Implementing Asynchronous Distributed Systems Using the IOA Toolkit

Chryssis Georgiou [1], Panayiotis P. Mavrommatis[2], Joshua A. Tauber[2]

[1] University of Cyprus, Department of Computer Science

[2] MIT Computer Science and Artificial Intelligence Laboratory

September 27, 2004

Contents

1 Introduction

This document is a report about the capabilities and performance of the IOA Toolkit, and in particular the tools that provide support for implementing and running distributed systems (checker, composer, code generator). The Toolkit compiles distributed systems specified in IOA into Java classes, which run on a network of workstations and communicate using the Message Passing Interface (MPI). In order to test the toolkit, several distributed algorithms were implemented, ranging from simple algorithms such as LCR leader election in a ring network to more complex algorithms such as the GHS algorithm for computing the minimum spanning tree in an arbitrary graph. All of our experiments completed successfully, and several runtime measurements were made.

2 Experiments

Implementation Platform The machines used are located in the Theory of Computation Group of the MIT Computer Science and Artificial Intelligence Laboratory, forming a Local Area Network. They are all Red Hat Linux machines and with Intel Pentium III to IV with clock speed ranging from 1 GHz to 3.2 GHz. Even though MPI sets up a connection between every pair of nodes, the algorithms only use the communication channels they need. For example, a node (i) in LCR only sends to node i+1 and only receives from node i-1.

2.1 LCR Leader Election

The algorithm of Le Lann, Chang and Roberts for Leader Election in a ring network was the first experiment in running an IOA program on a network of computers. The automaton definition that appears in [1](Section 15.1) was used, with some modifications. For all the algorithms that follow, the nodes are automatically numbered from 0 to (size - 1).

Automata Definitions The automata LCRProcess, LCRNode, SendMediator and ReceiveMediator were written. The mediator automata are given in Appendix C.1 (these automata implement the channel automata integrated with MPI functionality). The composed automaton (LCR) appears in Appendix C.2 (this is the one that is translated into Java code by the IOA Toolkit).

LCR Leader Election process automaton

```
type Status = enumeration of idle, voting, elected, announced

automaton LCRProcess(rank: Int, size: Int)
  signature
    input vote
    input RECEIVE(m: Int, const mod(rank - 1, size), const rank: Int)
    output SEND(m: Int, const rank: Int, const mod(rank+1, size))
```

```
    output leader(const rank)

  states
    pending: Mset[Int] := {rank},
    status: Status := idle

  transitions
    input vote
      eff status := voting
    input RECEIVE(m, j, i) where m > i
      eff pending := insert(m, pending)
    input RECEIVE(m, j, i) where m < i
    input RECEIVE(i, j, i)
      eff status := elected
    output SEND(m, i, j)
      pre status ≠ idle ∧ m ∈ pending
      eff pending := delete(m, pending)
    output leader(rank)
      pre status = elected
      eff status := announced
```

LCR Leader Election composition automaton

```
automaton LCRNode(rank: Int, size: Int)
  components
    P: LCRProcess(rank, size);
    RM[j:Int]: ReceiveMediator(Int, Int, j, rank)
                 where j = mod(rank-1, size);
    SM[j:Int]: SendMediator(Int, Int, rank, j)
                 where j = mod(rank+1, size)
```

Results The trace of a run on 8 nodes (on 4 machines) can be found in Appendix E.1. A snapshot of the trace, representing the **last five** transitions, is shown below.

A snapshot of the trace of LCR leader election

```
     transition: output SEND(7, 5, 6) in automaton LCR(5)
      on condor.csail.mit.edu at 7:25:37:280
     Modified state variables:
     P → Tuple, modified fields: {[pending -> ()] }
     SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
        Sequence, elements added: {7 } Elements removed: {}] }]}

     transition: output RECEIVE(7, 5, 6) in automaton LCR(6)
        on parrot.csail.mit.edu at 7:25:37:755
     Modified state variables:
     P → Tuple, modified fields: {[pending -> (7)] }

     transition: output SEND(7, 6, 7) in automaton LCR(6)
        on parrot.csail.mit.edu at 7:25:37:770
     Modified state variables:
     P → Tuple, modified fields: {[pending -> ()] }
     SM → Map, modified entries: {[7 -> Tuple, modified fields: {[toSend ->
```

```
   Sequence, elements added: {7 } Elements removed: {}] }]}

transition: output RECEIVE(7, 6, 7) in automaton LCR(7)
    on tui.csail.mit.edu at 7:25:37:872
Modified state variables:
P → Tuple, modified fields: {[status -> elected] }

transition: output leader(7) in automaton LCR(7)
   on tui.csail.mit.edu at 7:25:37:874
Modified state variables:
P → Tuple, modified fields: {[status -> announced] }
```

As the trace indicates, node 7's message has made its way around the ring and eventually returned to node 7. At that point, node 7 announced itself as the leader. Figure 2.1 shows the messages sent by the nodes. All messages were sent from node i to node $i+1 (\bmod 8)$ and the message with value i was sent first. The message with value 7 followed and made the round of the ring, to elect node 7 as the leader.

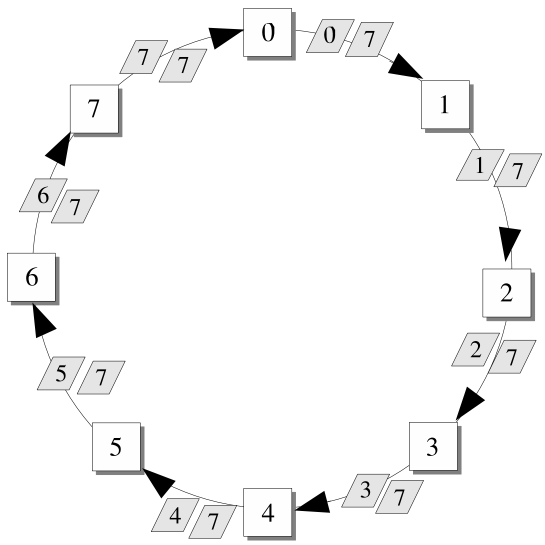


Figure 2.1: Running the LCR leader election algorithm on a ring of 8 nodes. The white squares represent the nodes, while the shaded parallelograms represent the messages sent.

2.2 Asynchronous Spanning Tree

The Asynchronous Spanning Tree Algorithm, (see Section 15.3 of [1]) was the next test for the Toolkit. The algorithm is still very simple: Given a general graph it computes a spanning tree on the graph. This was the first test of the Toolkit on arbitrary graphs, where each node had more than one incoming and outgoing communication channels.

Automata Definitions The AsynchSpanningTree automaton, as defined in [1](Section 15.3) was used. The process automaton and the composition one are listed below. The expanded automaton is shown in Appendix C.3.

