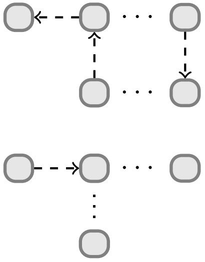
Towards Correct and Efficient Program Execution in Decentralized Networks: Programming Languages, Semantics, and Resource Management

Karl Palmskog
palmskog@kth.se
KTH Royal Institute of Technology

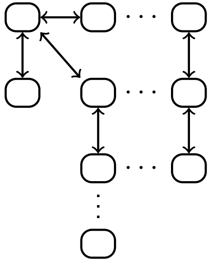
2014-10-24

Problem: Scalable Program Execution

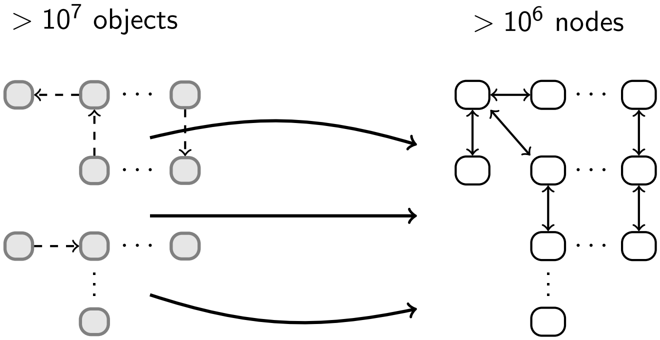
$> 10^7$ objects



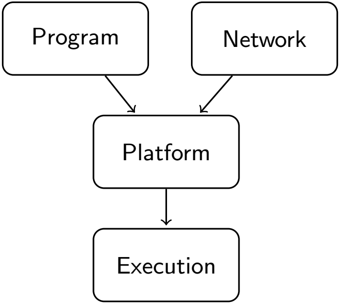
$> 10^6$ nodes



Problem: Scalable Program Execution



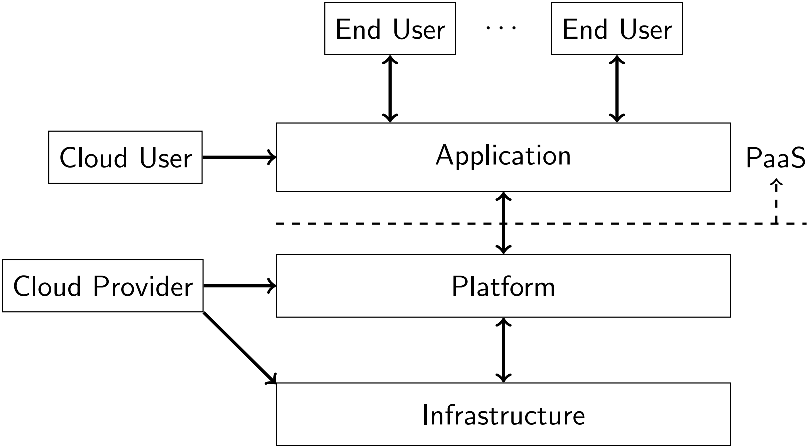
Vision: A Decentralized Program Execution Platform



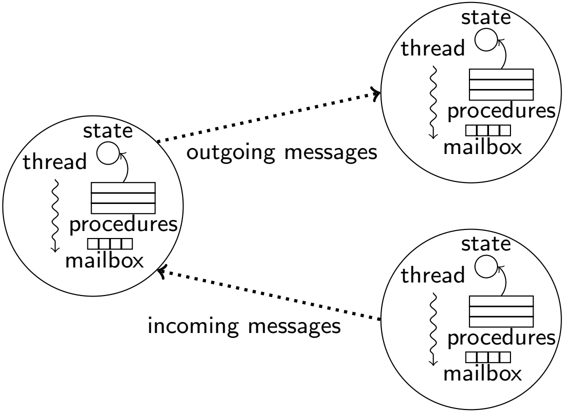
Desirable properties:

