COMP 322: Fundamentals of Parallel Programming

Lecture 22: Mutual Exclusion with Actors (contd)

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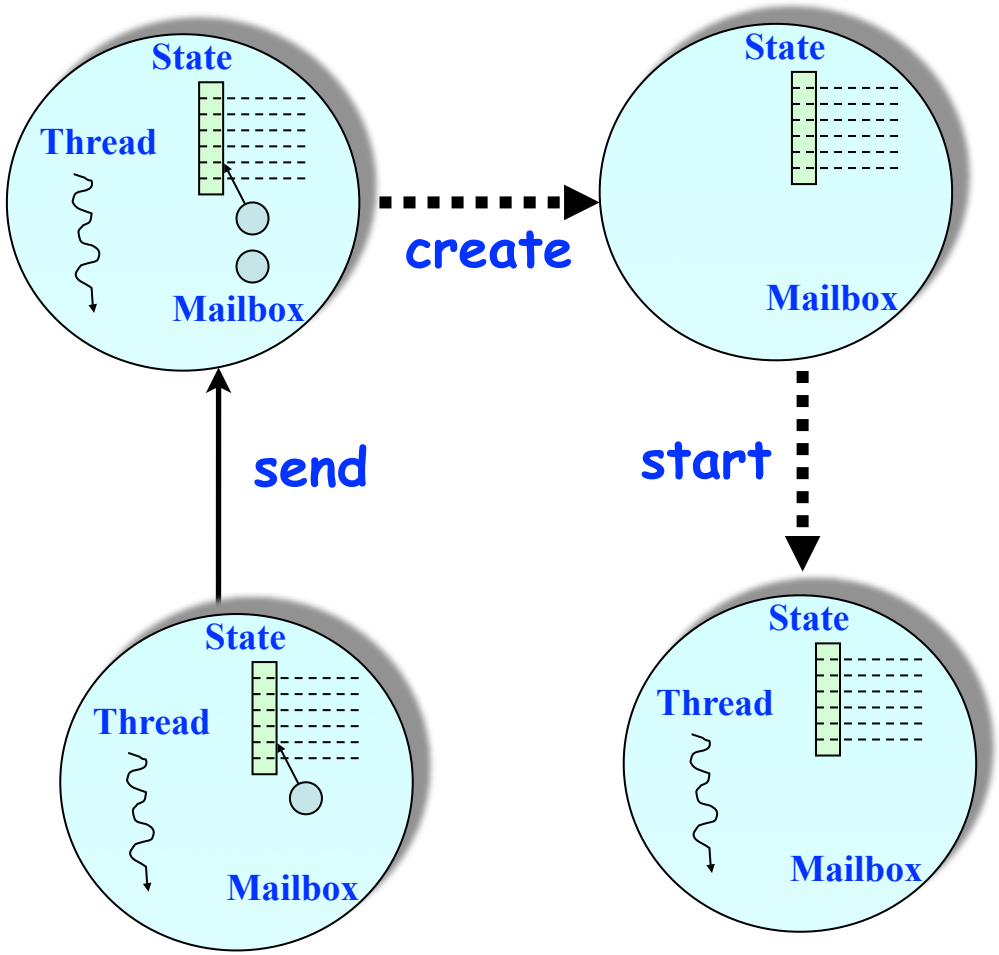
https://wiki.rice.edu/confluence/display/PARPROG/COMP322

Actor Acknowledgments

- Actor Model - Wikipedia
- "Actor Concurrency" by Alex Miller
  http://www.slideshare.net/alexmiller/actor-concurrency
- "The Actor Model - Towards Better Concurrency" by Dror Bereznitsky
  http://www.slideshare.net/drorbr/the-actor-model-towards-better-concurrency
- "Actors in Scala" by Philipp Haller and Frank Sommers

The Actor Model (Recap)

- An actor may:
  - process messages
  - read/write local state
  - create a new actor
  - start a new actor
  - send messages to other actors
  - terminate
- An actor processes messages sequentially
  - guaranteed mutual exclusion on accesses to local state



