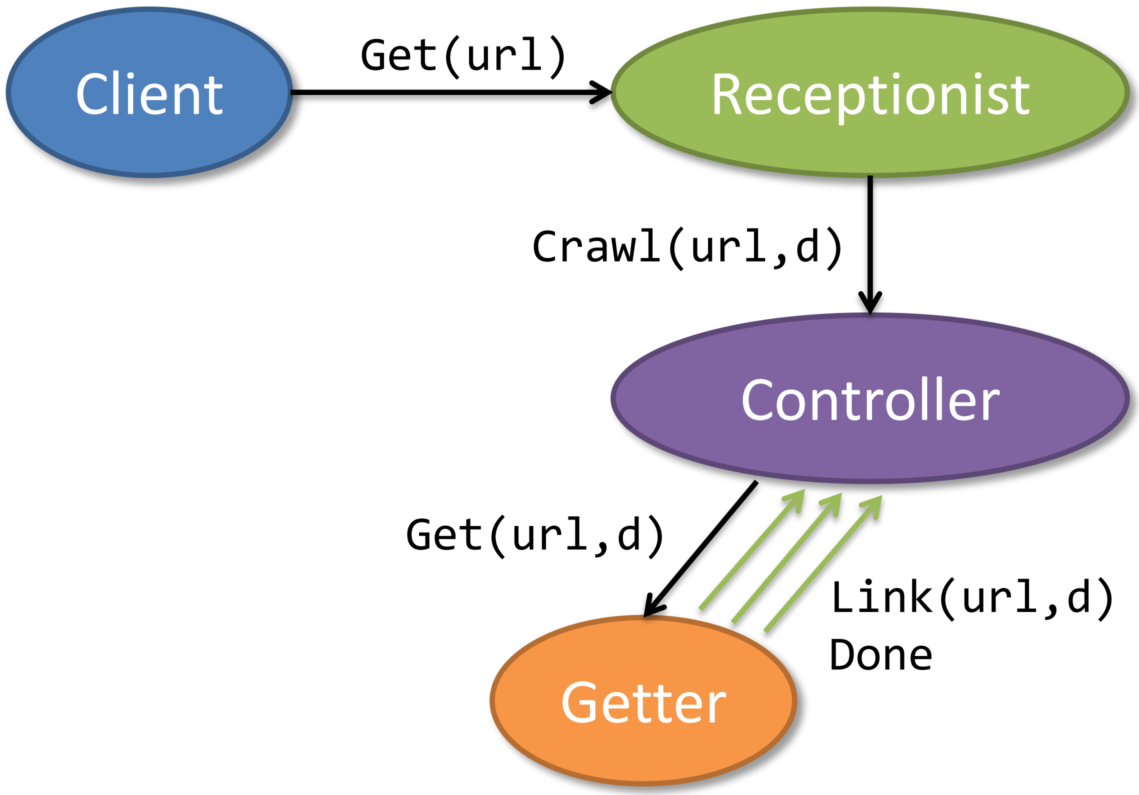

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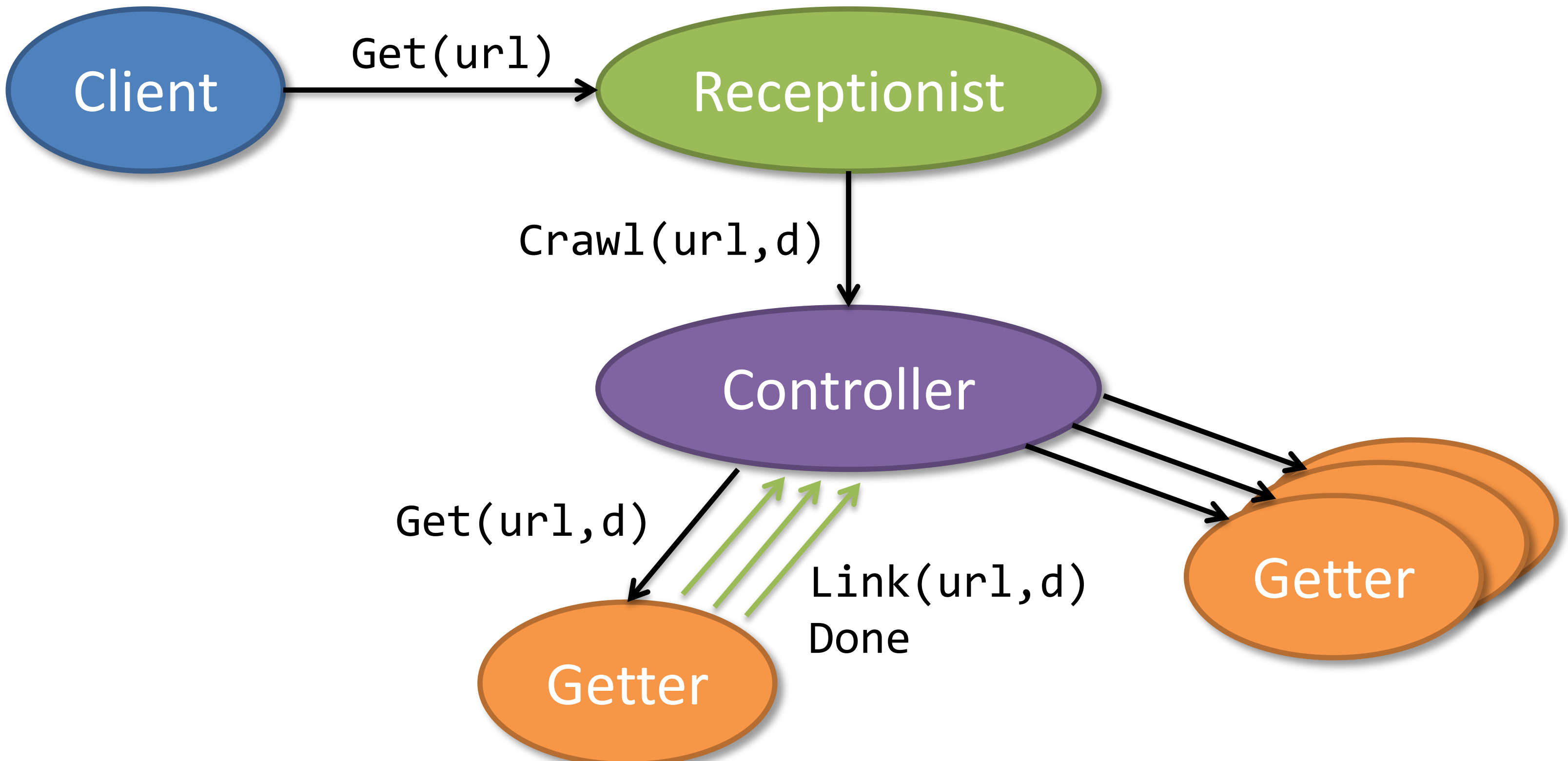