- scalable
- abstract
- rigorous
- implementable

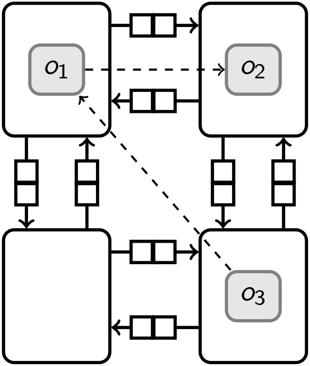
Application: Platform-as-a-Service Cloud Building Block



Message-Passing Programs at Runtime



Execution of Message Passing Programs in Networks



Three Problems

1. **correspondence** with network-oblivious executions
2. **adapt** executions to meet efficiency objectives
3. **conversion** of threaded programs to message-passing model

Contributions

Paper I: Location Independent Routing in Process Network Overlays

Paper II: Efficient and Fully Abstract Routing of Futures in Object Network Overlays

Paper III: ABS-NET: Fully Decentralized Runtime Adaptation for Distributed Objects

Paper IV: Decentralized Adaptive Power Control for Process Networks

Paper V: Dynamic Probabilistic Inference of Atomic Sets

Contributions

	Paper I	Paper II	Paper III	Paper IV	Paper V
theory	✓	✓	✓	✓	✓
practice			✓		✓
correspondence	✓	✓		✓	
adaptability			✓	✓	
conversion					✓

Adaptability Mechanisms

	Paper I	Paper II	Paper III	Paper IV
object mobility	✓	✓	✓	✓
node startup/shutdown				✓
message routing	✓	✓	✓	✓
task scheduling			✓	
message scheduling			✓	(✓)
buffering			✓	
synchrony			✓	
add/remove links				

Objectives

	Paper I	Paper II	Paper III	Paper IV
correspondence	✓	✓		✓
load balancing			✓	
network right-sizing				✓
minimal messaging			✓	
low stretch	✓	✓	✓	✓
self-stabilization	✓	✓	✓	✓
compactness				
confidentiality				

The Abstract Behavioral Specification (ABS) Language

ABS Properties

- formal modeling language for concurrent, distributed systems
- based on active objects
- separate level for immutable data and pure functions
- objects accessed only through interfaces

The Abstract Behavioral Specification (ABS) Language

ABS Properties

- formal modeling language for concurrent, distributed systems
- based on active objects
- separate level for immutable data and pure functions
- objects accessed only through interfaces

Our Use of ABS

Tool for case studies, used while working in EU FP7 HATS project

Paper I & Paper II

Location Independent Routing in Process Network Overlays &
Efficient and Fully Abstract Routing of Futures in Object Network Overlays

Adaptability Mechanisms:

- **object mobility**
- **routing**

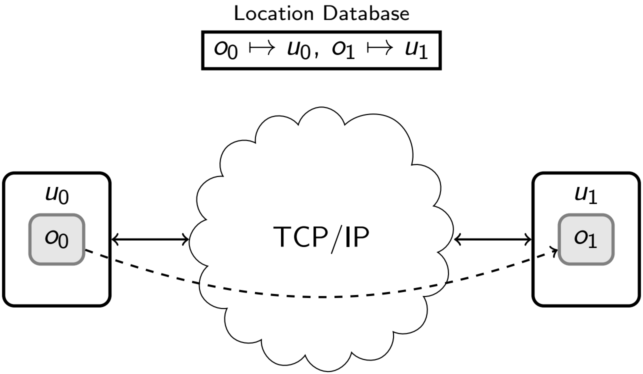
Objectives:

- **correspondence with network-oblivious behavior**
- low stretch
- self-stabilization