Actor Model

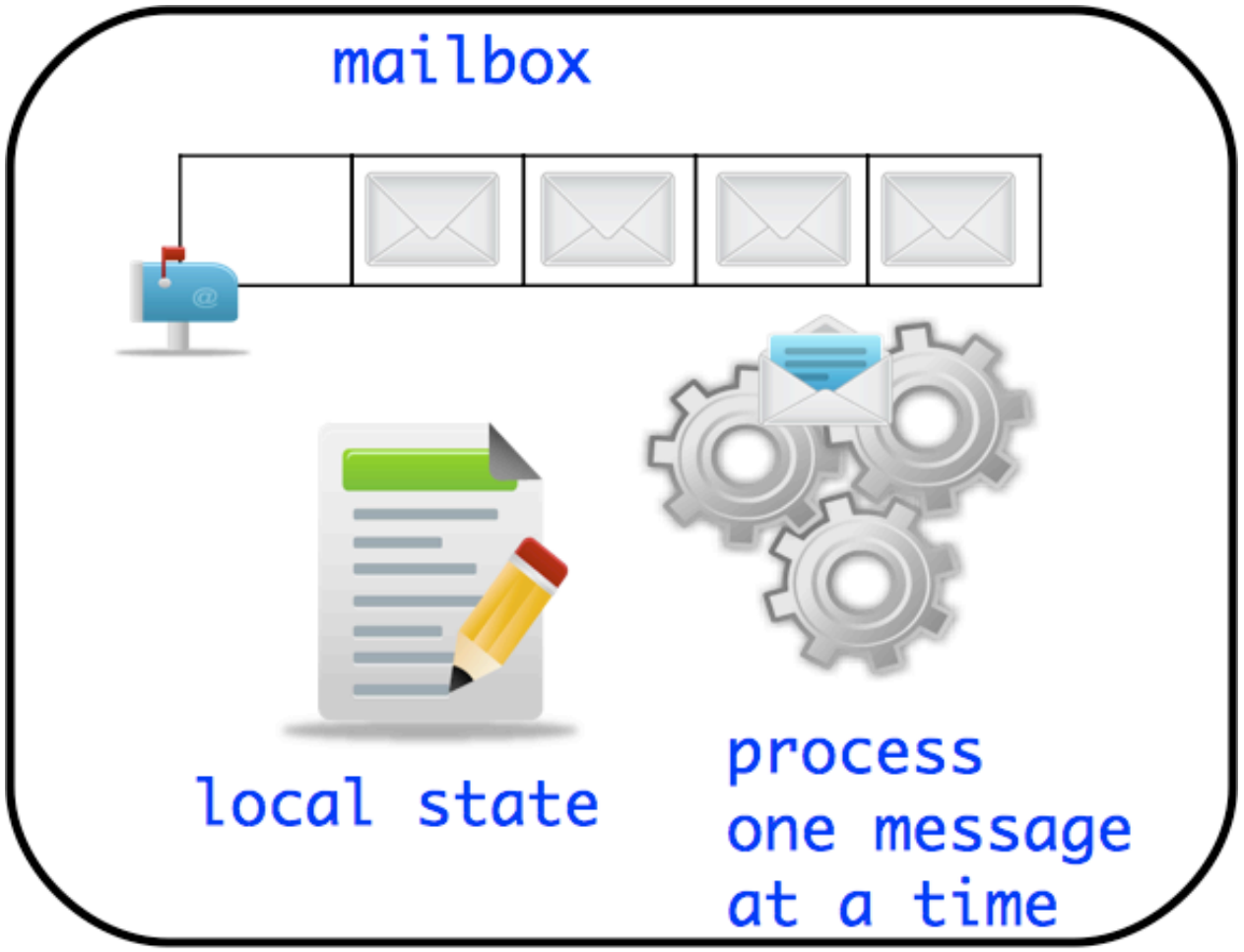
- A message-based concurrency model to manage mutable shared state
- First defined in 1973 by Carl Hewitt

  Further theoretical development by Henry Baker and Gul Agha
- Key Ideas:
  - Everything is an **Actor**!
  - Analogous to "everything is an object" in OOP
  - Encapsulate shared state in Actors
  - **Mutable state is not shared**
- Other important features (we will get to these later)
  - Asynchronous message passing
  - Non-deterministic ordering of messages

Actors' Behavior

- Actors are passive and lazy
  - Only respond if messages are sent to them
    - Messages may come from other actors or from main program (environment)
  - Only process one message at a time
    - Pending messages are stored in a "mailbox"
    - Parallelism comes from multiple actors processing messages in parallel
  - Mutate local state **only** while processing a message
  - Mutating local state can result in actor responding differently to subsequent messages

