Habanero-Scala: A Hybrid Programming model integrating Fork-Join and Actor models

MS Thesis Defense
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Introduction

- Multi-core processors → renewed interest in programming concurrency models
- Goal is to reduce the burden of reasoning about and writing concurrent programs
- Some popular programming models:
  - Fork/Join
  - Actors
  - Synchronous Message Passing
  - Partitioned Global Address Space
  - Software Transactional Memory

Thesis

A hybrid parallel programming model that integrates the Fork/Join Model and the Actor Model helps solve certain class of problems more productively and efficiently than either of the aforementioned models individually.

Outline

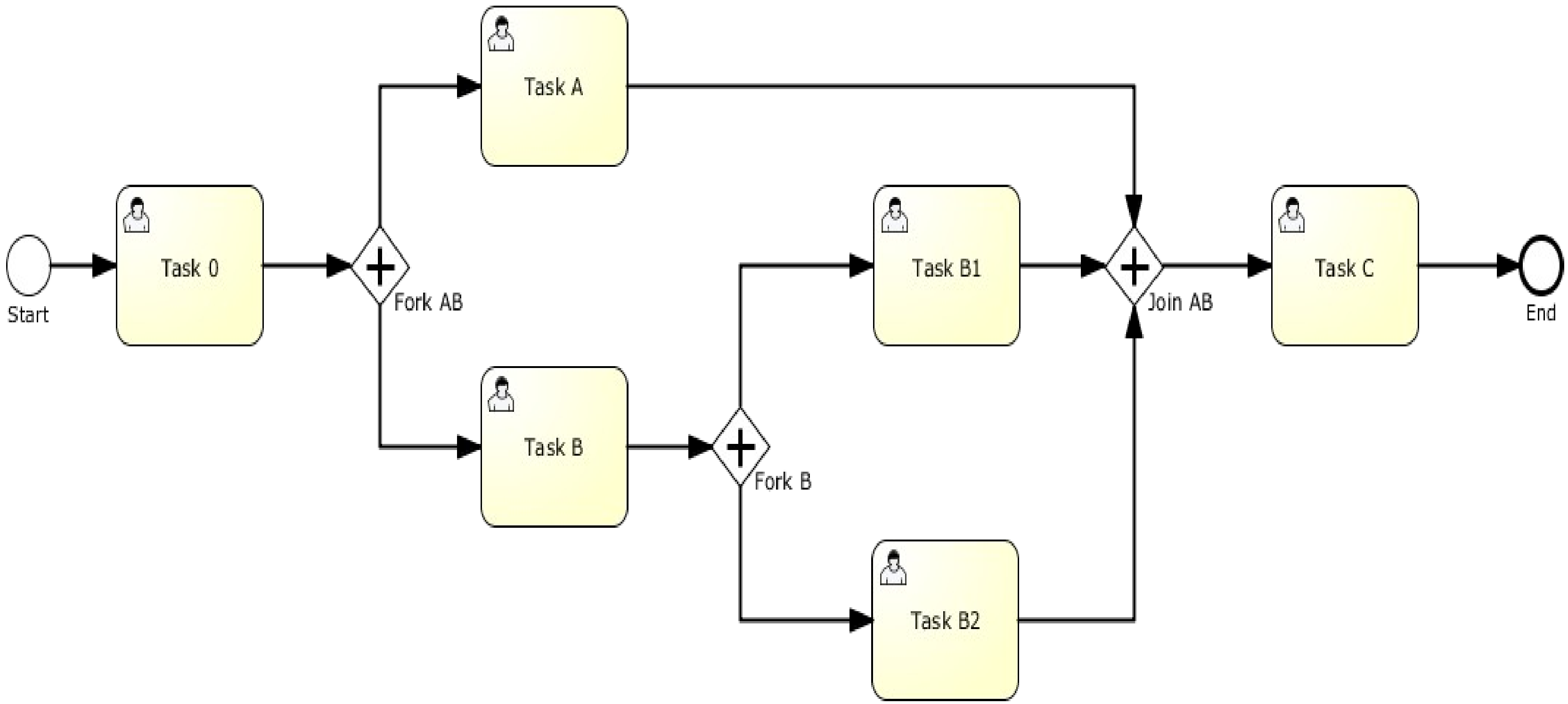
- The Fork/Join Model
- The Actor Model
- The Hybrid Model
- Applications of the Hybrid Model
- Implementation and Experimental Results

The Fork/Join Model (FJM)

- A special case of the Task Parallel Model
- Regained popularity due to Cilk from MIT
  - spawn/sync
- At Rice, we have Habanero-Java and Habanero-C
  - async/finish
  - soon a Habanero-Scala release

The Fork/Join Model (FJM)

- Parent tasks forks child tasks
- Synchronization when tasks join into another task



[image source: http://www.coopsoft.com/ar/ForkJoinArticle.html]

FJM problems

- Difficult to achieve data locality
  - tasks are free to access arbitrary data
- Fork and Join are not expressive enough for general synchronization and coordination between tasks
- Additional synchronization/coordination constructs
  - Phasers
  - Data Driven constructs

Phasers

- Support Collective and Point-to-Point synchronization
- Pros:
  - Can guarantee deadlock freedom
- Cons:
  - Phaser registration limits synchronization between arbitrary tasks
  - Blocking calls do not scale in current implementations when there are more tasks than workers

Data-Driven Futures (DDFs)

- Arbitrary producer-consumer relationships
- Single assignment from producer
- Pros:
  - Creation of task independent of data consumed
  - Accesses to values inside the DDF are guaranteed to be race-free and deterministic
- Cons:
  - Strict ordering enforced for tasks waiting on multiple DDFs

DDF – Quicksort

```
public static void quicksort(final int[] inArr,
                             final DataDrivenFuture result) {
  if (inArr.length == 1) {
    result.put(inArr);
  } else {
    final int pivotIndex = selectPivot(inArr);
    final int pivotValue = inArr[pivotIndex];
    final DataDrivenFuture left = new DataDrivenFuture();
    async {
      final int[] lessThanArr = getLessThan(inArr, pivotValue);
      quicksort(lessThanArr, left);
    }
    final DataDrivenFuture right = new DataDrivenFuture();
    async {
      final int[] moreThanArr = getMoreThan(inArr, pivotValue);
      quicksort(moreThanArr, right);
    }
    final int[] center = getEqualsTo(inArr, pivotValue);
    async await(left, right) {
      final int[] sorted = merge(left.get(), center, right.get());
      result.put(sorted);
} } }
```


habanero-java code

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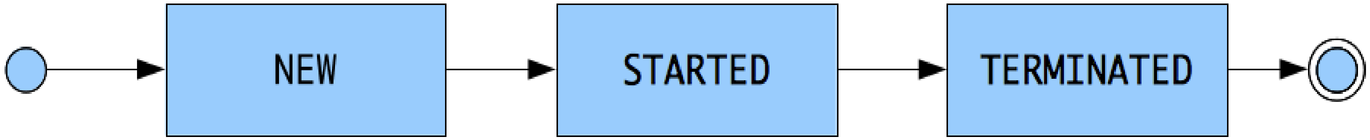
The Actor Model