Asynchronous Spanning Tree process automaton

```
type Message = enumeration of search, null

automaton sTreeProcess(i: Int)
  signature
    input RECEIVE(m: Message, const i: Int, j: Int)
    output SEND(m: Message, const i: Int, j: Int)
    output PARENT(j: Int)

  states
    nbrs: Set[Int] := {},
    parent: Int := -1, % -1 for null
    reported: Bool := false,
    send: Map[Int, Message]

  transitions
    input RECEIVE(m, i, j)
       eff
         if i ≠ 0 ∧ parent = -1 then
            parent := j;
            for k:Int in nbrs - {j} do
              send[k] := search
            od
         fi
    output SEND(m, i, j)
      pre send[j] = search
      eff send[j] := null
    output PARENT(j)
      pre parent = j ∧ reported = false
      eff reported := true
```

Asynchronous Spanning Tree composition automaton

```
type Message = enumeration of search, null

automaton sTreeNode(i:Int)
  components
    P: sTreeProcess(i);
    RM[j:Int]: ReceiveMediator(Message, Int, i, j);
    SM[j:Int]: SendMediator(Message, Int, i, j)
```

Results Figure 2.2 shows a graph of 16 nodes connected in a 4×4 grid that was used on some of our tests. The source node was node 0. Some of the spanning trees computed are also shown in Figure 2.2. A snapshot of the trace follows, showing nodes 1 and 4 sending their message to node 5. The message of node 1 arrives first and thus node 5 announces node 1 as its parent. The complete trace of this run can be found in Appendix E.2.

Trace snapshot of the Asynchronous Spanning Tree algorithm

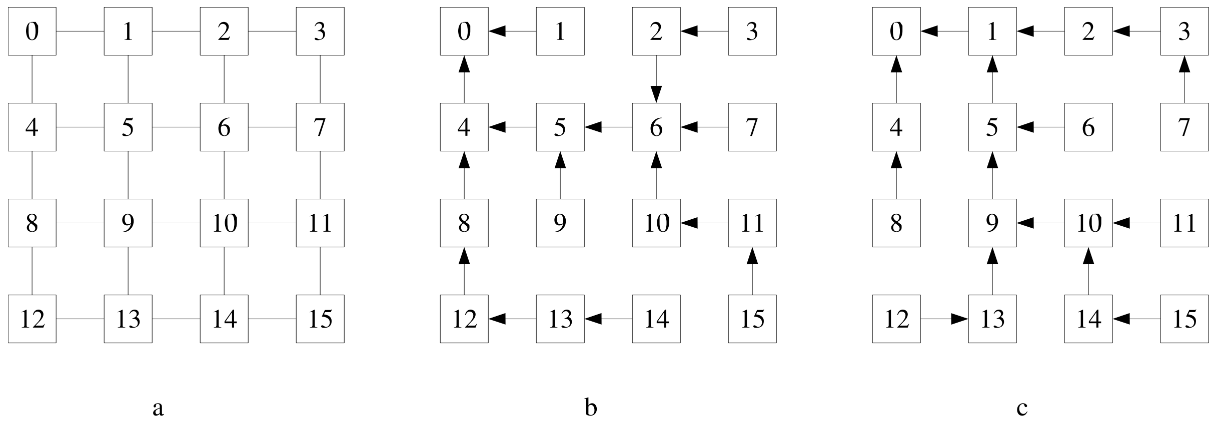


Figure 2.2: The 4×4 grid used to test the Asynchronous Spanning Tree Algorithm, along with 2 different spanning trees computed from 2 different runs of the algorithm.

```
transition: output SEND(search, 1, 5) in automaton sTreeNode(1) on
  blackbird.csail.mit.edu
Modified state variables:
P → [nbrs: (0 2 5), parent: 0, reported: true, send:
   ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output SEND(search, 4, 5) in automaton sTreeNode(4) on
  parrot.csail.mit.edu
Modified state variables:
P → [nbrs: (0 5 8), parent: 0, reported: true, send:
   ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(search, 5, 1) in automaton sTreeNode(5) on
  parrot.csail.mit.edu
Modified state variables:
P → [nbrs: (1 4 6 9), parent: 1, reported: false, send:
   ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort

transition: output PARENT(1) in automaton sTreeNode(5) on
  parrot.csail.mit.edu
Modified state variables:
P → [nbrs: (1 4 6 9), parent: 1, reported: true, send:
   ioa.runtime.adt.MapSort]
```

2.3 Asynchronous Broadcast Convergecast

This is essentially an extension of the previous algorithm, where along with the construction of a spanning tree, a broadcast and convergecast take place (using the computed spanning tree). The source node was node 0, and the message 99 (a dummy message) was broadcast on the network. Some complexity is added compared to the previous algorithm by the fact that different kinds of messages are exchanged.

Automata Definitions The AsynchBcastAck automaton, as defined in [1](section 15.3) was used. The process automaton and the composition automaton are shown below. The expanded automaton is given in Appendix C.4.

Asynchronous Broadcast Convergecast process automaton

```
type Kind = enumeration of bcast, ack
type BCastMsg = tuple of kind: Kind , w: Int
type Message = union of msg: BCastMsg, kind: Kind

automaton bcastProcess(rank: Int, nbrs: Set[Int])
  signature
    input RECEIVE(m: Message, const rank, j: Int)
    output SEND(m: Message, const rank, j: Int)
    internal report(const rank)

  states
    val: Int := -1,                    % -1 = special value denoting null
    parent: Int := -1,
    reported: Bool := false,
    acked: Set[Int] := {},
    send: Map[Int, Seq[Message]]

initially
    rank = 0 ⇒
       (val = 99 ∧                    %% 99 = the value to be broadcast
        (∀ j: Int
         ((j ∈ nbrs) ⇒ send[j] = {} ⊢ msg([bcast, val]))))

 transitions
    output SEND(m, rank, j)
      pre m = head(send[j])
      eff send[j] := tail(send[j])
    input RECEIVE(m, rank, j)
       eff
         if m = kind(ack) then
           acked := acked ∪ {j}
         else
           if val = -1 then
             val := m.msg.w;
             parent := j;
             for k:Int in nbrs - {j} do
               send[k] := send[k] ⊢ m
             od
           else
               send[j] := send[j] ⊢ kind(ack)
```

```
      fi
    fi
  internal report(rank) where rank = 0
    pre acked = nbrs;
        reported = false
    eff reported := true
  internal report(rank) where rank ≠ 0
    pre parent ≠ -1;
        acked = nbrs - {parent};
        reported = false
    eff send[parent] := send[parent] ⊢ kind(ack);
        reported := true;
```

Asynchronous Broadcast Convergecast composition automaton

```
type Message = union of msg: BCastMsg, kind: Kind

automaton bcastNode(i:Int)
  components
    P: bcastProcess(i);
    RM[j:Int]: ReceiveMediator(Message, Int, i, j);
    SM[j:Int]: SendMediator(Message, Int, i, j)
```

Results The algorithm was tested on several graphs. One of them is shown in Figure 2.3 (a). Figure 2.3 (b) and (c) depicts some of the spanning trees that were computed and the communication sequence; the numbers next to the nodes represent the sequence at which the nodes reported done (through the internal `report` action). A snapshot of the trace is listed below, showing nodes 1 and 4 reporting that they are done. At that point, node 0 is enabled and after some communication between these nodes, node 0 also reports done. The complete trace of this run is shown in Appendix E.3.