Actor



Actor Analogy - Email

- Email accounts are a good simple analogy to Actors
- To notify some information to (i.e. change some state of) A1 another account A2 sends an email (i.e. sends a message) to A1
- A1 has a mailbox to store all incoming messages
- A1 can read (i.e. process) one email at a time
  - At least that is what normal people do :)
- Reading an email can change how you respond to a subsequent email
  - e.g. receiving pleasant news while reading current email can affect the response to a subsequent email
- Actor creation (stretching the analogy)
  - Create a new email account that can send/receive messages

Actor Life Cycle

Actor states

- New: Actor has been created
  - e.g., email account has been created
- Started: Actor can receive and process messages
  - e.g., email account has been activated
- Terminated: Actor will no longer processes messages
  - e.g., termination of email account after graduation

Using Actors in HJ

- Create your custom class which extends hj.lang.Actor<Object> ,and implement the void process() method

```
class MyActor extends Actor<Object> {
  protected void process(Object message) {
    System.out.println("Processing " + message);
} }
```

- Instantiate and start your actor

```
Actor<Object> anActor = new MyActor(); anActor.start()
```

- Send messages to the actor

```
anActor.send(aMessage); //aMessage can be any object in general
```

- Use a special message to terminate an actor

```
protected void process(Object message) {
  if (message.someCondition()) exit();
}
```

- Actor execution implemented as async tasks in HJ
  - Can use finish to await their completion

Hello World Example

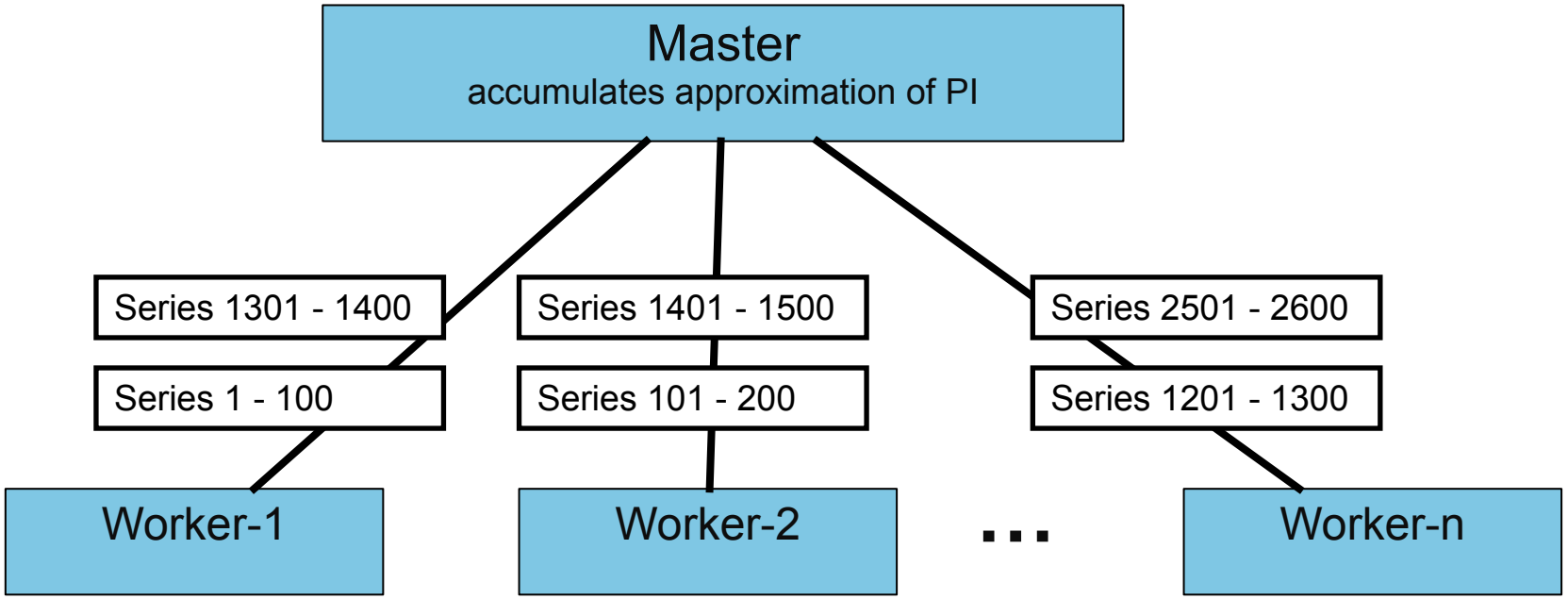
```
1. public class HelloWorld {
2.   public static void main(String[] args) {
3.     EchoActor actor = new EchoActor();
4.     actor.start(); // don't forget to start the actor
5.     actor.send("Hello"); // asynchronous send (returns immediately)
6.     actor.send("World");
7.     actor.send(EchoActor.STOP_MSG);
8.   }
9. }
10.class EchoActor extends Actor<Object> {
11.  static final Object STOP_MSG = new Object();
12.  private int messageCount = 0;
13.  protected void process(final Object msg) {
14.    if (STOP_MSG.equals(msg)) {
15.       println("Message-" + messageCount + ": terminating.");
16.       exit(); // never forget to terminate an actor
17.     } else {
          messageCount += 1;
18.       println("Message-" + messageCount + ": " + msg);
19.} } }
```