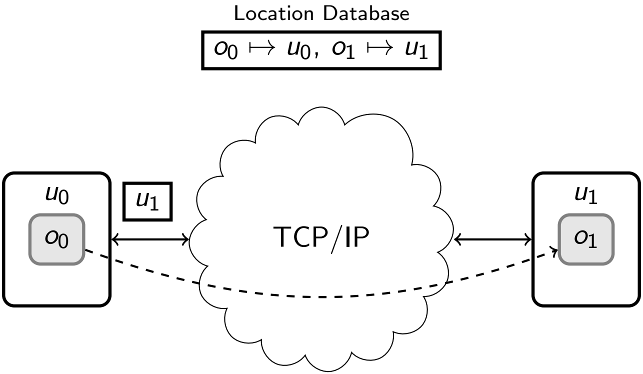
Paper I & Paper II Summary

1. defines fragments of ABS (μABS and mABS)
2. defines standard network-oblivious program behavior
3. introduces location independent routing for network-aware program behavior
4. proves *contextual equivalence* of the behaviors

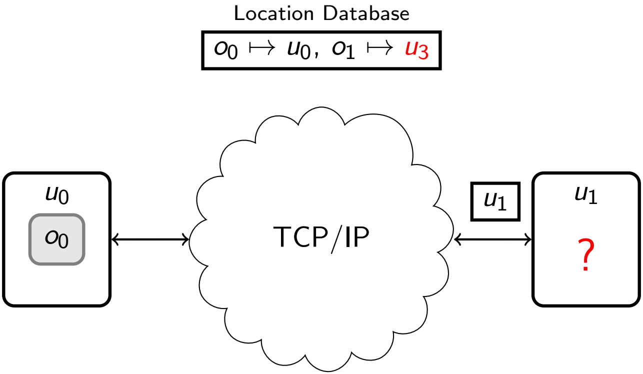
Location Transparency in the Message Passing Model



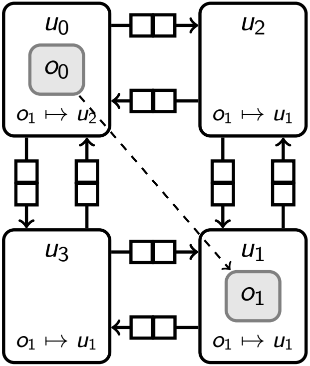
Location Transparency in the Message Passing Model



Location Transparency in the Message Passing Model

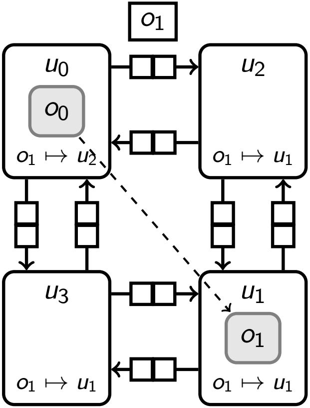


Location Independent Routing



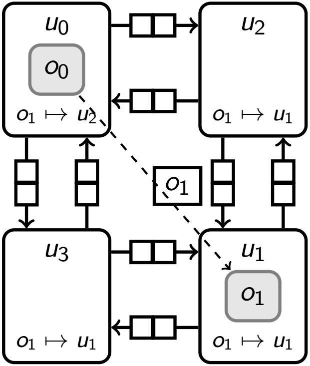
- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

Location Independent Routing, continued



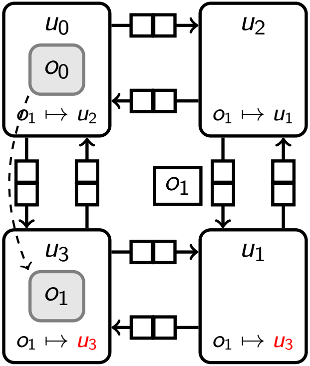
- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

Location Independent Routing, continued



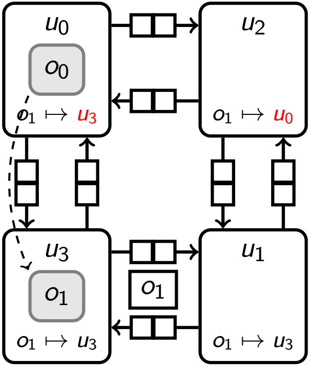
- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

Location Independent Routing, continued



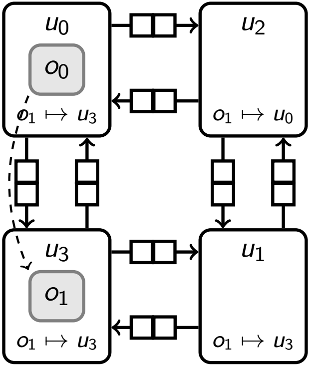
- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