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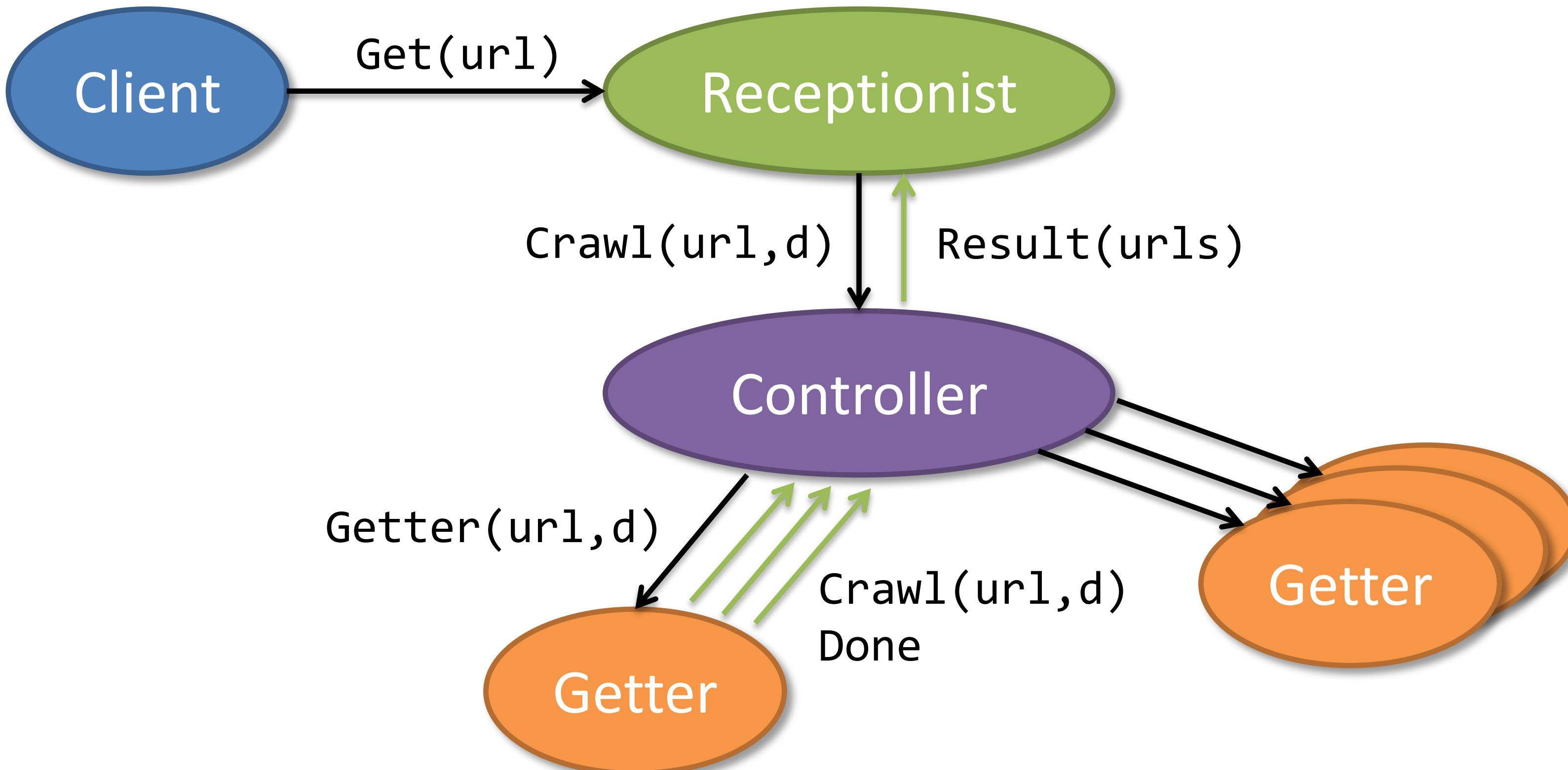