Trace snapshot of the Asynchronous Broadcast Convergecast algorithm

```
     transition: internal report(1) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (2 5), nbrs: (0 2 5), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 1, 0) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (2 5), nbrs: (0 2 5), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 4, 8) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: internal report(4) in automaton bcastNode
```

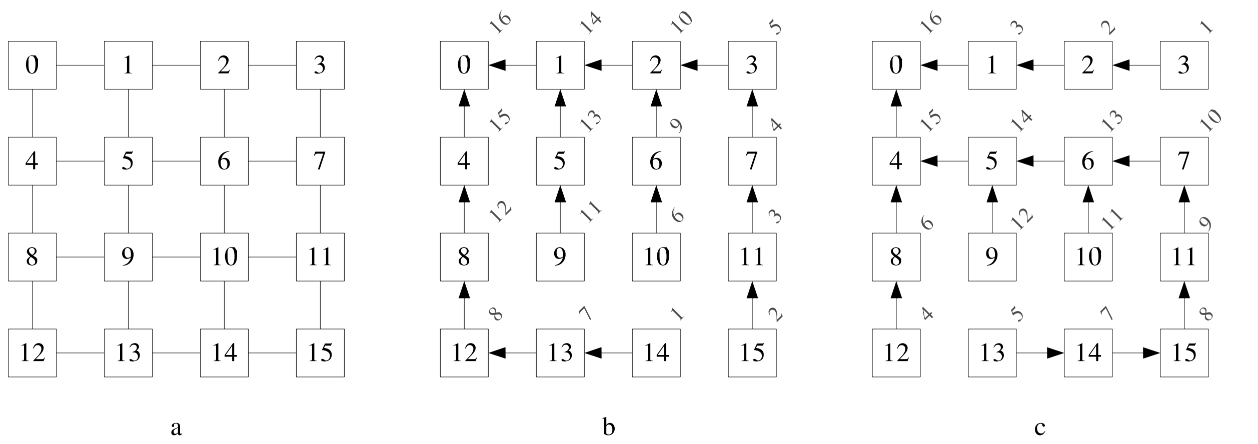


Figure 2.3: The grid shown in (a) was used to test the algorithm. (b) and (c) show the spanning trees computed in two (different) runs and the numbers next to the nodes indicate the sequence at which the nodes reported done.

```
    Modified state variables:
    P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

    transition: output SEND(kind(ack), 4, 0) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 0, 1) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (1), nbrs: (1 4), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 0, 4) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (1 4), nbrs: (1 4), parent: -1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
    RM → ioa.runtime.adt.MapSort

    transition: internal report(0) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (1 4), nbrs: (1 4), parent: -1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
```

2.4 Leader Election Using Broadcast Convergecast

In page 500 of [1], the author describes how the Asynchronous Broadcast Convergecast algorithm can be used to implement a leader election algorithm on a general graph using the Asynchronous Broadcast Convergecast algortithm. The main idea is to have every node act as a source node and create its own spanning tree, broadcast its UID using this spanning tree and hear from all the other nodes via a convergecast. During this convergecast, along with the acknowledge message, the children also send what they consider as the maximum UID in the network. The parents gather the maximum UIDs from the children, compare it to their own UID and send the maximum to their own parents. Thus, each source node learns the maximum UID in the network and the node whose UID equals the maximum one announces itself as a leader.

Automata Definitions The process and composition automata are shown below. The expanded automaton is defined in Appendix C.5.

Leader Election Using Broadcast Convergecast process automaton

```
type Kind = enumeration of bcast, ack
type BCastMsg = tuple of kind: Kind, w: Int
type AckMsg = tuple of kind:Kind, mx: Int
type MSG = union of bmsg: BCastMsg, amsg: AckMsg, kind: Kind
type Message = tuple of msg: MSG, source: Int

automaton bcastLeaderProcess(rank: Int)
  signature
    input RECEIVE(m: Message, i: Int, j: Int)
    output SEND(m: Message, i: Int, j: Int)
    internal report(i: Int, source: Int)
    internal finished
    output LEADER
  states
    nbrs: Set[Int],
    val: Map[Int, Int],                % initialially -1 (null) for all nodes
    parent: Map[Int, Int],             % initialially -1 (null) for all nodes
    reported: Map[Int, Bool],          % initialially false for all nodes
    acked: Map[Int, Set[Int]],         % initialially {} for all nodes
    send: Map[Int, Int, Seq[Message]], % First variable: source.
    max: Map[Int, Int],     % The max value found in the network , initially i
    elected: Bool := false,
    announced: Bool := false
  initially
    (∀ j: Int
      ((0 ≤ j ∧ j < 16) ⇒
       (rank = j  ⇒ val[j] = rank
        ∧ rank ≠ j ⇒ val[j] = -1
        ∧ parent[j] = -1
        ∧ acked[j] = {}
        ∧ max[j] = rank
        ∧(∀ k:Int
            (send[j,k] = {} ∧
             (k ∈ nbrs ∧ rank = j) ⇒
              send[j, k] = {} ⊢ [bmsg([bcast, 99]), j]))))
 transitions
```

```
output SEND(m, i, j)
  pre m = head(send[m.source, j])
  eff send[m.source, j] := tail(send[m.source, j])
input RECEIVE(m, i, j)
  eff if m.msg = kind(ack) then
        acked[m.source] := acked[m.source] ∪ {j}
      elseif tag(m.msg) = amsg then
        if max[m.source] < m.msg.amsg.mx then
           max[m.source] := m.msg.amsg.mx;
        fi;
        acked[m.source] := acked[m.source] ∪ {j}
      else %BcastMsg
        if val[m.source] = -1 then
          val[m.source] := m.msg.bmsg.w;
          parent[m.source] := j;
          for k:Int in nbrs - {j} do
            send[m.source, k] := send[m.source, k] ⊢ m
          od
        else
            send[m.source, j] := send[m.source, j] ⊢ [kind(ack), m.source]
        fi
      fi
internal finished
  pre acked[rank] = nbrs ∧
      reported[rank] = false
  eff reported[rank] := true;
      if (max[rank] = rank) then
        elected := true
      fi;
output LEADER
  pre elected = true ∧ announced = false
  eff announced := true
internal report(i, source) where i ≠ source
  pre parent[source] ≠ -1 ∧
      acked[source] = nbrs - {parent[source]} ∧
      reported[source] = false
  eff send[source, parent[source]] :=
       send[source, parent[source]] ⊢ [amsg([ack, max[source]]), source];
      reported[source] := true;
```

Leader Election Using Broadcast Convergecast composition automaton

```
automaton bcastLeaderNode(i:Int)
  components
    P: bcastLeaderProcess(i);
    RM[j:Int]: ReceiveMediator(Message, Int, i, j);
    SM[j:Int]: SendMediator(Message, Int, i, j)
```

Results This algorithm was also tested on the 4×4 grid that was used in the two previous algotithms (see Figure 2.3 (a)). The algorithm terminated correctly and announced node 15 as the leader. A snapshot of the trace is shown below. The complete trace of this run can be found on the web, at `http://theory.csail.mit.edu:/~pmavrom/ioaReport.html`