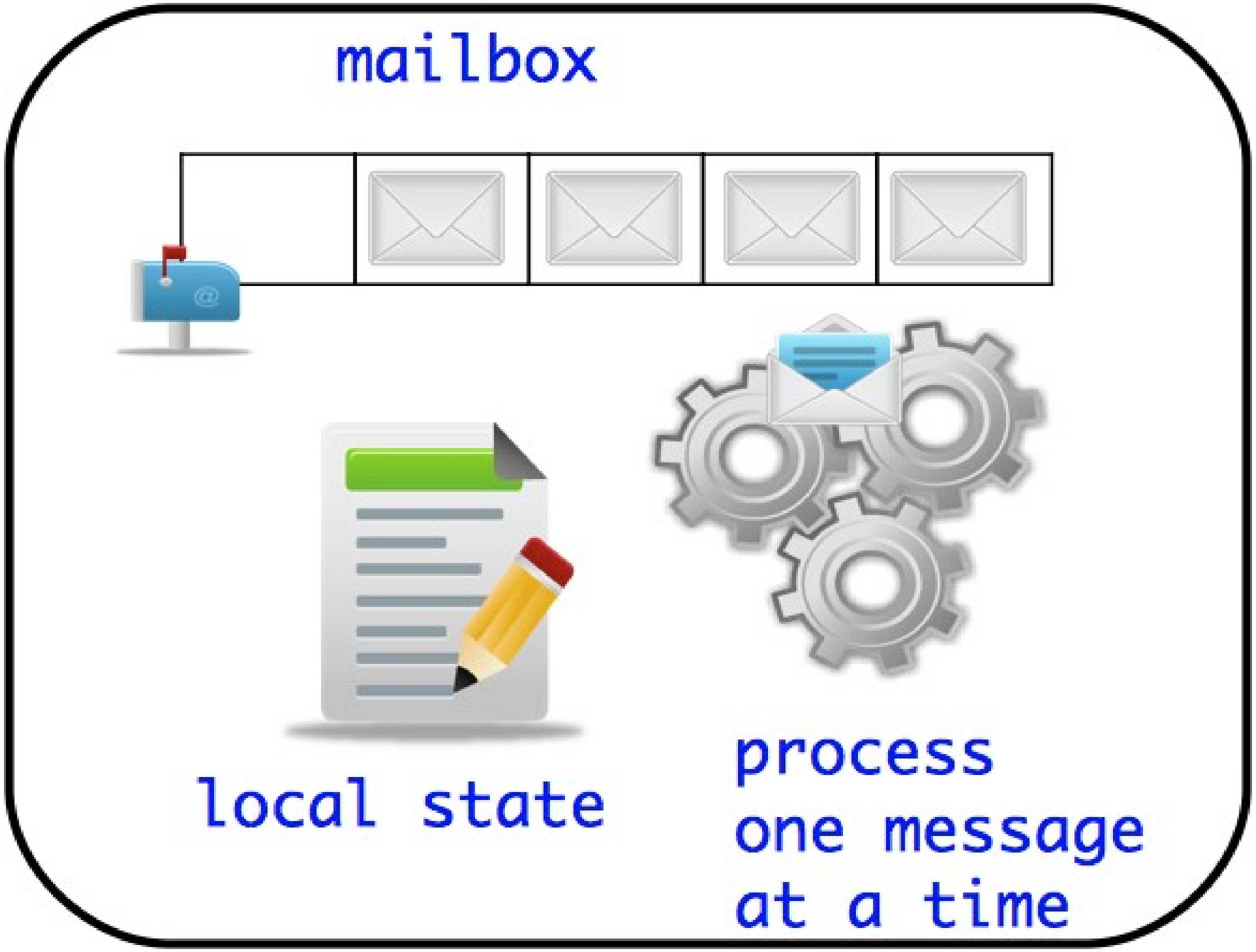
- A message-based concurrency model
- First defined in 1973 by Carl Hewitt
  - Research for Artificial Intelligence on Distributed machines
- Key concepts
  - An Actor encapsulates mutable state
  - Actors coordinate using *asynchronous* messaging
  - Non-deterministic ordering of messages