Location Independent Routing, continued



- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

Location Independent Routing, continued



- routing tables with next hops at each node
- routing information exchange between neighbors
- up-to-date tables give optimal routes (stretch 1)

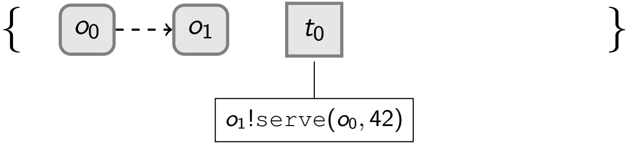
μABS program

```
class Server() { ,
  serve(from, x){ r,
    r = foo(x);
    from!response(r)
  }
}
```

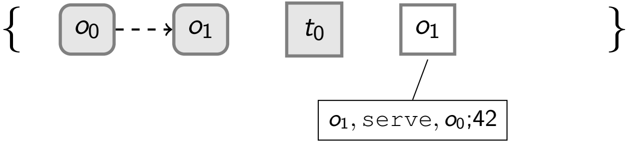
```
class Client(arg) { ,
  use(server){ ,
    server!serve(self, arg)
  }

  response(y){ ,
    ext!output(y)
  }
}
```

```
{
  server, client,
  server = new Server();
  client = new Client(42);
  client!use(server)
}
```

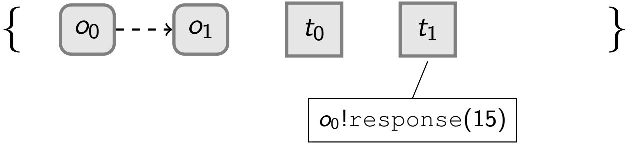
Standard Behavior



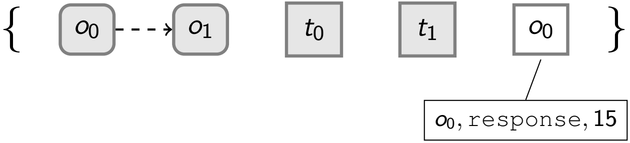
Standard Behavior, continued



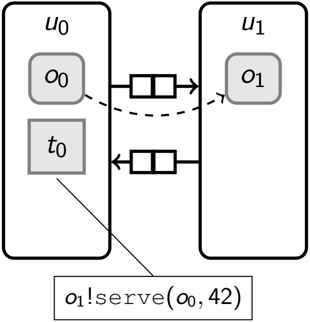
Standard Behavior, continued



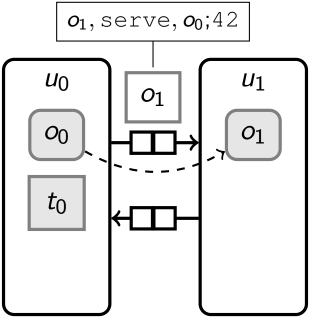
Standard Behavior, continued



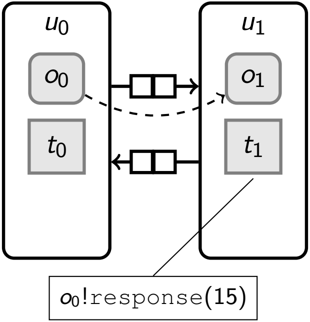
Network-Aware Behavior



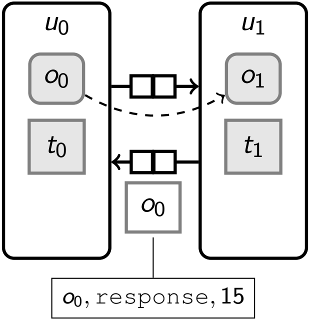
Network-Aware Behavior, continued



Network-Aware Behavior, continued



Network-Aware Behavior, continued



Contextual Equivalence

Definition

An observation, or **barb**, *obs* is a method call of the form $ext!method(v_1, \ldots, v_n)$.