Trace snapshot of the Leader Election Using Broadcast Convergecast algorithm

---

```
transition: output RECEIVE([msg: amsg([kind: ack, mx: 13]), source: 14],
   14, 10) in automaton bcastLeader(14) on drake.csail.mit.edu at 9:07:20:455
Modified state variables:
P → Tuple, modified fields: {[acked -> Map, modified entries: {[14 -> (10
   13 15)]}] }
SM → Map, modified entries: {[10 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {[msg: amsg([kind: ack, mx: 14]),
   source: 11] }] [sent -> Sequence, elements added: {[msg: amsg([kind: ack, mx:
   14]), source: 11] } Elements removed: {}] }]}
c2 → 7

transition: internal finished() in automaton bcastLeader(14)
   on drake.csail.mit.edu at 9:07:20:464
Modified state variables:
P → Tuple, modified fields: {[reported -> Map, modified entries: {[14 ->
   true]}] }
c2 → 14
k → 15

transition: output RECEIVE([msg: amsg([kind: ack, mx: 14]), source: 15],
   15, 11) in automaton bcastLeader(15) on loon.csail.mit.edu at 9:07:20:684
Modified state variables:
P → Tuple, modified fields: {[acked -> Map, modified entries: {[15 -> (11
   14)]}] }
SM → Map, modified entries: {[11 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {[msg: amsg([kind: ack, mx: 15]),
   source: 4] }] [sent -> Sequence, elements added: {[msg: amsg([kind: ack, mx:
   15]), source: 4] } Elements removed: {}] }]}
c2 → 7

transition: internal finished() in automaton bcastLeader(15)
   on loon.csail.mit.edu at 9:07:20:687
Modified state variables:
P → Tuple, modified fields: {[reported -> Map, modified entries: {[15 ->
   true]}] [elected -> true] }
c2 → 15

transition: output LEADER() in automaton bcastLeader(15)
   on loon.csail.mit.edu at 9:07:20:689
Modified state variables:
P → Tuple, modified fields: {[announced -> true] }
```

2.5 Unrooted Spanning Tree to Leader Election

The algorithm **STtoLeader** of [1](page 501) was implemented as the next test for the Toolkit. The algorithm takes as input an unrooted spanning tree and returns a leader. The automaton listed below was written, according to the description of the algorithm.

Automata Definitions The process and composition automata are listed below, while the expanded automaton can be found in Appendix C.6.

Unrooted Spanning Tree to Leader Election process automaton

```
type Status = enumeration of idle, elected, announced
type Message = enumeration of elect
axioms ChoiceSet(Int for E)

automaton sTreeLeaderProcess(rank: Int, nbrs:Set[Int])
  signature
    input RECEIVE(m: Message, const rank: Int, j: Int)
    output SEND(m: Message, const rank: Int, j: Int)
    output leader
  states
    receivedElect: Set[Int],
    sentElect: Set[Int],
    status: Status,
    send: Map[Int, Seq[Message]]
   initially
      true ⇒
            receivedElect = {}
            ∧ sentElect = {}
            ∧ status = idle
            ∧ (size(nbrs) = 1 ⇒
                   send[chooseRandom(nbrs)]
                    = send[chooseRandom(nbrs)] ⊢ elect)
  transitions
    input RECEIVE(m, i, j)
      eff receivedElect := insert(j, receivedElect);
          if size(receivedElect) = size(nbrs) - 1 then
             send[chooseRandom(nbrs - receivedElect)] :=
               send[chooseRandom(nbrs - receivedElect)] ⊢ elect;
             sentElect :=
               insert(chooseRandom(nbrs - receivedElect), sentElect)
          elseif receivedElect = nbrs then
             if j ∈ sentElect then if i > j then status := elected fi
             else status := elected
             fi
          fi
    output SEND(m, i, j)
      pre m = head(send[j])
      eff send[j] := tail(send[j])
    output leader
      pre status = elected
      eff status := announced
```

Unrooted Spanning Tree to Leader Election composition automaton

```
automaton sTreeLeaderNode(rank:Int, nbrs:Set[Int])
  components
    P: sTreeLeaderProcess(rank, nbrs);
    RM[j:Int]: ReceiveMediator(Message, Int, rank, j);
    SM[j:Int]: SendMediator(Message, Int, rank, j)
```

Results The algorithm was tested on several graphs and different spanning trees as input. A spanning tree on a 4×4 grid is shown in Figure 2.4. The algorithm worked correctly, announcing only one node as the leader. A snapshot of the trace is listed below. In that specific run, the edge between nodes 5 and 6 had *elect* messages sent in both directions, with node 6 being elected as the leader, having a larger UID. The complete trace of this run can be found in Appendix E.4.

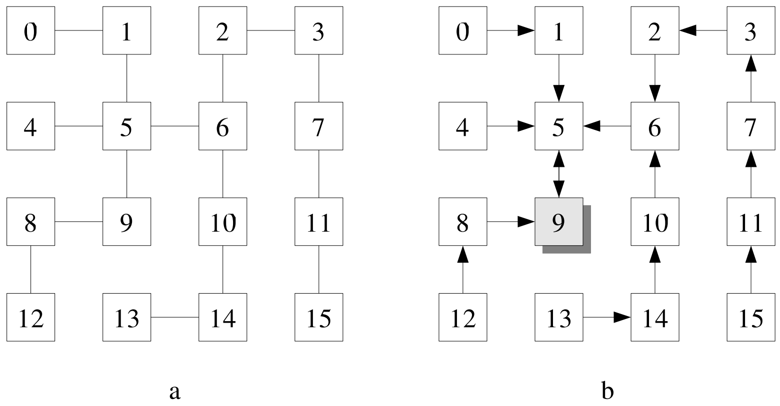


Figure 2.4: (a) shows the unrooted spanning tree used in one run. In (b), the arrows show the direction of the messages in a specific run, where the edge between nodes 5 and 9 had *elect* messages sent in both directions. Node 9, with a larger UID was elected as the leader.

Trace Snapshot of the Unrooted Spanning Tree to Leader Election

```
transition: output SEND(elect, 6, 5) in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:15:112
Modified state variables:
P → Tuple, modified fields: {[send -> Map, modified entries: {[5 ->
   Sequence, elements added: {} Elements removed: {elect }]}] }
SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {elect } Elements removed: {}] }]}
k → 5
tempNbrs2 → (10 2)

transition: output SEND(elect, 5, 6) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:16:182
Modified state variables:
P → Tuple, modified fields: {[send -> Map, modified entries: {[6 ->
   Sequence, elements added: {} Elements removed: {elect }]}] }
SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {elect } Elements removed: {}] }]}
k → 6
tempNbrs2 → (1 4 9)

transition: output RECEIVE(elect, 5, 6) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:16:494
Modified state variables:
P → Tuple, modified fields: {[receivedElect -> (1 4 6 9)] }
SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {elect }]
   [sent -> Sequence, elements added: {elect } Elements removed: {}] }]}
```

```
    transition: output RECEIVE(elect, 6, 5) in automaton sTreeLeader(6)
 on drake.csail.mit.edu at 9:29:16:554
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (10 2 5)] [status ->
       elected] }
    SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend ->
       Sequence, elements added: {} Elements removed: {elect }] [sent ->
       Sequence, elements added: {elect } Elements removed: {}] }]}

    transition: output leader() in automaton sTreeLeader(6)
    on drake.csail.mit.edu at 9:29:16:559
    Modified state variables:
    P → Tuple, modified fields: {[status -> announced] }
```

2.6 GHS Minimum Spanning Tree

The last algorithm we ran using the Toolkit was the algorithm of Gallager, Humblet and Spira for finding the minimum-weight spanning tree in an arbitrary graph. Welch, Lamport and Lynch give an I/O automaton definition of the GHS algorithm in [2], which is used as a basis for our automata definitions. One technical detail in running this version of the algorithm is that the edge weights needed to be unique. This algorithm is significantly longer than the previous ones, with 7 different messages exchanged and 12 state variables for each automaton.

Automata Definitions The automaton below defines the algorithm and the composition with the mediator automata is shown after that. The expanded automaton can be found in Appendix C.7.