Actor - Lifecycle

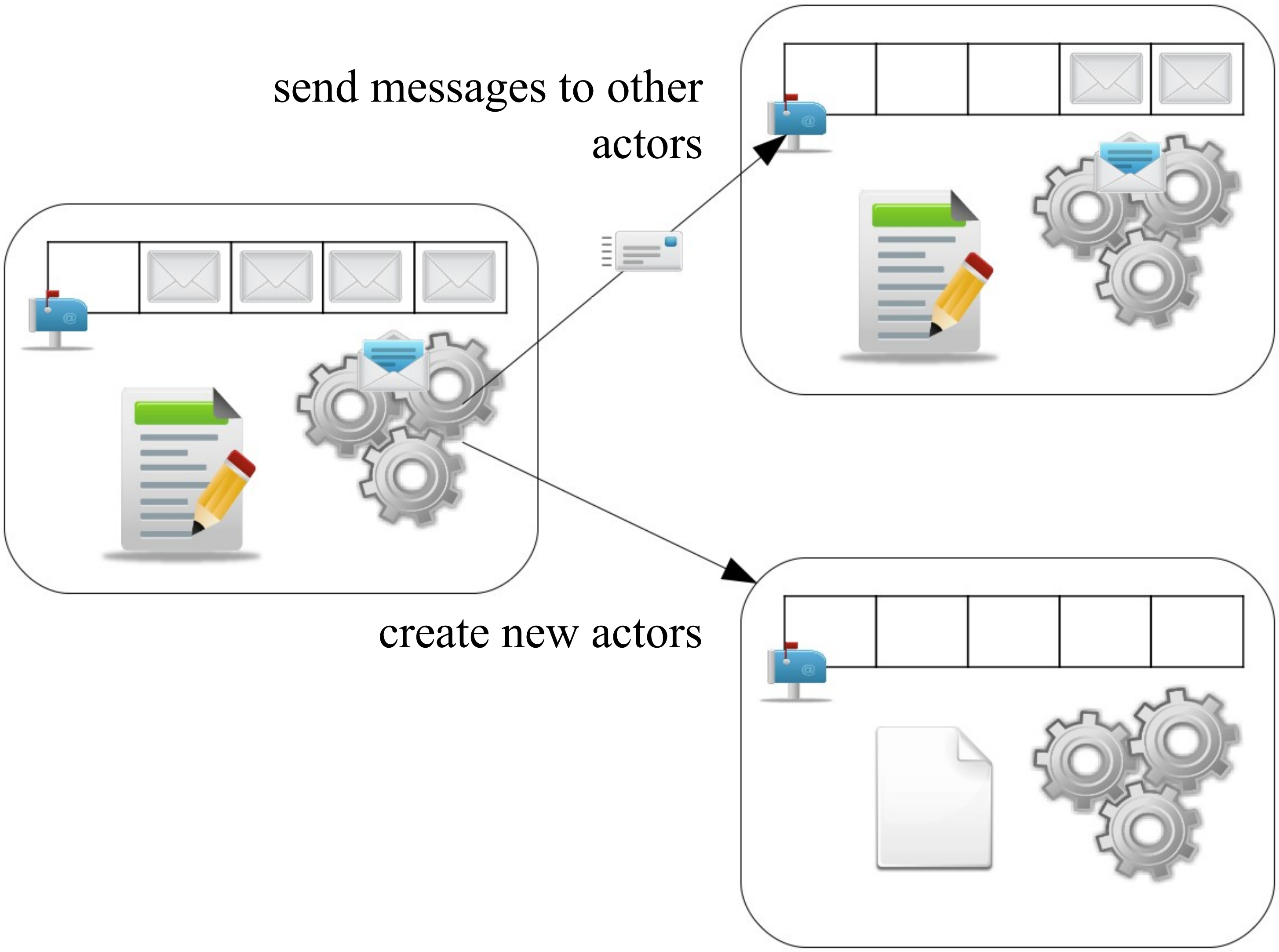


- new: actor instance has been created
- started: actor can receive and process messages sent to it
- terminated: actor will no longer process messages sent to it

Actors



Actor - Interactions



Actor – PingPong Example

```scala
object ScalaActorPingPong {
  def run(numMsgs: Int): Unit = {
    val latch = new CountDownLatch(2)

    val pong = new ScPong(verbose, latch)
    val ping = new ScPing(numMsgs, pong, latch)
    ping.start
    pong.start
    ping ! ScStart

    latch.await()
} }

class ScPong(verbose: Boolean,
    latch: CountDownLatch) extends Actor {
  def act() {
    var pongCount = 0
    loop {
      react {
        case ScPing =>
          sender ! ScPong
          pongCount = pongCount + 1
        case ScStop =>
          latch.countDown()
          exit('stop)
} } } }
```

```scala
class ScPing(count: Int, pong: Actor,
    latch: CountDownLatch) extends Actor {
  def act() {
    var pingsLeft = count
    loop { react {
        case ScStart =>
          pong ! ScPing
          pingsLeft = pingsLeft - 1
        case ScSendPing =>
          pong ! ScPing
          pingsLeft = pingsLeft - 1
        case ScPong =>
          if (pingsLeft > 0)
            self ! ScSendPing
          else {
            pong ! ScStop
            latch.countDown()
            exit('stop)
          }
} } } }
```

scala code

Actor – *pro et contra*

- Pros
  - No data races
  - Easier to achieve data locality
  - Allows arbitrary coordination between actors
- Cons
  - Harder to implement synchronous messaging
  - Requires support for pattern matching on messages in implementations
  - Hard to implement concurrent objects since actors serialize message processing

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The Hybrid Model

- Uses the Async/Finish model (AFM)
  - AFM is a generalization of the FJM
- Actors mapped onto the AFM
  - Mapping needs to be seamless
  - No additional constraints on actors
- Benefits
  - extend actor capabilities in the hybrid model
  - allow arbitrary coordination patterns between tasks

Actors and Async/Finish Tasks

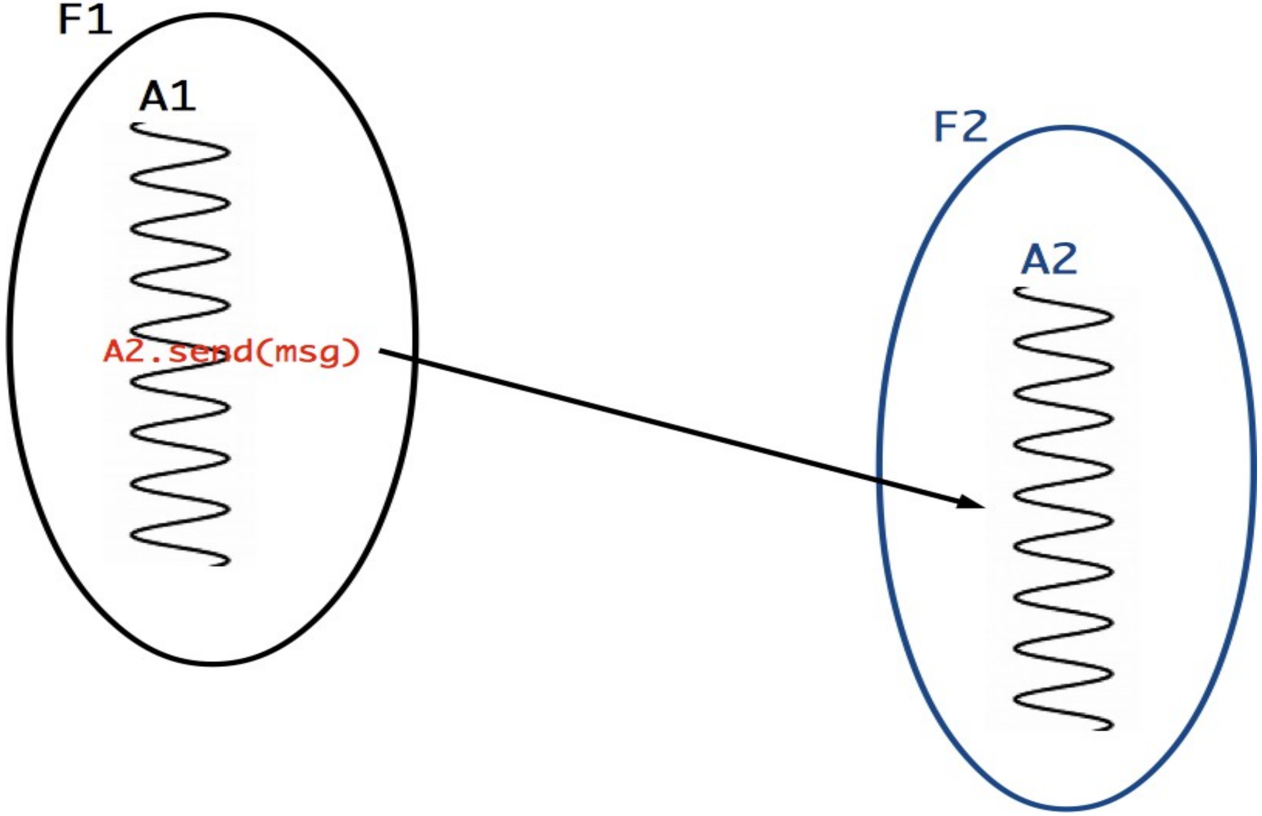
- Actor creation:
  - synchronous operation (i.e. trivial)
- Actor termination:
  - synchronous operation (i.e. trivial)
  - all future send requests can be ignored synchronously

Actors and Async/Finish Tasks...