Sends are asynchronous in actor model, but HJ Actor library preserves order of messages between same sender and receiver

Pi Computation Example

$$\pi = 4\sum_{k=0}^{\infty}\frac{(-1)^k}{2k+1} = \frac{4}{1} - \frac{4}{3} + \frac{4}{5} - \frac{4}{7} + \frac{4}{9} - \cdots.$$

- Use Master-Worker technique:



Source: http://www.enotes.com/topic/Pi

Pi Calculation --- Master Actor

```
1. class Master extends Actor<Object> {
2.   private double result = 0; private int nrMsgsReceived = 0;
3.   private Worker[] workers;
4.   Master(nrWrkrs, nrEls, nrMsgs) {...} // constructor
5.   void start() {
6.     super.start(); // Starts the master actor
7.     // Create and start workers
8.     workers = new Worker[nrWrkrs];
9.     for (int i = 0; i < nrwrkrs; i++) {
10.      workers[i] = new Worker();
11.      workers[i].start();
12.    }
13.    // Send messages to workers
14.    for (int j = 0; j < nrMsgs; j++) {
15.      someWrkr = ... ; // Select worker for message j
16.      someWrkr.send(new Work(...));
17.    }
18.  } // start()
```

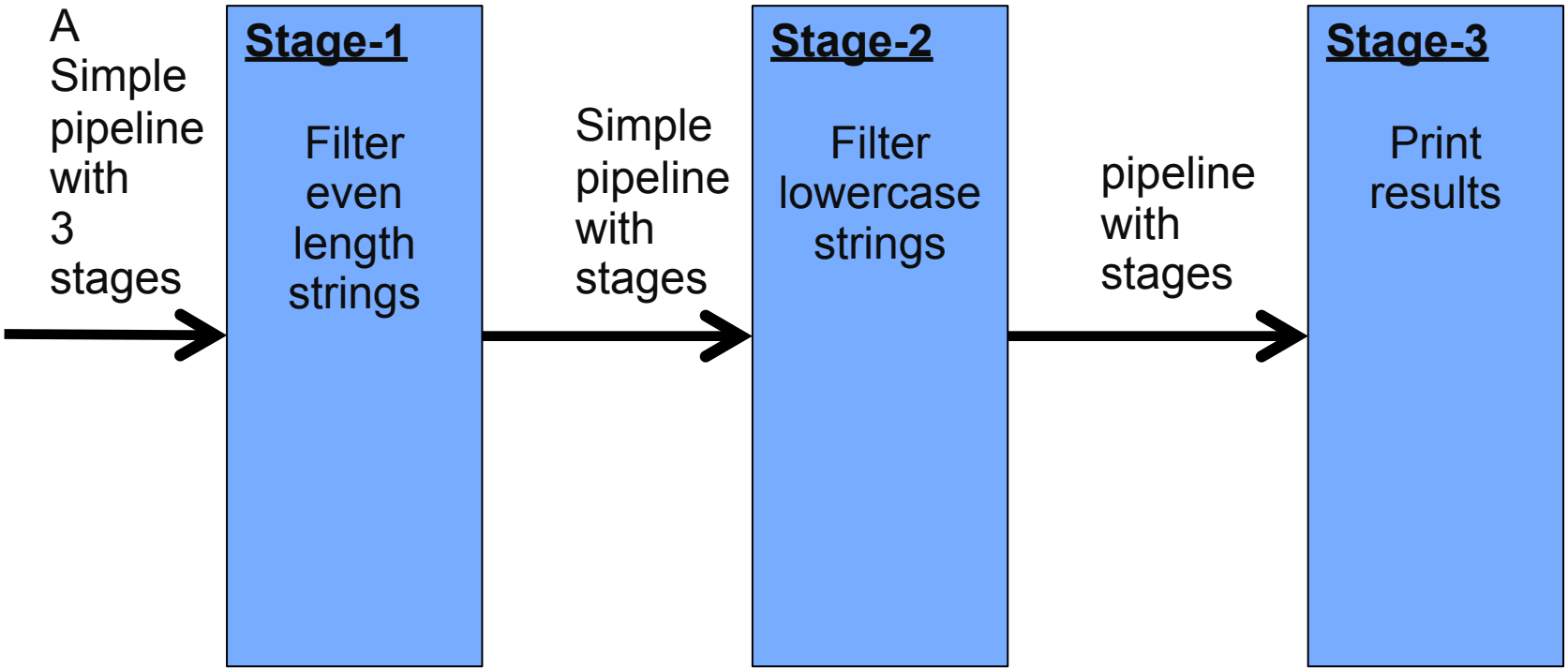

Pi Calculation --- Master Actor (contd)

```
19.   void exit() {
20.     for (int i = 0; i < nrWrkrs; i++) workers[i].send(new Stop());
21.     super.exit(); // Terminates the actor
22.   } // exit()
23.   void process(final Object msg) {
24.     if (msg instanceof Result) {
25.       result += ((Result) msg).result;
26.       nrMsgsReceived += 1;
27.       if (nrMsgsReceived == nrMsgs) exit();
28.     }
29.     // Handle other message cases here
30.   } // process()
31. } // Master
32.  . . .
33.  // Main program
34.  Master master = new Master(w, e, m);
35.  finish master.start();
36.  println("PI = " + master.getResult());
```


Pi Calculation --- Worker Actor

```
1. class Worker extends Actor<Object> {
2.   void process(Object msg) {