GHS process automaton

```
type Nstatus = enumeration of sleeping, find, found
type Edge = tuple of s: Int, t: Int
type Link = tuple of s: Int, t: Int
type Lstatus = enumeration of unknown, branch, rejected
% Message Types
type Msg = enumeration of CONNECT, INITIATE, TEST, REPORT, ACCEPT,
                          REJECT, CHANGEROOT
type ConnMsg = tuple of msg: Msg, l: Int
type Status = enumeration of find, found
type InitMsg = tuple of msg: Msg, l: Int, c: Null[Edge], st: Status
type TestMsg = tuple of msg: Msg, l: Int, c: Null[Edge]
type ReportMsg = tuple of msg: Msg, w: Int
type Message = union of connMsg: ConnMsg, initMsg: InitMsg,
                        testMsg: TestMsg, reportMsg: ReportMsg,
                        msg: Msg
uses ChoiceSet(Link)

%%
%  automaton GHSProcess: Process of GHS Algorithm for min. spanning tree
%  rank: The UID of the automaton, automatically initialized by MPI
%  size: The size of the network, automatically initialized by MPI
%  links: Set of Links with source = rank (L_p(G))
```

```
%  weight: Maps the Links ∈ links to their weight
%%
automaton GHSProcess(rank: Int, size: Int, links: Set[Link], weight: Map[Link, Int])
  signature
    input startP
    input RECEIVE(m: Message, const rank, i: Int)
    output InTree(l:Link)
    output NotInTree(l: Link)
    output SEND(m: Message, const rank, j: Int)
    internal ReceiveConnect(qp: Link, l:Int)
    internal ReceiveInitiate(qp: Link, l:Int, c: Null[Edge], st: Status)
    internal ReceiveTest(qp: Link, l:Int, c: Null[Edge])
    internal ReceiveAccept(qp: Link)
    internal ReceiveReject(qp: Link)
    internal ReceiveReport(qp: Link, w: Int)
    internal ReceiveChangeRoot(qp: Link)

  states
    nstatus: Nstatus,
    nfrag: Null[Edge],
    nlevel: Int,
    bestlink: Null[Link],
    bestwt: Int,
    testlink: Null[Link],
    inbranch: Link,
    findcount: Int,
    lstatus: Map[Link, Lstatus],
    queueOut: Map[Link, Seq[Message]],
    queueIn: Map[Link, Seq[Message]],
    answered: Map[Link, Bool],
    % Temporary variables
    min: Int, minL: Null[Link], S: Set[Link]
  initially
    true ⇒ nstatus = sleeping
           ∧ nfrag = nil
           ∧ nlevel = 0
           ∧ bestlink = embed(chooseRandom(links))
           ∧ bestwt = weight[chooseRandom(links)]
           ∧ testlink = nil
           ∧ inbranch = chooseRandom(links)
           ∧ findcount = 0
           ∧ ∀ l: Link
             (l ∈ links ⇒
                lstatus[l] = unknown
                ∧ answered[l] = false
                ∧ queueOut[l] = {}
                ∧ queueIn[l] = {})
  transitions
   % INPUT ACTIONS
   input startP
     eff if nstatus = sleeping then
           %WakeUp
           minL := embed(chooseRandom(links)); min := weight[minL.val];
           for tempL:Link in links do
             if weight[tempL] < min then minL := embed(tempL); min := weight[tempL] fi;
           od;
```

```
        lstatus[minL.val] := branch; nstatus := found;
        queueOut[minL.val] := queueOut[minL.val] ⊢ connMsg([CONNECT, 0]);
        %EndWakeUp
      fi
input RECEIVE(m: Message, i:Int, j:Int)
  eff queueIn[[i,j]] := queueIn[[i,j]] ⊢ m
% OUTPUT ACTIONS
output InTree(l: Link)
  pre answered[l] = false ∧ lstatus[l] = branch
  eff answered[l] := true
output NotInTree(l: Link)
  pre answered[l] = false ∧ lstatus[l] = rejected
  eff answered[l] := true
output SEND(m: Message, i: Int, j: Int)
  pre m = head(queueOut[[i,j]])
  eff queueOut[[i,j]] := tail(queueOut[[i,j]])
% INTERNAL ACTIONS
internal ReceiveConnect(qp: Link, l: Int)
  pre head(queueIn[qp]) = connMsg([CONNECT, l])
  eff queueIn[qp] := tail(queueIn[qp]);
      if nstatus = sleeping then
        %WakeUp
        minL := embed(chooseRandom(links)); min := weight[minL.val];
        for tempL:Link in links do
          if weight[tempL] < min then minL := embed(tempL); min := weight[tempL] fi;
        od;
        lstatus[minL.val] := branch; nstatus := found;
        queueOut[minL.val] := queueOut[minL.val] ⊢ connMsg([CONNECT, 0]);
        %EndWakeUp
      fi;
      if l < nlevel then
        lstatus[[qp.t,qp.s]] := branch;
        if testlink ≠ nil then
          queueOut[[qp.t,qp.s]] := queueOut[[qp.t,qp.s]] ⊢ initMsg([INITIATE,
            nlevel, nfrag, find]);
          findcount := findcount + 1
        else
          queueOut[[qp.t,qp.s]] := queueOut[[qp.t,qp.s]] ⊢ initMsg([INITIATE,
            nlevel, nfrag, found])
        fi;
      else
        if lstatus[[qp.t,qp.s]] = unknown then
          queueIn[qp] := queueIn[qp] ⊢ connMsg([CONNECT, l])
        else
          queueOut[[qp.t,qp.s]] := queueOut[[qp.t,qp.s]] ⊢ initMsg([INITIATE,
            nlevel+1, embed([qp.t, qp.s]), find])
        fi
      fi
 internal ReceiveInitiate(qp: Link, l:Int, c: Null[Edge], st: Status)
   pre head(queueIn[qp]) = initMsg([INITIATE, l, c, st])
   eff queueIn[qp] := tail(queueIn[qp]);
       nlevel := l;
       nfrag := c;
       if st = find then nstatus := find else nstatus := found fi;
       % - Let S = { [p,q] : lstatus[[p,r]] = branch, r ≠ q} -
       S := {};
```

```
        for pr: Link in links do
          if pr.t ≠ qp.s ∧ lstatus[pr] = branch then
             S := S ∪ {pr}
          fi
        od;
        for k: Link in S do
          queueOut[k] := queueOut[k] ⊢ initMsg([INITIATE, l, c, st])
        od;
        if st = find then
          inbranch := [qp.t, qp.s];
          bestlink := nil;