- Starting an Actor:
  - will determine the finish scope for the actor
  - actor will start processing messages asynchronously in this finish scope
  - needs to keep the finish scope “alive” to process any messages sent to it in the future
    - use *lingering* task technique (in a couple of slides)

Actors and Async/Finish Tasks...

- Sending messages:



  - possible via *lingering* task technique

Lingering Tasks

- Provide a hook into some finish scope
- Use the *lingering* task to spawn new send and message processing tasks
- One *lingering* task per actor
  - created when the actor is started
  - *lingering* task completes execution only when the actor terminates
    - no more child tasks spawned

Message Processing invariant

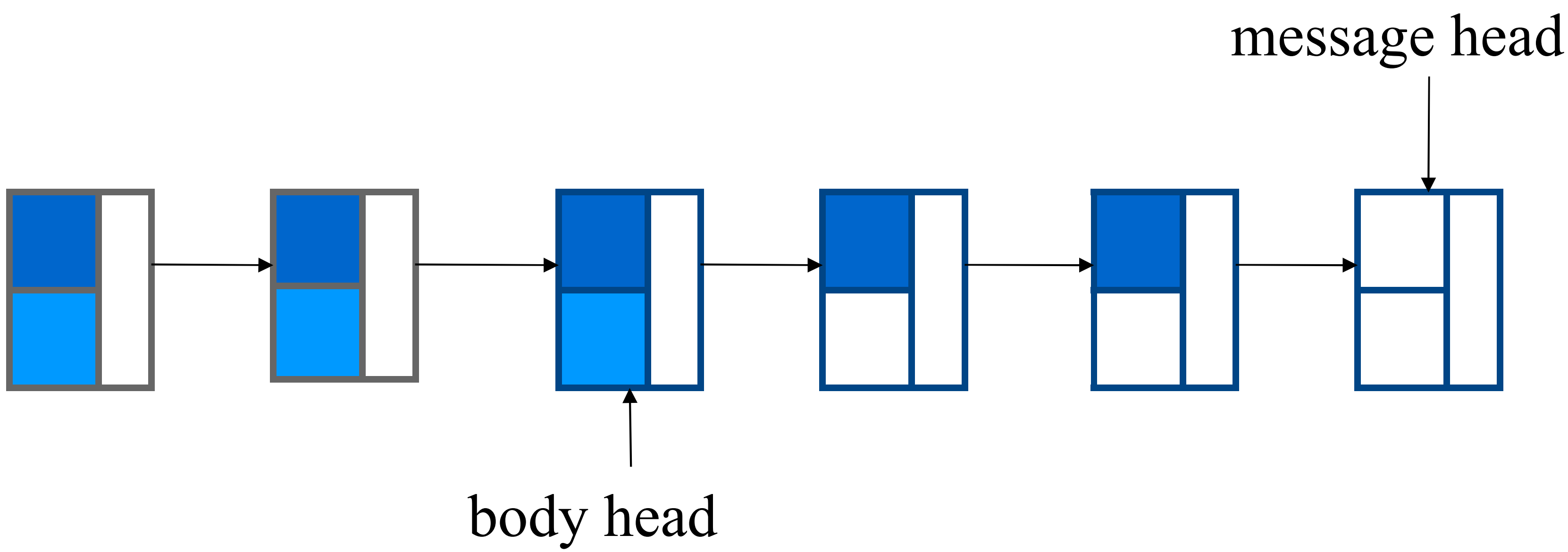
- *lingering* task provides the finish scope
- still need to enforce invariant of actor processing only one message at a time
- one-to-one mapping between a message and a task that processes it
- use Data-Driven Controls (DDCs)

Data-Driven Control

- has two fields
  - a data
  - an execution body
- dynamic single assignment of both fields
- task is scheduled when both data and body available

class DataDrivenControl	
data	Some-Message
body	Some-Runnable

Message Processing invariant...



- actor mailbox is a concurrent linked-list of DDCs
- DDC tasks inherit finish scope from the *lingering* task

Actors mapped to AFM

- Asynchronous messaging handled
- One message processed at a time invariant preserved
- Additional constructs used
  - *lingering* tasks
  - data-driven controls
- No extra constraints placed on the Actors
- Benefits:
  - easier termination detection
  - parallelize actors

Termination detection in actor programs

- Two existing techniques
  - users explicitly manage blocking constructs
  - detect quiescence
- AFM mapping makes it easy
  - wrap actors in a finish scope
  - finish scope is blocked under all async spawned inside it have not terminated
    - actor alive → *lingering* task pending
    - actor terminated → *lingering* task complete

Hybrid Actor – PingPong

```
object LightweightActorPingPong {
  def run(numMsgs: Int): Unit = {
    finish {
      val pong = new LwPongActor()
      val ping = new LwPingActor(numMsgs, pong)
      ping.start
      pong.start
      ping ! LwStart
  } }

class LwPongActor extends HabaneroReactor {
  private var pongCount = 0

  override def behavior() = {
    case LwPing(sender) =>
      sender ! LwPong(self)
      pongCount = pongCount + 1
    case LwStop =>
      exit()
  } }
```