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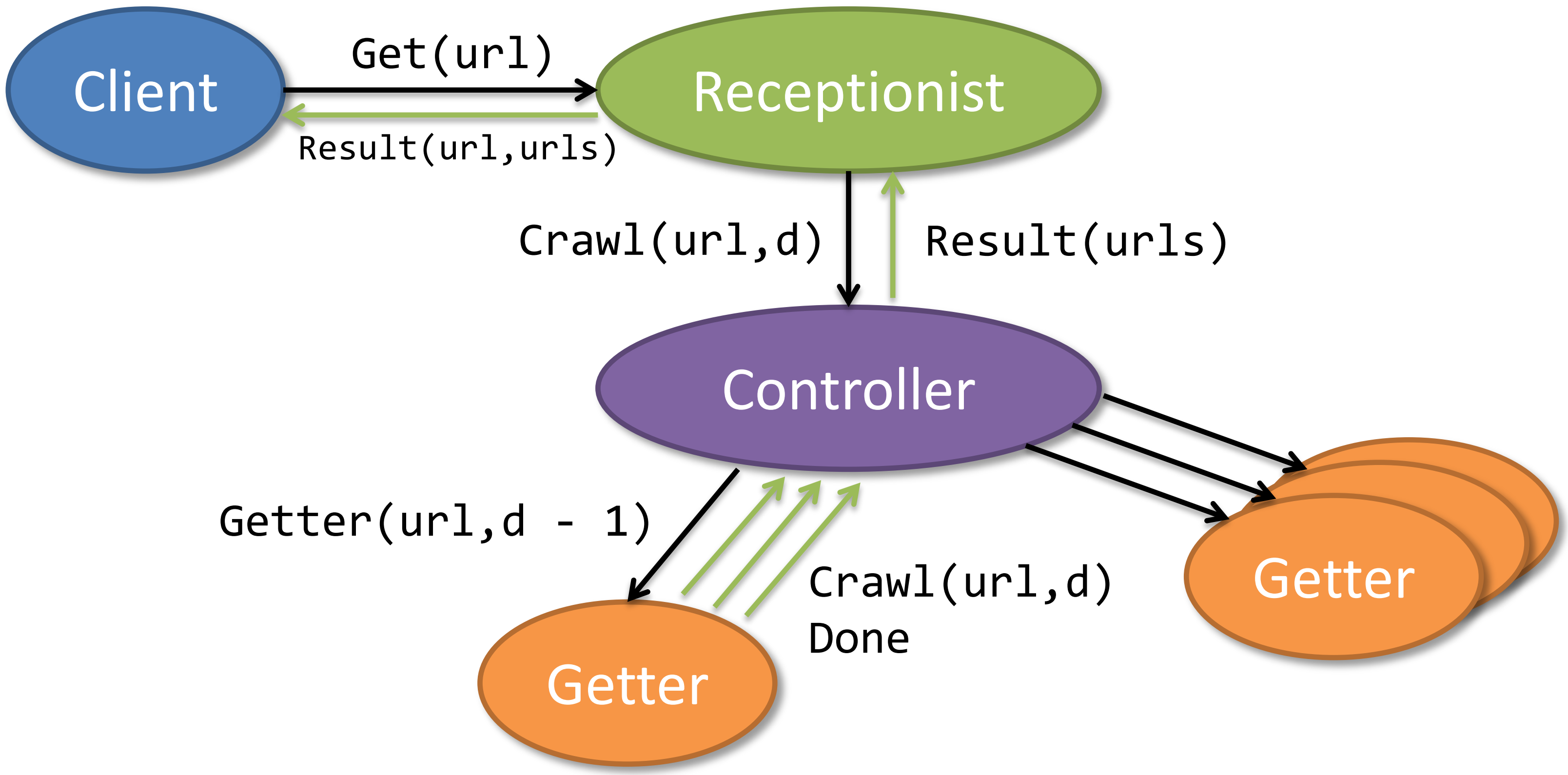

Plan of Action

- 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)
}
```

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)
        children += 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)
  }
  ...
}
```

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
        }
  }
}
```

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

The Receptionist (4)

```scala
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

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