          bestwt := 10000000; % Infinity
          %TestP
          minL := nil; min := 10000000; % Infinity
          for templ:Link in links do
            if weight[templ] < min ∧ lstatus[templ] = unknown then
              minL := embed(templ); min := weight[templ]
            fi;
          od;
          if minL ≠ nil then
            testlink := minL;
            queueOut[minL.val] := queueOut[minL.val] ⊢ testMsg([TEST, nlevel, nfrag]);
          else
            testlink := nil;
            %Report
            if findcount = 0 ∧ testlink = nil then
              nstatus := found;
              queueOut[inbranch] := queueOut[inbranch] ⊢ reportMsg([REPORT, bestwt])
            fi
            %EndReport
          fi;
          %EndTestP
          findcount := size(S)
        fi

internal ReceiveTest(qp: Link, l: Int, c: Null[Edge])
  pre head(queueIn[qp]) = testMsg([TEST, l, c])
  eff queueIn[qp] := tail(queueIn[qp]);
      if nstatus = sleeping then
        %WakeUp
        minL := embed(chooseRandom(links)); min := weight[minL.val];
        for templ:Link in links do
          if weight[templ] < min then minL := embed(templ); min := weight[templ] fi;
        od;
        lstatus[minL.val] := branch; nstatus := found;
        queueOut[minL.val] := queueOut[minL.val] ⊢ connMsg([CONNECT, 0]);
        %EndWakeUp
      fi;
      if l > nlevel then
        queueIn[qp] := queueIn[qp] ⊢ testMsg([TEST, l, c]);
      else
        if c ≠ nfrag then
          queueOut[[qp.t, qp.s]] := queueOut[[qp.t, qp.s]] ⊢ msg(ACCEPT)
        else
          if lstatus[[qp.t, qp.s]] = unknown then lstatus[[qp.t, qp.s]] := rejected fi;
          if testlink ≠ embed([qp.t, qp.s]) then
```

```
            queueOut[[qp.t, qp.s]] := queueOut[[qp.t, qp.s]] ⊢ msg(REJECT)
          else
            %Test
            minL := nil; min := 10000000; % Infinity
            for tempL:Link in links do
             if weight[tempL] < min ∧ lstatus[tempL] = unknown then
               minL := embed(tempL); min := weight[tempL]
             fi;
            od;
            if minL ≠ nil then
             testlink := minL;
             queueOut[minL.val] := queueOut[minL.val] ⊢ testMsg([TEST, nlevel, nfrag]);
            else
              testlink := nil;
              %Report
              if findcount = 0 ∧ testlink = nil then
                nstatus := found;
                queueOut[inbranch] := queueOut[inbranch] ⊢ reportMsg([REPORT, bestwt])
              fi
              %EndReport
            fi;
            %EndTest
          fi;
        fi;
      fi;

internal ReceiveAccept(qp: Link)
  pre head(queueIn[qp]) = msg(ACCEPT)
  eff queueIn[qp] := tail(queueIn[qp]);
      testlink := nil;
      if weight[[qp.t, qp.s]] < bestwt then
        bestlink := embed([qp.t, qp.s]);
        bestwt := weight[[qp.t, qp.s]];
      fi;
      %Report
      if findcount = 0 ∧ testlink = nil then
        nstatus := found;
        queueOut[inbranch] := queueOut[inbranch] ⊢ reportMsg([REPORT, bestwt])
      fi
      %EndReport

internal ReceiveReject(qp: Link)
  pre head(queueIn[qp]) = msg(REJECT)
  eff queueIn[qp] := tail(queueIn[qp]);
      if lstatus[[qp.t, qp.s]] = unknown then lstatus[[qp.t, qp.s]] := rejected fi;
      %Test
      minL := nil; min := 10000000; % Infinity
      for tempL:Link in links do
        if weight[tempL] < min ∧ lstatus[tempL] = unknown then
          minL := embed(tempL); min := weight[tempL]
        fi;
      od;
      if minL ≠ nil then
        testlink := minL;
        queueOut[minL.val] := queueOut[minL.val] ⊢ testMsg([TEST, nlevel, nfrag]);
      else
```

```
        testlink := nil;
        %Report
         if findcount = 0 ∧ testlink = nil then
           nstatus := found;
           queueOut[inbranch] := queueOut[inbranch] ⊢ reportMsg([REPORT, bestwt])
         fi
        %EndReport
      fi
      %EndTest

  internal ReceiveReport(qp: Link, w: Int)
    pre head(queueIn[qp]) = reportMsg([REPORT, w])
    eff queueIn[qp] := tail(queueIn[qp]);
        if [qp.t, qp.s] ≠ inbranch then
          findcount := findcount -1;
          if w < bestwt then
            bestwt := w;
            bestlink := embed([qp.t, qp.s])
          fi;
          %Report
          if findcount = 0 ∧ testlink = nil then
            nstatus := found;
            queueOut[inbranch] := queueOut[inbranch] ⊢ reportMsg([REPORT, bestwt])
          fi
          %EndReport
        else
          if nstatus = find then
            queueIn[qp] := queueIn[qp] ⊢ reportMsg([REPORT, w])
          elseif w > bestwt then
            %ChangeRoot
            if lstatus[bestlink.val] = branch then
              queueOut[bestlink.val] := queueOut[bestlink.val] ⊢ msg(CHANGEROOT)
            else
              queueOut[bestlink.val] := queueOut[bestlink.val] ⊢
                connMsg([CONNECT, nlevel]) ;
              lstatus[bestlink.val] := branch
            fi
            %EndChangeRoot
          fi
        fi

  internal ReceiveChangeRoot(qp: Link)
    pre head(queueIn[qp]) = msg(CHANGEROOT)
    eff queueIn[qp] := tail(queueIn[qp]);
        %ChangeRoot
        if lstatus[bestlink.val] = branch then
          queueOut[bestlink.val] := queueOut[bestlink.val] ⊢ msg(CHANGEROOT)
        else
          queueOut[bestlink.val] := queueOut[bestlink.val] ⊢ connMsg([CONNECT, nlevel]) ;
          lstatus[bestlink.val] := branch
        fi
        %EndChangeRoot
```