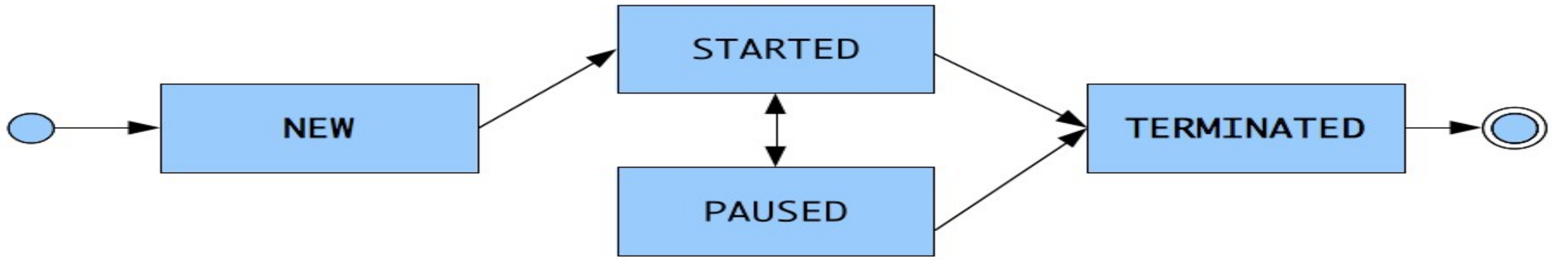
```
class LwPingActor(count: Int,
    pong: HabaneroReactor)
    extends HabaneroReactor {

  private var pingsLeft = count

  override def behavior() = {
    case LwStart =>
      pong ! LwPing(self)
      pingsLeft = pingsLeft - 1
    case LwSendPing =>
      pong ! LwPing(self)
      pingsLeft = pingsLeft - 1
    case LwPong(sender) =>
      if (pingsLeft > 0)
        self ! LwSendPing
      else {
        pong ! LwStop
        exit()
      }
} }
```


habanero-scala code

Parallelizing Actors

- Traditionally actor message processing (MP) has been sequential
- Under the AFM, we can use of two techniques to parallelize the MP
  - Use finish construct in MP body and spawn child tasks (asyncs)
  - allow *escaping* asyncs inside MP body
    - WAIT! What about the single message processing invariant?
    - use pause and resume

Pause and Resume an Actor



- paused state
  - actor will no longer process messages sent to it
- new operations:
  - pause(): move from started to paused state
  - resume(): move from paused to started state
- pause actor before returning from MP body
- resume actor when safe to process next message

New constructs in Hybrid model

- Event-driven tasks in AFM
- Non-blocking receives for actors
- Stateless actors

Event-Driven Tasks

- Actors are AFM tasks with continuations
- Actors (tasks) can resume continuations when they receive messages
- Tasks can coordinate by messaging each other

Hybrid – Quicksort

```
class QuicksortActor(parent: QuicksortActor,
    positionRelativeToParent: Position) extends HabaneroReactor {

  private val selfActor = this
  var result: ListBuffer[Int] = null
  private var numFragments = 0

  def notifyParentAndTerminate() = {
    if (parent ne null) parent ! Result(result, positionRelativeToParent)
    exit()
  }
  override def behavior() = {
    case Sort(data) =>
      val dataLength: Int = data.length
      if (dataLength < QuicksortConfig.CUTOFF) {
        result = quicksortSeq(data)
        notifyParentAndTerminate()
      } else {
        val pivot = data(dataLength / 2)
        async {
          val leftUnsorted = filterLessThan(data, pivot)
          val leftActor = new QuicksortActor(selfActor, LEFT)
          leftActor.start(); leftActor ! Sort(leftUnsorted)
        }
        async { /* similar code for right fragment */ }
        result = filterEqualsTo(data, pivot)
        numFragments += 1
      }
    case Result(data, position) =>
      if (position eq LEFT) result = data ++ result
      else if (position eq RIGHT) result = result ++ data
      numFragments += 1
      if (numFragments == 3) notifyParentAndTerminate()
  } }
```

habanero-scala code

Non-blocking receives

- Simulates synchronous communication **without** blocking

```
class ActorSimulatingReceive() extends ParallelActor {
  override def behavior() = {
    case msg: SomeMessage =>
      ...
      val theDdf = ddf[ValueType]()
      anotherActor ! new Message(theDdf)
      pause() // temporarily disable further message processing
      asyncAwait(theDdf) {
        val responseVal = theDdf.get()
        // process the current message
        ...
        resume() // enable further message processing
      }
      // return in paused state
  }
}
```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Stateless Actors

- Actors with no state, can actively process multiple messages without violating actor constraints

```
class StatelessActor() extends ParallelActor {
  override def behavior() = {
    case msg: SomeMessage =>
      async {
        // process the current message
      }
      if (enoughMessagesProcessed) {
        exit()
      }
      // return immediately to be ready to process the next message
  }
}
```


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Hybrid Model – *pro et contra*

- Pros
  - easier to achieve data locality using places
  - provides new coordination construct (actors) for arbitrary computation DAGs in AFM style
  - actors seamlessly interact with any of the other AFM compliant constructs (DDF, Phaser, etc.)
- Cons
  - possible data-races inside actors
  - all started actors need to be explicitly terminated

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Hybrid Model – Applications

- Multiple Producer-Consumer with Bounded Buffer
  - producers, consumers and buffer are all actors
  - producers and consumer bodies can be parallelized
  - no data-races in the buffer as only one message processed at a time

Hybrid Model – Applications...

- Pipelined Parallelism
  - natural fit with the AM since each stage can be represented as an actor
  - single message processing
  - stages however need to ensure ordering of messages while processing them
  - introduce parallelism within the stages to reduce effects of slowest stage of pipeline
  - e.g. Sieve of Eratosthenes

Hybrid Model – Applications...

- Speculative Parallelization
  - common while processing data structures such as trees and graphs
  - each node represented as an actor
  - nodes can coordinate with other nodes for dependences but execute in parallel when no dependences exist
  - hybrid model can be used to exploit the parallelism inside the actors
  - e.g. Online (Hierarchical) Facility Location

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Habanero-Scala

- Reference implementation of the hybrid model
- Scala is the host language
  - DSL features mean no new compiler required
  - runs on the JVM like Habanero-Java (HJ)
    - use library approach to port HJ constructs
    - use Scala DSL to retain close to HJ syntax
  - pattern matching constructs allows elegant support for actors
- Supports finish, async, futures, DDF, Phasers,...