Definition

Two well-formed runtime configurations are **contextually equivalent** if they are in a relation that:

- is closed under reductions
- is closed under context applications
- preserves barbs

Correspondence Result

Theorem

A well-formed network-oblivious runtime configuration is contextually equivalent to its network-aware counterpart.

Paper III

ABS-NET: Fully Decentralized Runtime Adaptation for Distributed Objects

Adaptability Mechanisms:

- **object mobility**
- routing
- task scheduling & message scheduling
- buffering
- synchrony

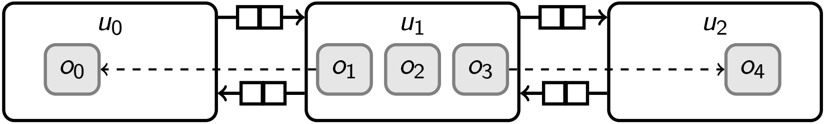
Objectives:

- **load balancing**
- **minimal messaging**
- low stretch
- self-stabilization

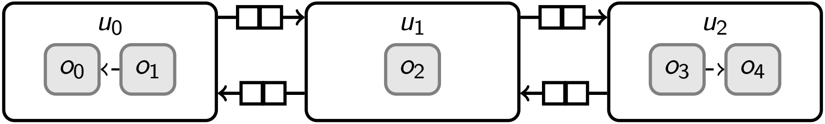
Paper III Summary

1. defines network-aware behavior of full Core ABS
2. simulates behavior using TCP/IP on network topologies
3. measures progress towards objectives for strategies

Load Balancing and Minimal Messaging



Load Balancing and Minimal Messaging, continued



Procedures

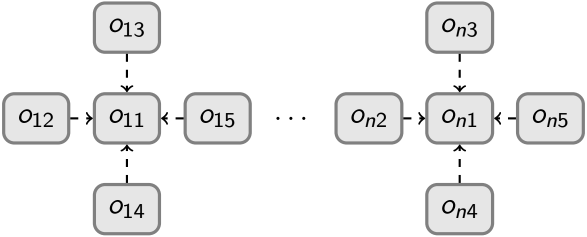
for each active object o **do**
  u' is a neighbour chosen uniformly at random
  l is the current load
  l' is the last known load of u'
  if $l > l' + 1$ **then**
    send o to u' with probability $1 - l'/l$

Procedures, continued

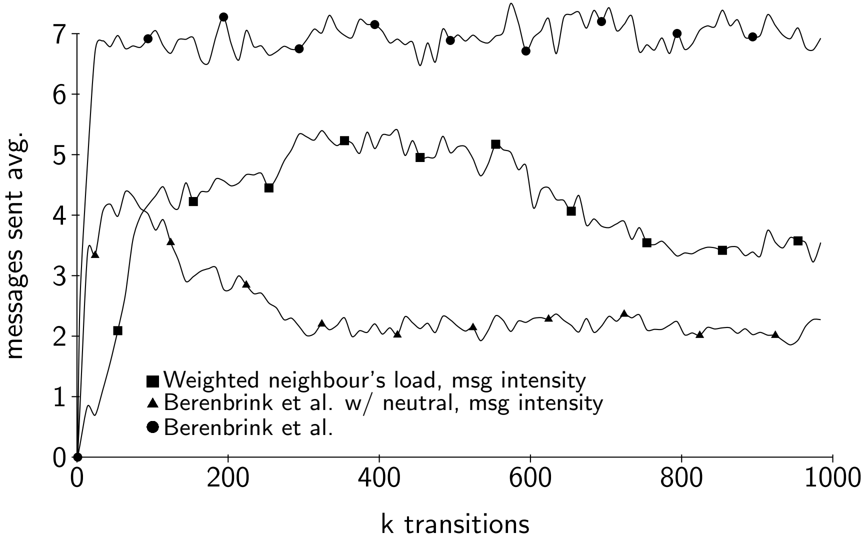
for each active object o **do**
  u' is a neighbour chosen uniformly at random
  l is the current load
  l' is the last known load of u'
  if $l > l'$ **then**
    send o to u' with probability $1 - l'/l$