GHS composition automaton

```
automaton GHSNode(rank: Int, size: Int, links: Set[Link], weight: Map[Link, Int])
  components
    P: GHSProcess(rank, size, links, weight);
    RM[j:Int]: ReceiveMediator(Message, Int, rank, j);
    SM[j:Int]: SendMediator(Message, Int, rank, j)
```

Results One of the graphs that were used to test the algorithm is shown in Figure 2.5 (a). The (unique) minimum spanning tree computed by the algorithm is shown in Figure 2.5 (b). A snapshot of the trace follows, showing the beginning of the algorithm with node 0 waking up (after a `start` action), sending a `CONNECT` message to its minimun weight outgoing edge (1) and reporting this edge as part of the minimum spanning tree. The complete trace of this run can be found at `http://theory.csail.mit.edu:/~pmavrom/ioaReport.html`. The algorithm ran correctly, returning the unique minimum spanning tree in all cases.

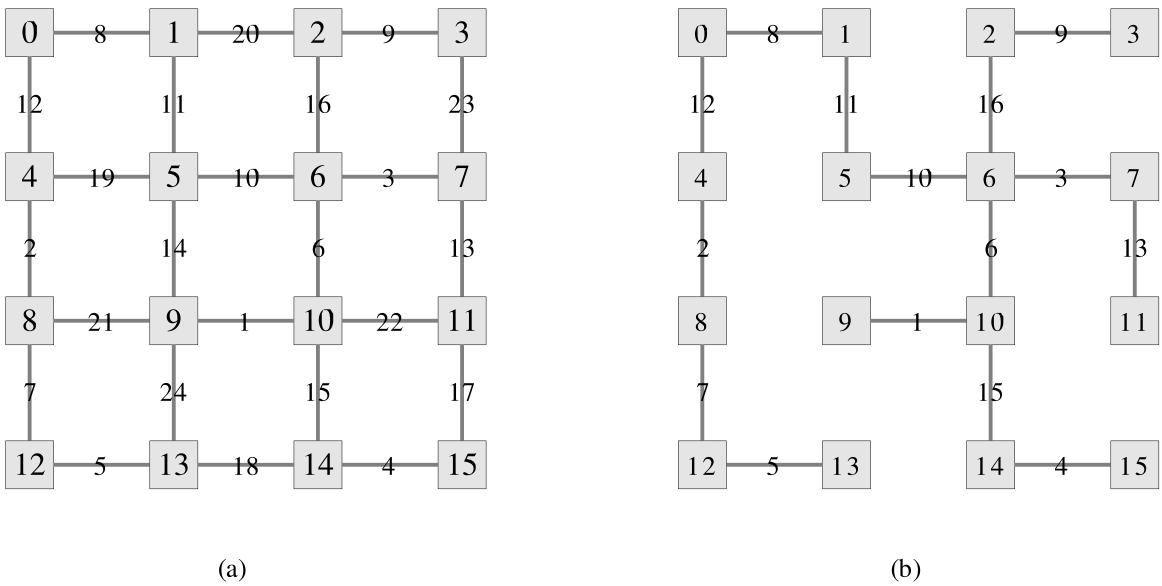


Figure 2.5: (a) shows one of the graphs used to test the GHS algorithm. In (b), the (unique) minimum spanning tree computed by the algorithm

Trace snapshot of the GHS algorithm

```
Initialization starts (0) on loon.csail.mit.edu at 7:05:55:830
Modified state variables:
P → [nstatus: sleeping, nfrag: nil, nlevel: 87, bestlink: nil, bestwt:
```

```
   87, testlink: nil, inbranch: [s: 87, t: 87], findcount: 87, lstatus: Map{},
   queueOut: Map{}, queueIn: Map{}, answered: Map{}, min: 87, minL: nil, S: ()]
RM → Map{}
SM → Map{}
links → ([s: 0, t: 1] [s: 0, t: 4])
lnk → [s: 87, t: 87]
lnks → ()
rank → null
size → null
tempL → [s: 87, t: 87]
tempLinks → ()
weight → Map{[[s: 0, t: 1] -> 8] [[s: 0, t: 4] -> 12] }
Initialization ends
transition: input startP() in automaton GHS(0)
   on loon.csail.mit.edu at 7:05:55:852
Modified state variables:
P → [nstatus: found, nfrag: nil, nlevel: 0, bestlink: embed([s: 0, t:
   4]), bestwt: 12, testlink: nil, inbranch: [s: 0, t: 1], findcount: 0, lstatus:
   Map{[[s: 0, t: 1] -> branch] [[s: 0, t: 4] -> unknown] }, queueOut: Map{[[s: 0,
   t: 1] -> {connMsg([msg: CONNECT, l: 0])}] [[s: 0, t: 4] -> {}] }, queueIn:
   Map{[[s: 1, t: 0] -> {}] [[s: 4, t: 0] -> {}] }, answered: Map{[[s: 0, t: 1] ->
   false] [[s: 0, t: 4] -> false] }, min: 8, minL: embed([s: 0, t: 1]), S: ()]
   RM → Map{[1 -> [status: idle, toRecv: {}, ready: false]] [4 -> [status:
   idle, toRecv: {}, ready: false]] }
SM → Map{[1 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [4 ->
   [status: idle, toSend: {}, sent: {}, handles: {}]] }
links → ([s: 0, t: 1] [s: 0, t: 4])
lnk → [s: 87, t: 87]
lnks → ()
rank → 0
size → 16
tempL → [s: 0, t: 4]
tempLinks → ()
weight → Map{[[s: 0, t: 1] -> 8] [[s: 0, t: 4] -> 12] }

transition: output SEND(connMsg([msg: CONNECT, l: 0]), 0, 1) in automaton
   GHS(0) on loon.csail.mit.edu at 7:05:55:864
Modified state variables:
P → Tuple, modified fields: {[queueOut -> Map, modified entries: {[[s: 0,
   t: 1] -> Sequence, elements added: {} Elements removed: {connMsg([msg: CONNECT,
   l: 0]) }]}}] }
SM → Map, modified entries: {[1 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {connMsg([msg: CONNECT, l: 0]) } Elements removed: {}]
   }]}
lnk → Tuple, modified fields: {[s -> 0] [t -> 1] }

transition: output InTree([s: 0, t: 1]) in automaton GHS(0)
   on loon.csail.mit.edu at 7:05:55:915
Modified state variables:
P → Tuple, modified fields: {[answered -> Map, modified entries: {[[s: 0,
   t: 1] -> true]}] }
SM → Map, modified entries: {[1 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {connMsg([msg: CONNECT, l: 0]) }]
   [sent -> Sequence, elements added: {connMsg([msg: CONNECT, l: 0]) } Elements
   removed: {}] }]}
```

3 Results

Figures 3.6, 3.7 and 3.8 depict the runtime results of the algorithms on 1 node per machine, a constant number of nodes and a constant number of machines respectively. The runtimes were measured in seconds, from the time when the first node started initialization until the time at which the algorithm terminated, and they are averages on 10 runs. The tables in Appendix D show the raw data collected from our experiments. In Figure 3.6(a) to (b) the relationship between time and number of nodes is not very clear due to the short time taken, number of nodes and messages exchanged. Figure 3.6(d) however, where the number of messages exchanged is large shows the clear (linear) relation.

4 Conclusions

During the months of June and July 2004 we had the opportunity to test the capabilities and the performance of the version of the toolkit that was then available. We started by mostly modifying the Java code the Toolkit generated to get LCR up and running. The toolkit was then gradually modified to automate the manual changes we had to make in Java. By the Spanning Tree to Leader algorithm the Toolkit was completely automated to provide Java code that compiled and ran successfully. After that, and after making sure that simple algorithms such as a simple broadcast and convergecast could be run, we implemented a more complicated algorithm, the GHS algorithm for computing the minimum spanning tree in an arbitrary graph. The successfull implementation of this algorithm makes us very confident that the toolkit can be used to implement complex distributed systems successfully.

Performance We now comment on some performance issues:

1. Scalability: As Figure 3.6 suggests, the Toolkit is scalable. Letting the number of nodes double increases the runtime but no more than twice the previous runtime. Moreover, Figure 3.6(e) shows that the rate of increase of the running time is smaller as the number of messages increases.

2. Setup time: The time required for MPI to set up all the connections and enable the nodes to initialize was not measured in the runtime results. However, when the number of nodes was large, this time was also quite significant (around 5-10 minutes).

3. Resource usage: The generated programs used all the available processing power available to them during the whole run. This was mainly because there was no pause between suceessive tests for incoming or outgoing messages.

5 Comments and Suggestions on the Toolkit

- The NDR Language, used both in the scheduler and the initialization block could be extended to support the `for v:T in s:Set[T]` statement, which is already used in IOA. This would make the code much cleaner since using the current syntax, these loops are implemented using a while loop and an extra set of two or more variables.