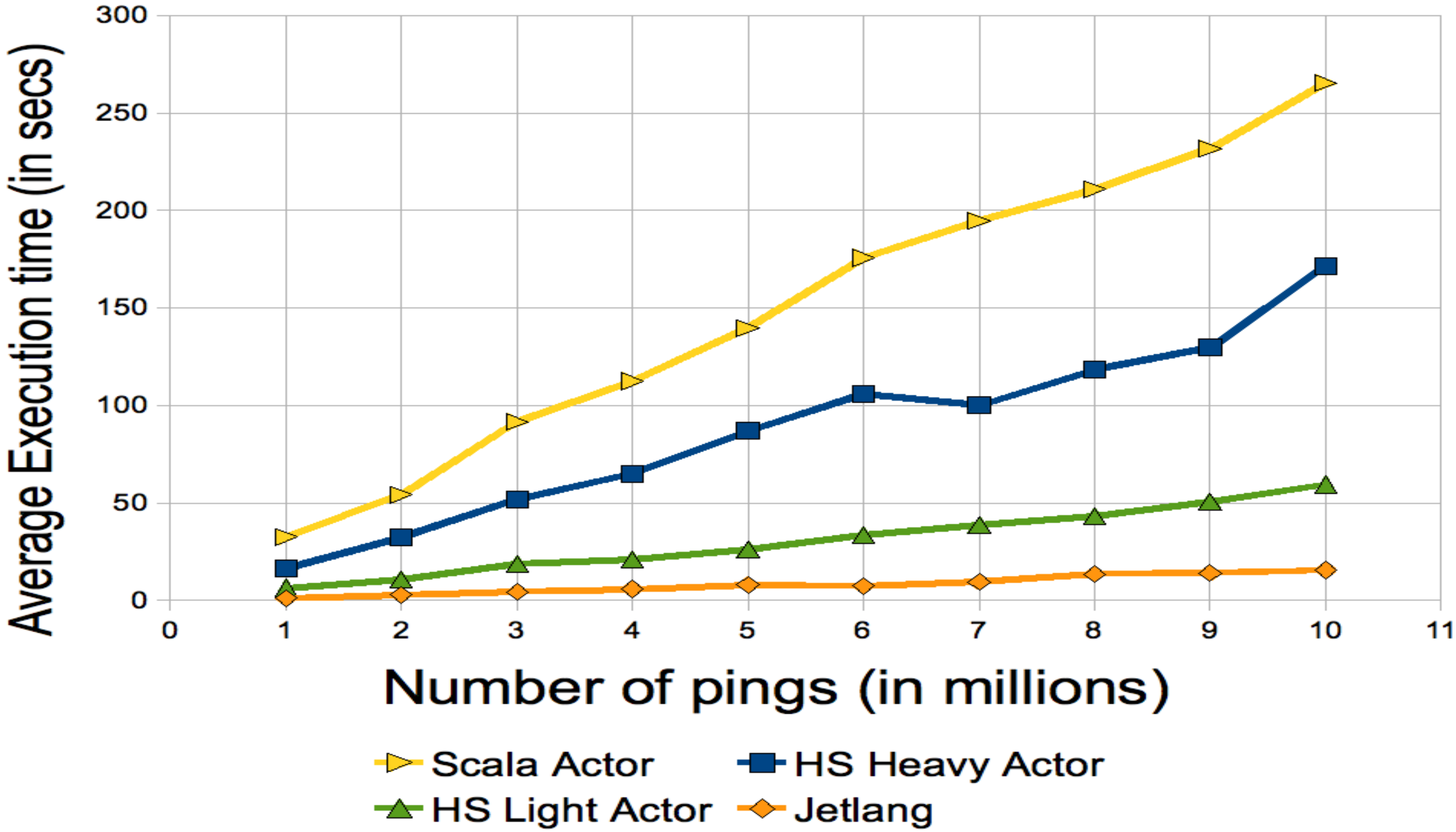
Habanero-Scala Actors

- *heavy* actors
  - standard Scala actors extended to fit the hybrid model
  - no support for pause/resume
  - heavy as standard Scala actors use exceptions for control flow
- *light* actors
  - support pause resume (thus non-blocking receives)
  - use DDCs for control flow
  - supports become/unbecome operations that allow actor to change behavior

Experimental Setup

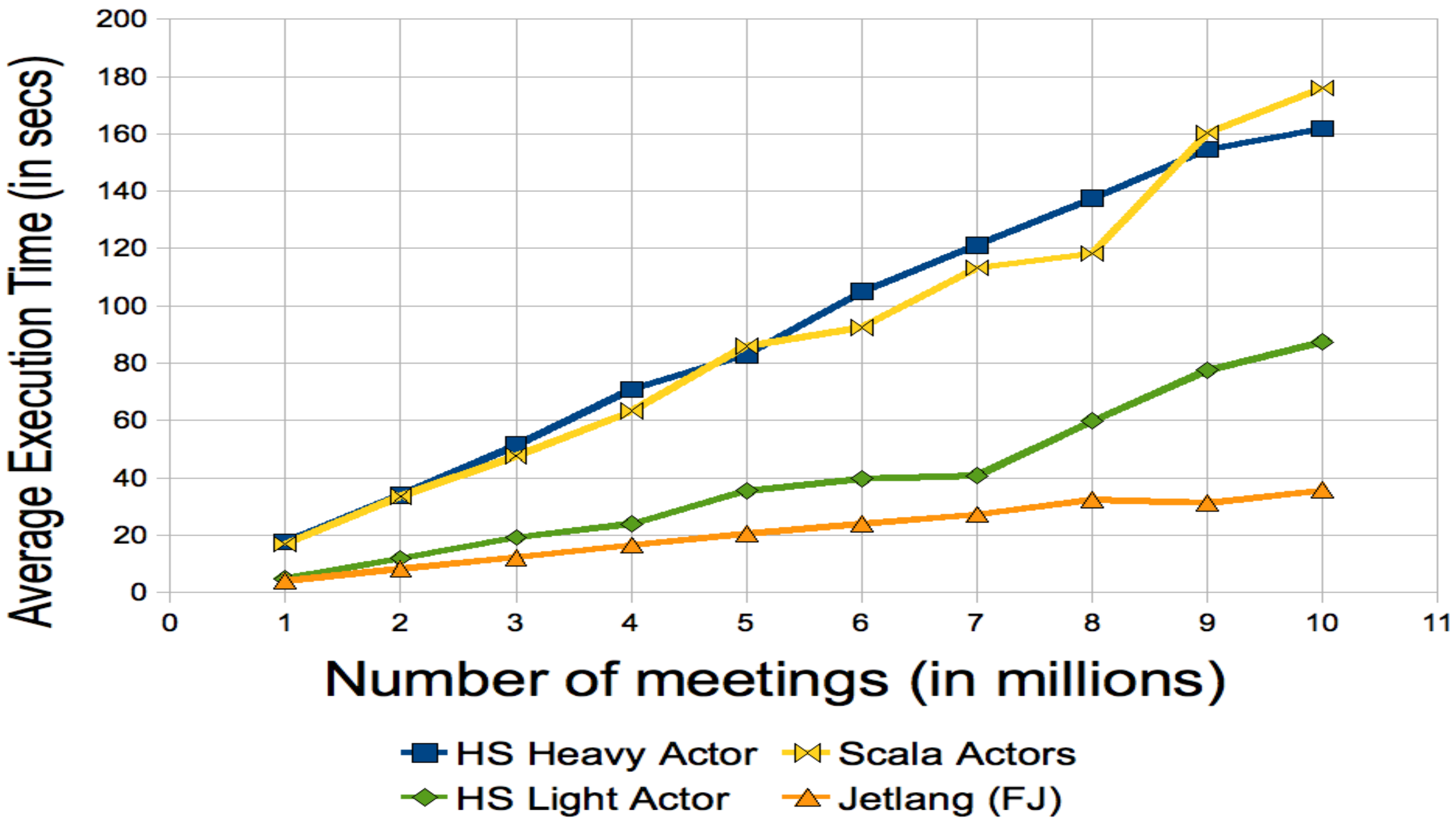
- Intel Xeon 2.4GHz system
- 16-core (quad-socket, quad-core per socket)
- 32 GB memory, running Red Hat Linux (RHEL 5)
- Sun Hotspot JDK 1.6
- Scala version 2.9.1.final
- latest versions of Habanero-Java and Habanero-Scala from Rice subversion repository
- geometric mean of best eight out of ten runs in the same JVM instance reported