3.     if (msg instanceof Stop) exit();
4.     else if (msg instanceof Work) {
5.       Work wm = (Work) msg;
6.       double result = calculatePiFor(wm.start, wm.end)
7.       master.send(new ResultMessage(result));    }
8.   } // process()
9.
10.  private double calculatePiFor(int start, int end) {
11.    double acc = 0.0;
12.    for (int i = start; i < end; i++) {
13.      acc += 4.0 * (1 - (i % 2) * 2) / (2 * i + 1);
14.    }
15.    return acc;
16.  }
17. } // Worker
```


Simple Pipeline



Simple Pipeline using HJ Actors

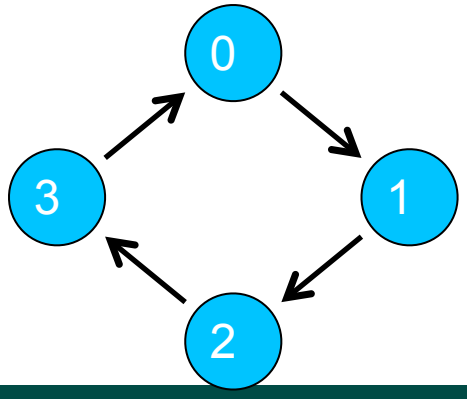
```
1.    // Main program
2.    finish {
3.      Actor<Object> firstStage =
4.        new EvenLengthFilter(
5.          new LowerCaseFilter(
6.            new LastStage()));
7.      firstStage.start(); // starts others
8.      firstStage.send("pipeline");
9.      firstStage.send(new StopMessage());
10.   }
11.
12.class LastStage extends Actor {
13.   protected void process(Object msg) {
14.     if (msg instanceof StopMessage) {
15.       exit();
16.     } else if (msg instanceof String) {
17.       System.out.println(msg);
18.} } }
```


Simple Pipeline using HJ Actors (contd)

```
19.class LowerCaseFilter extends Actor {
20.  protected void process(Object msg) {
21.    if (msg instanceof StopMessage) {
22.      exit(); nextStage.send(msg);
23.    } else if (msg instanceof String) {
24.      String str = (String) msg;
25.      if (str.toLowerCase().equals(str)) {
26.        nextStage.send(str);
27.} } } }
28.class EvenLengthFilter extends Actor {
29.  protected void process(Object msg) {
30.    if (msg instanceof StopMessage) {
31.      nextStage.send(msg);
32.      exit();
33.    } else if (msg instanceof String) {
34.      String msgStr = (String) msg;
35.      if (msgStr.length() % 2 == 0) {
36.        nextStage.send(msgStr);
37.} } } }
```