Star Program

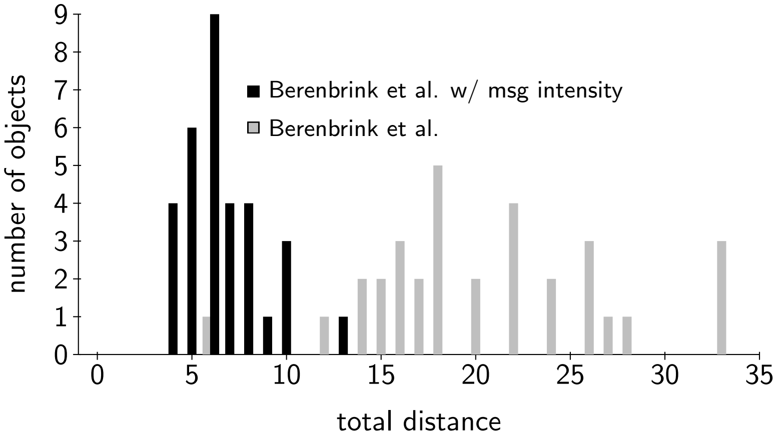
- Communication only between fringe and center objects
- Fringes and their centers need to be on nodes at close distance



Star Program on Grid



Star Program Object Distance Distribution



Paper IV

Decentralized Adaptive Power Control for Process Networks

Adaptability Mechanisms:

- **node startup/shutdown**
- object mobility
- routing

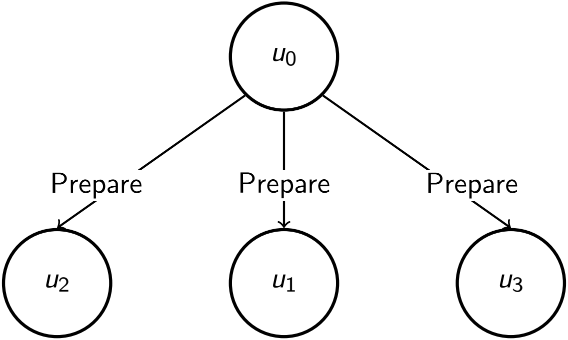
Objectives:

- **network right-sizing**
- load balancing
- minimal messaging
- low stretch
- self-stabilization

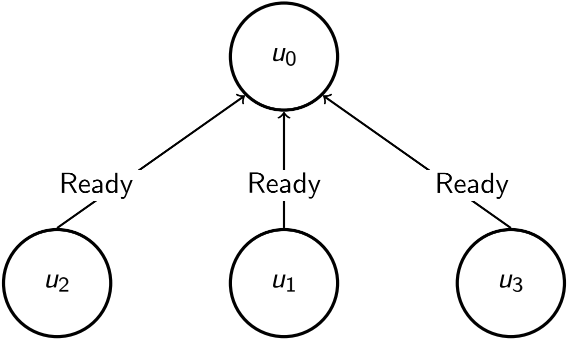
Paper IV Summary

1. defines protocol for controlled startup/shutdown of nodes
2. gives evidence that object behavior is preserved and progresses
3. outlines network right-sizing procedures