Ping-Pong Benchmark



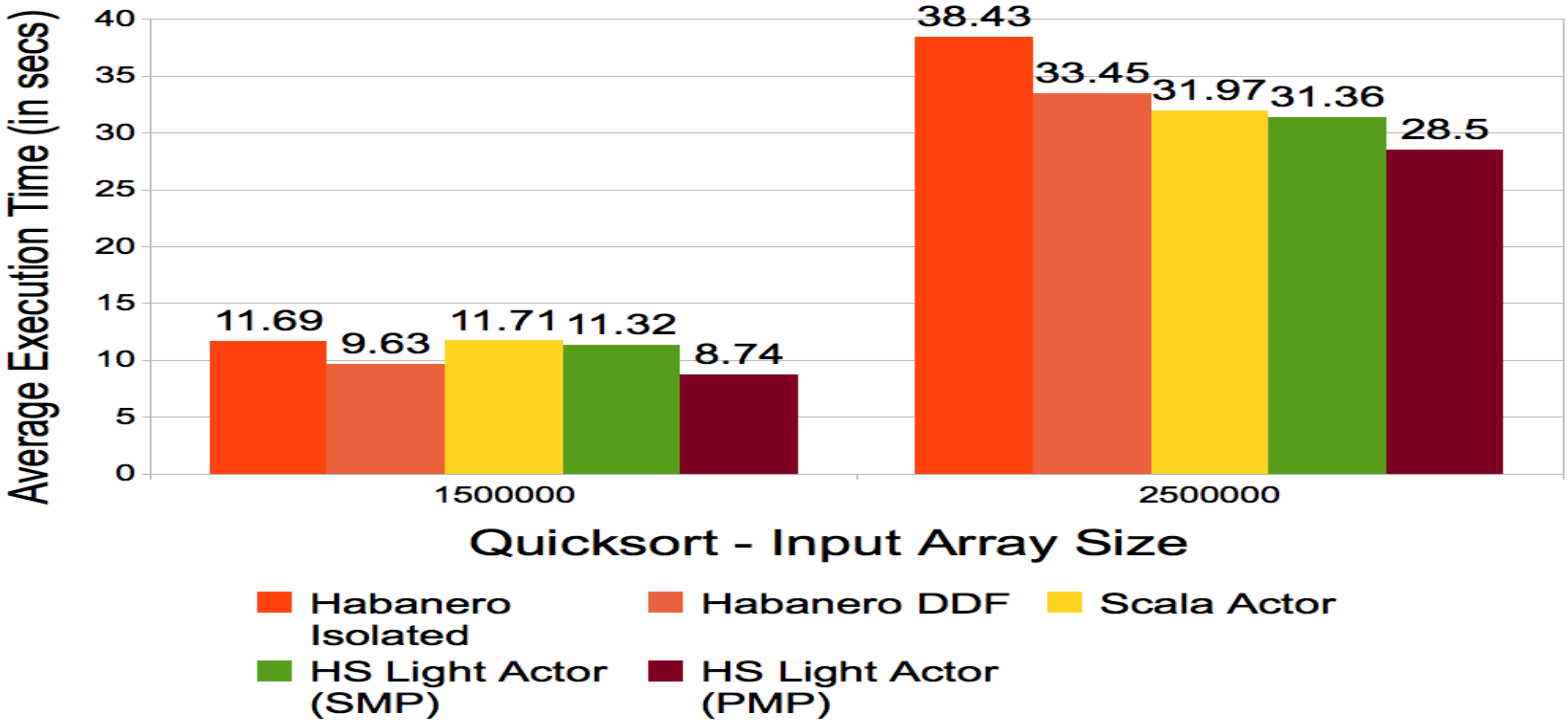
- measures raw message throughput
- Jetlang fastest, provides a low-level messaging API
- HS Light actor faster than standard Scala actors: no exceptions