ThreadRing (Coordination) Example

```
1.  finish {
2.    int numThreads = 4;
3.    int numberOfHops = 10;
4.    ThreadRingActor[] ring =
        new ThreadRingActor[numThreads];
5.    for(int i=numThreads-1;i>=0; i--) {
6.      ring[i] = new ThreadRingActor(i);
7.      ring[i].start();
8.      if (i < numThreads - 1) {
9.        ring[i].nextActor(ring[i + 1]);
10.   } }
11.   ring[numThreads-1].nextActor(ring[0]);
12.   ring[0].send(numberOfHops);
13. }
```




```
14. class ThreadRingActor
15.     extends Actor<Object> {
16.   private Actor<Object> nextActor;
17.   private final int id;
18.   ...
19.   public void nextActor(
        Actor<Object> nextActor) {...}
20.   void process(Object theMsg) {
21.     if (theMsg instanceof Integer) {
22.       Integer n = (Integer) theMsg;
23.       if (n > 0) {
24.         println("Thread-" + id +
25.           " active, remaining = " + n);
26.         nextActor.send(n - 1);
27.       } else {
28.         println("Exiting Thread-" +
    id);
29.         nextActor.send(-1);
30.         exit();
31.       }
32.     } else {
33.     /* ERROR - handle appropriately */
34. } } }
```


Integer Counter Example

Without Actors:

```
1. int counter = 0;
2. public void foo() {
3.   // do something
4.   isolated {
5.     counter++;
6.   }
7.   // do something else
8. }
9. public void bar() {
10.  // do something
11.  isolated {
12.    counter--;
13.  } }
```

- Can also use atomic variables instead of isolated

With Actors:

```
14.class Counter extends Actor {
15.  private int counter = 0; // local state
16.  public void process(Message msg) {
17.    if (msg instanceof IncMessage) {
18.      counter++;
19.    } else if (msg instanceof DecMessage){
20.      counter--;
21.} } }

14.   Counter counter = new Counter();
15.   public void foo() {
16.  // do something
17.  counter.send(new IncrementMessage(1));
18.  // do something else
19.}
20.   public void bar() {
21.  // do something
22.  counter.send(new DecrementMessage(1));
23.}
```


Limitations of Actor Model

- Deadlocks possible
  - Deadlock occurs when all started (but non-terminated) actors have empty mailboxes
- Data races possible when messages include shared objects
- Simulating synchronous replies requires some effort
  - e.g., does not support addAndGet()
- Implementing truly concurrent data structures is hard
  - No parallel reads, no reductions/accumulators
- Difficult to achieve global consensus
  - Finish and barriers not supported as first-class primitives

==> These limitations can be overcome by using a hybrid model that combines task parallelism with actors

Actors - Simulating synchronous replies

- Actors are inherently asynchronous
- Synchronous replies require blocking operations e.g., async await

```
class CountMessage {
  ... ddf = new DataDrivenFuture();
  int localCount = 0;

static int getAndIncrement(
        CounterActor counterActor) {

   ... msg = new CountMessage();
   counterActor.send(msg);
   // use ddf to wait for response
   // THREAD-BLOCKING
   finish { async await(msg.ddf) { }}
   // return count from the message
   return msg.localCount;
} }
```

```
class CounterActor extends Actor {
   int counter = 0;
   void process(Object m) {

      if (m instanceof CountMessage){
         CountMessage msg = ...
         counter++;
           msg.localCount = counter;
           msg.ddf.put(true);
       } ...
    } }
```