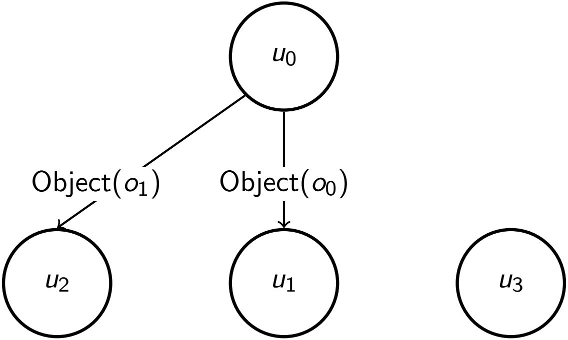
Shutdown Protocol



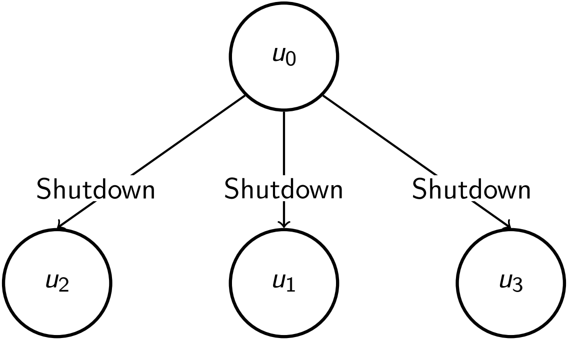
Shutdown Protocol, continued



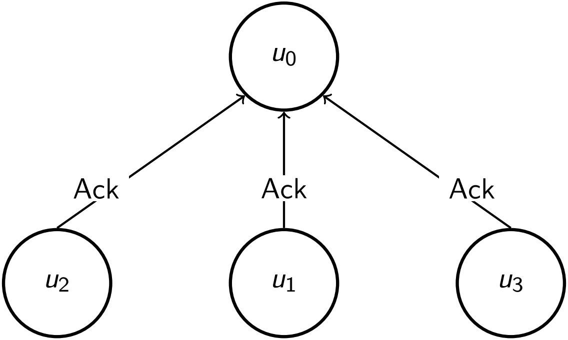
Shutdown Protocol, continued



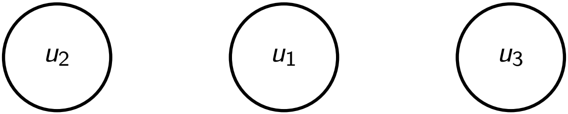
Shutdown Protocol, continued



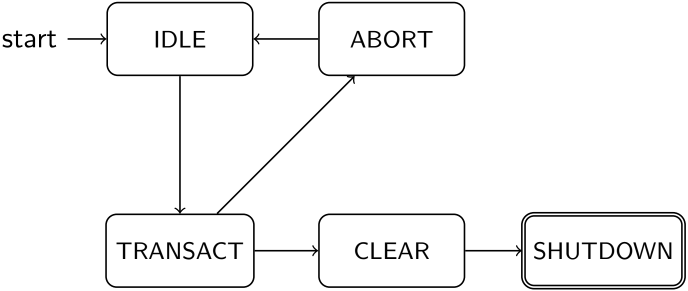
Shutdown Protocol, continued



Shutdown Protocol, continued



Node Shutdown State Machine



Shutdown Protocol Correctness

Safety

Whenever a node shuts down:

- no object is located on the node
- no object-related messages are incoming/outgoing

Liveness

If a node attempts to shut down, it will eventually shut down.

Shutdown Protocol Correctness

Safety

Whenever a node shuts down:

- no object is located on the node
- no object-related messages are incoming/outgoing

Liveness

If a node attempts to shut down, it will eventually shut down.

Evidence

- bounded safety model verified in the Spin model checker
- transition system safety lemmas proved in Coq proof assistant

Paper V

Dynamic Probabilistic Inference of Atomic Sets

one step of a conversion process taking shared-memory programs to the message-passing model

Java Class

```
class ArrayList {
  int size;
  Object[] entries;

  Object get(int i) {
    synchronized(lock) {
      if (0 <= i && i < this.size) {
        return this.entries[i];
      } else {
        return null;
      }
    }
  }

  void addAll(ArrayList o) {
    synchronized(lock) {
      this.size += o.size;
    }
    /*... copy elements ...*/
  }
}
```

Annotated Java Class

```
class ArrayList {
  atomicset L;
  atomic(L) int size;
  atomic(L) Object[] entries;

  Object get(int i) {
    if (0 <= i && i < this.size) {
      return this.entries[i];
    } else {
      return null;
    }
  }

  void addAll(unitfor(L) ArrayList o) {
    this.size += o.size;
    /*... copy elements ...*/
  }
}
```

Elements of Data-Centric Synchronization: Atomic Sets, Units of Work, and Aliases