Chameneos Benchmark



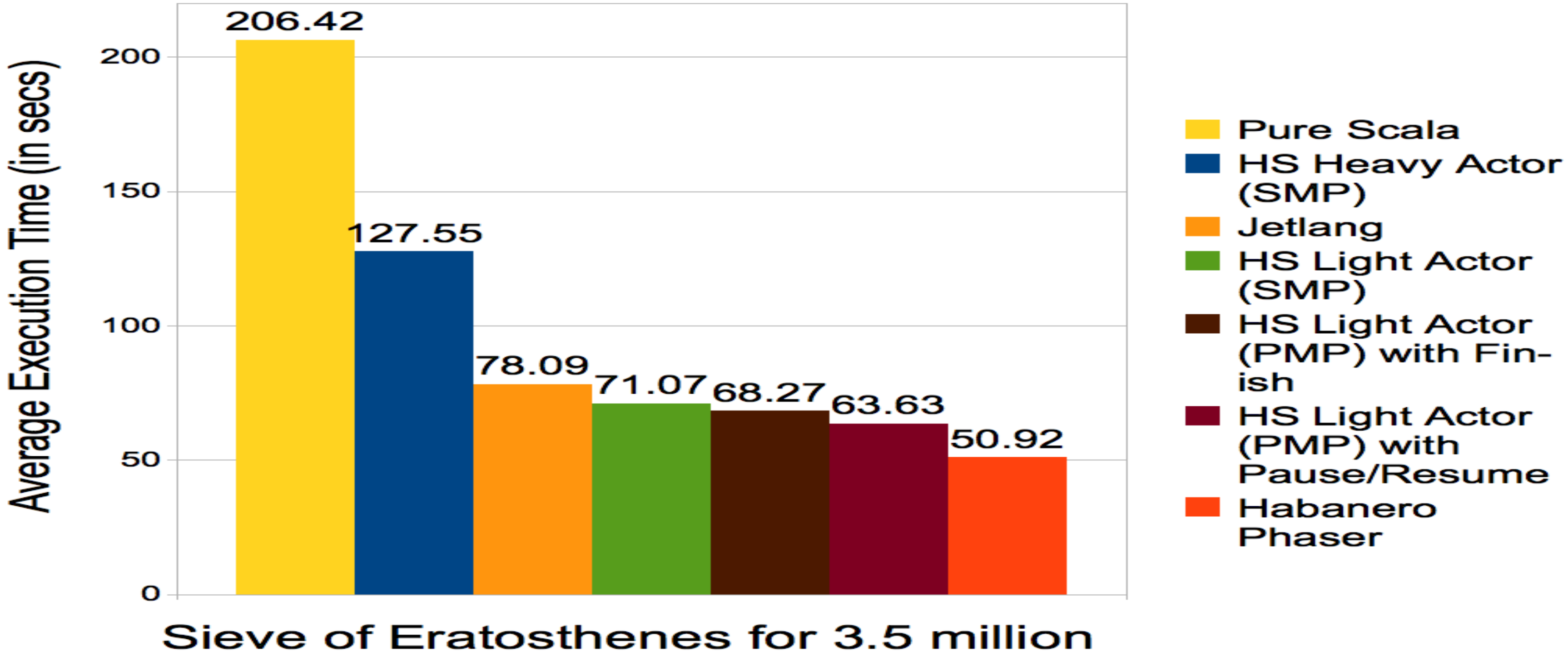
- measures cost of synchronization
- Jetlang again fastest
- HS Light actor faster than standard Scala actors

Quicksort Benchmark



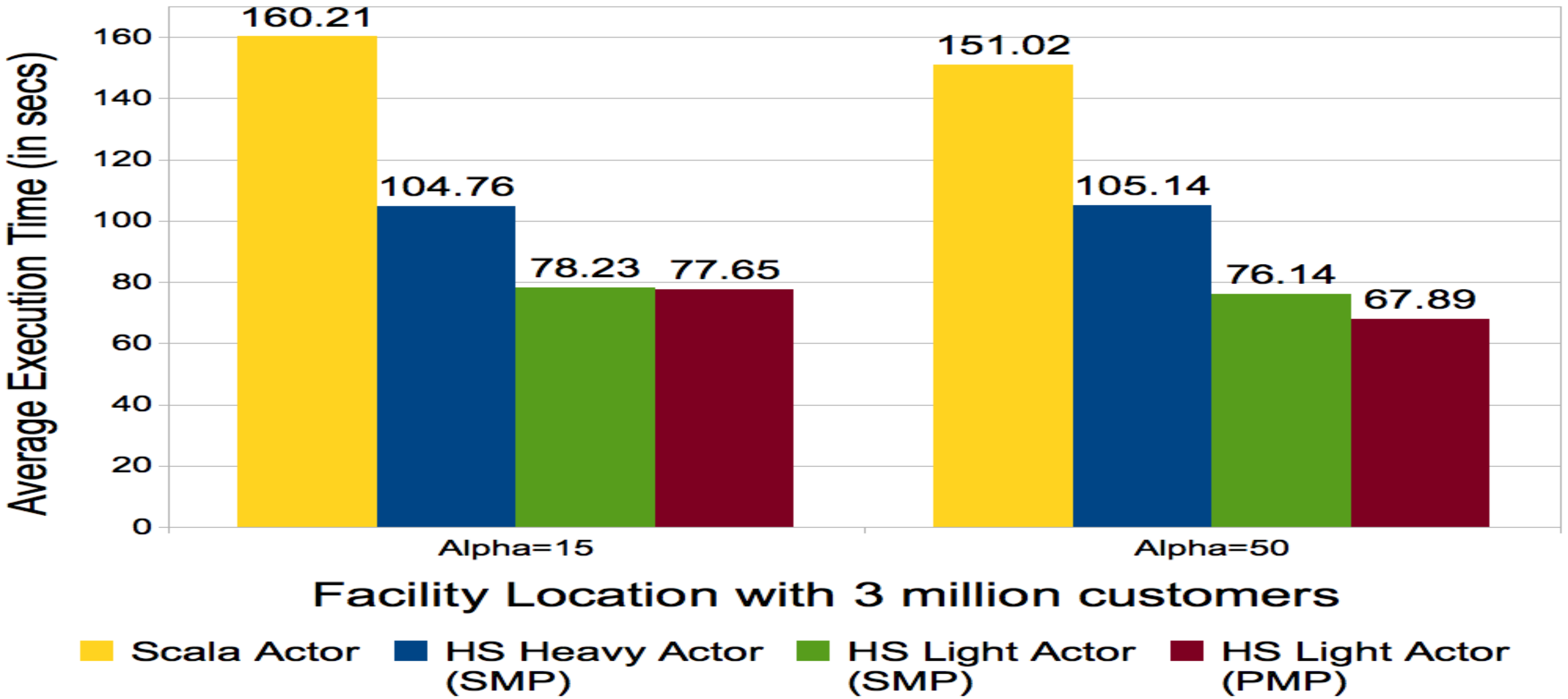
- Hybrid solution fastest, up to 22% faster than pure Actor solution
- Hybrid faster than DDFs for larger arrays as evaluation from partial results gets more profitable
- Habanero Isolation based solution does not scale

Sieve of Eratosthenes



- Phaser solution fastest: tuned to not create more tasks than workers
- Hybrid solution up to 10% faster than Light actor solution
- Hybrid solution faster than Jetlang solution
- Pause-Resume faster than Finish version
- Heavy actor faster than Scala version: thread binding benefits

Hierarchical Facility Location



- Larger alpha → more customers to process while creating children → more benefits of parallelism from hybrid model
- Hybrid solution fastest, up to 11% faster than pure Actor solution
- Heavy actors faster than Scala actors: thread binding

Contributions

- A hybrid programming model that integrates the Fork/Join model and the Actor model
- An implementation: Habanero-Scala
  - the Actor model using data-driven constructs in the Async/Finish model
  - the hybrid programming model supporting async/finish/… and pause/resume
- A study of application characteristics that are amenable to being more efficiently solved using the hybrid model compared to the FJM or AM

Future work

- Batch message processing, as in Jetlang, to avoid extraneous creation of tasks
- Use the Hybrid model to port Async Finish model constructs to a distributed memory system

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Thank you!

[image source: http://www.jerryzeinfeld.com/tag/question-of-the-day/]