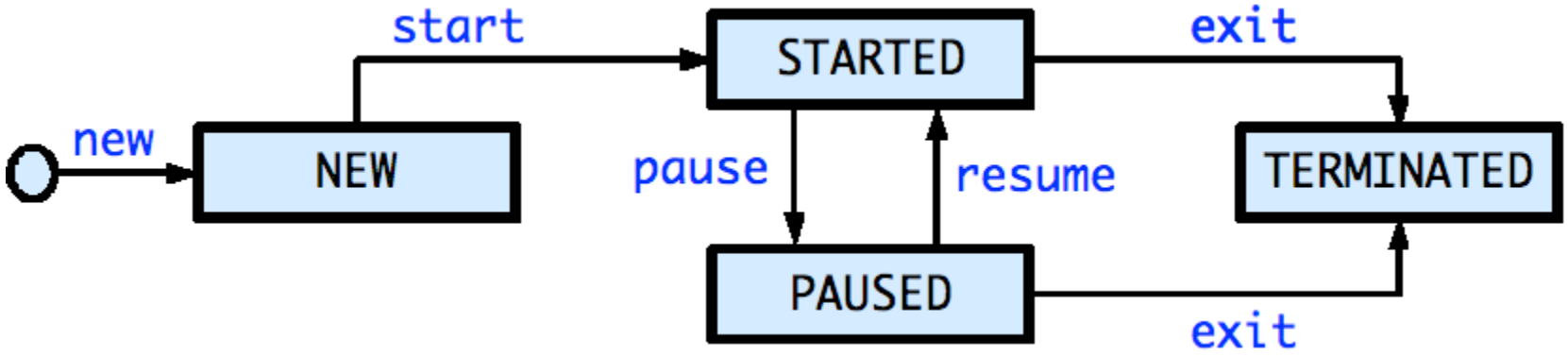

Actors – Global Consensus

- Global consensus is a variant of synchronous reply
  - More complicated because a group of actors is involved
- Non-blocking solutions can be complex e.g.,
  - First send message from master actor to participant actors signaling intention
  - Wait for all participants to reply they are ready. Participants start ignoring messages sent to them apart from the master
  - Once master confirms all participants are ready, master sends the request to each participant and waits for reply from each
  - Master notifies participants that consensus has been reached, everyone can go back to normal functioning

Parallelizing Actors in HJ

- Two techniques:
  - Use finish construct to wrap asyncs in message processing body
    - Finish ensures all spawned asyncs complete before next message is
  - Allow escaping asyncs inside process() message
    - WAIT! Won't escaping asyncs violate the one-message-at-a-time rule in actors
    - Solution: Use pause and resume

Actors: pause and resume



- Paused state: actor will not process subsequent messages until it is resumed
- Pause an actor before returning from message processing body with escaping asyncs
- Resume actor when it is safe to process the next message
- Akin to Java's wait/notify operations with locks

Synchronous Reply using Async-Await (without pause/resume)

```
1. class SynchronousReplyActor1 extends Actor {
2. void process(Message msg) {
3.     if (msg instanceof Ping) {
4.         finish {
5.             DataDrivenFuture<T> ddf = new DataDrivenFuture<T>();
6.             otherActor.send(ddf);
7.             async await(ddf) {
8.                 T synchronousReply = ddf.get();
9.                 // do some processing with synchronous reply
10.            }
11.        }
12.    } else if (msg instanceof ...) { ... } } }
```


Synchronous Reply using Pause/Resume

```
1.  class SynchronousReplyActor2 extends Actor {
2.    void process(Message msg) {
3.      if (msg instanceof Ping) {
4.        DataDrivenFuture<T> ddf = new DataDrivenFuture<T>();
5.        otherActor.send(ddf);
6.        async await(ddf) { // this async processes synchronous reply
7.           T synchronousReply = ddf.get();
8.           // do some processing with synchronous reply
9.           resume(); // allow actor to process next message
10.       }
11.       pause(); // when paused, the actor doesn't process messages
12.     } else if (msg instanceof ...) { ... } } }
```


Other uses of hybrid actor+task parallelism

- Can use finish to detect actor termination
- Event-driven tasks
- Stateless Actors
  - If an actor has no state, it can process multiple messages in parallelism
- Pipeline Parallelism
  - Actors represent pipeline stages
  - Use tasks to balance pipeline by parallelizing slower stages

Summary of Mutual Exclusion approaches in HJ

- Isolated --- analogous to critical sections
- Object-based isolation, isolated(a, b, ...)
  - Single object in list --- like monitor operations on object
  - Multiple objects in list --- deadlock-free mutual exclusion on sets of objects
- Java atomic variables --- optimized implementation of object-based isolation
- Java concurrent collections --- optimized implementation of monitors
- Actors --- different paradigm from task parallelism (mutual exclusion by default)