Atomic Set

Group of fields in a class connected by a consistency invariant

Example

In the `ArrayList`

- Invariant: `entries[i]` valid if `i < size`
- Atomic set
  $L = \{$ `size`, `entries` $\}$

Elements of Data-Centric Synchronization: Atomic Sets, Units of Work, and Aliases

Atomic Set

Group of fields in a class connected by a consistency invariant

Unit of Work

Method that preserves the invariant when executed sequentially

Example

In the `ArrayList`

- Instance methods are units of work for all atomic sets of the object
- `addAll(ArrayList)` is a unit of work for the other list's atomic set L

Elements of Data-Centric Synchronization: Atomic Sets, Units of Work, and Aliases

Atomic Set

Group of fields in a class connected by a consistency invariant

Unit of Work

Method that preserves the invariant when executed sequentially

Alias

Combines atomic sets

Example

- Class `DownloadManager` with field `urls`
- Field declaration:
  ```
  atomic(U)
  ArrayList urls|L=this.U|;
  ```
- Atomic set U now contains `urls.size` and `urls.entries`

Converting a Program to Atomic Sets Requires Understanding its Concurrency Structure

- Data-centric synchronization looks beneficial
- But: must *understand* old synchronization to convert it

Conversion Experience of Dolby et al.:

- Takes several hours for rather simple programs
- 2 out of 6 programs lack synchronization of some classes
- 2 out of 6 programs accidentally introduced global locks

Converting a Program to Atomic Sets Requires Understanding its Concurrency Structure

- Data-centric synchronization looks beneficial
- But: must *understand* old synchronization to convert it

Conversion Experience of Dolby et al.:

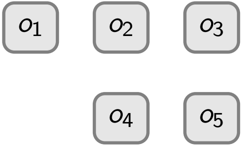
- Takes several hours for rather simple programs
- 2 out of 6 programs lack synchronization of some classes
- 2 out of 6 programs accidentally introduced global locks

Our Algorithm

Avoid conversion errors by automatically determining annotations from program traces using Bayesian probabilistic inference

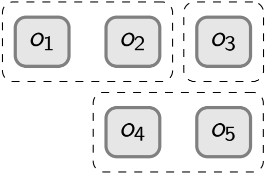
Actorization

- atomic sets and aliases define actor boundaries
- transform program to use interfaces and initialize actors
- actorized program executes in cloud with preserved behavior



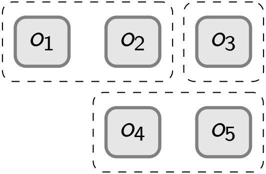
Actorization

- atomic sets and aliases define actor boundaries
- transform program to use interfaces and initialize actors
- actorized program executes in cloud with preserved behavior



Actorization

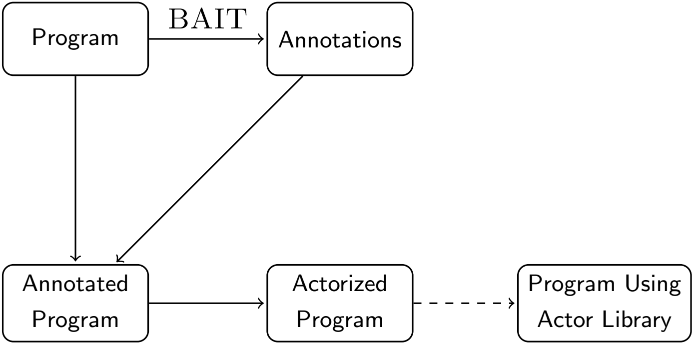
- atomic sets and aliases define actor boundaries
- transform program to use interfaces and initialize actors
- actorized program executes in cloud with preserved behavior



Problem

Units of Work spanning multiple actors

Actorization Steps



Conclusions

	Paper I	Paper II	Paper III	Paper IV	Paper V
theory	✓	✓	✓	✓	✓
practice			✓		✓
correspondence	✓	✓		✓	
adaptability			✓	✓	
conversion					✓

Environmental Conditions to be Addressed

- node crash failures
- node Byzantine failures
- link failures
- honest-but-curious adversaries
- active node-corrupting adversaries