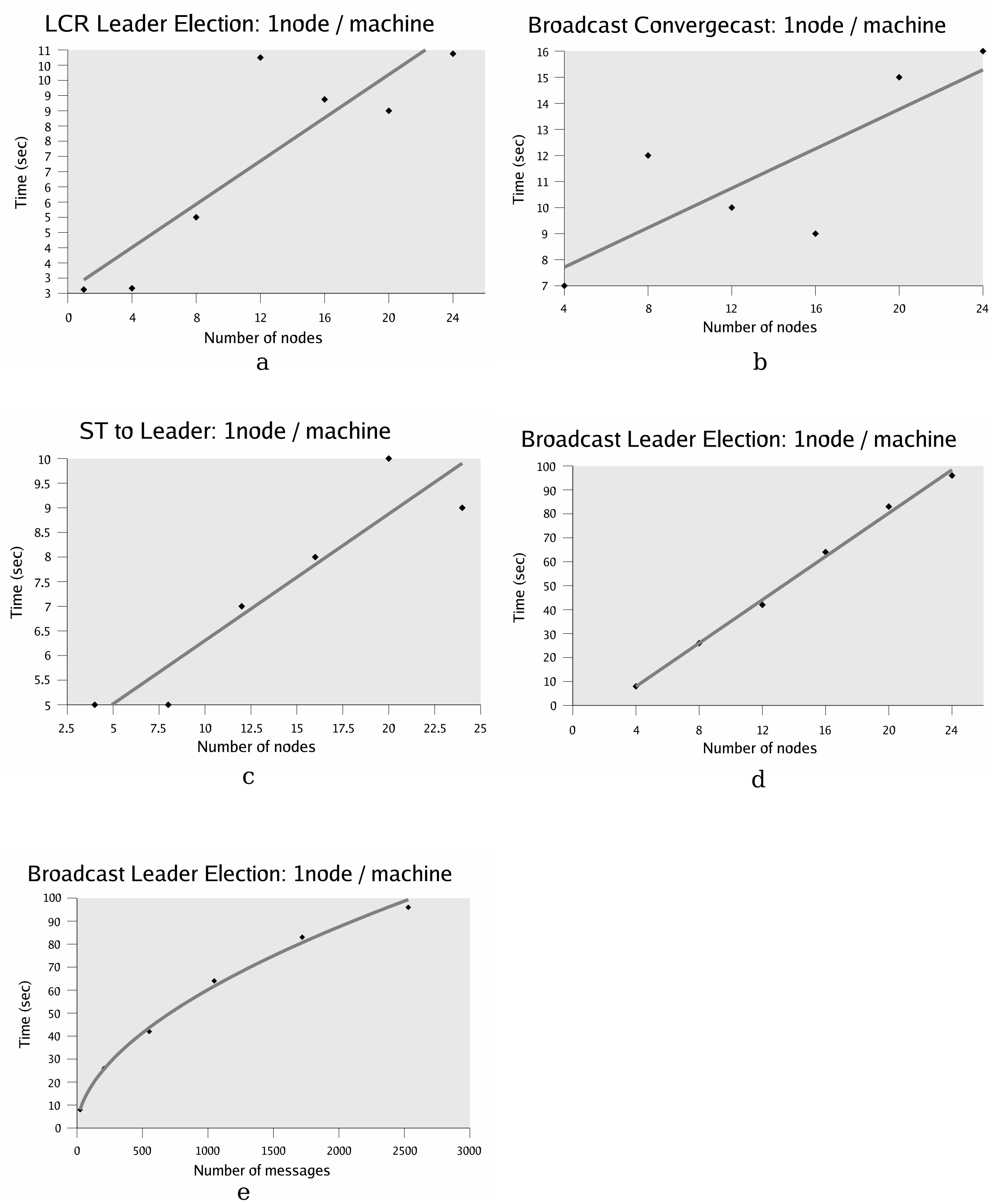


Figure 3.6: (a) to (d) show the time taken to complete the algorithm in regard to the number of nodes. (e) shows the time of Broadcast Leader Election in regard to the number of messages exchanged.

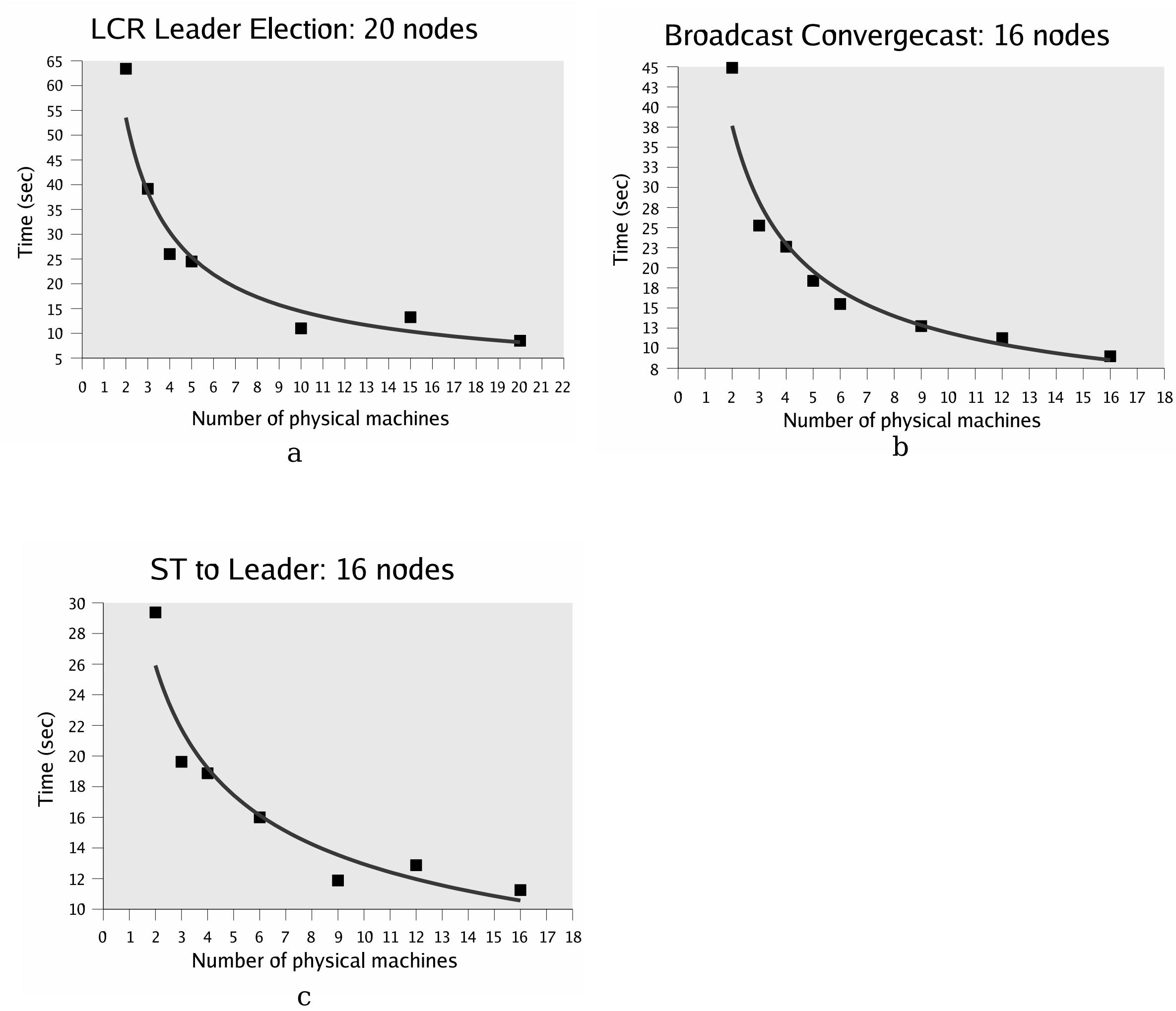
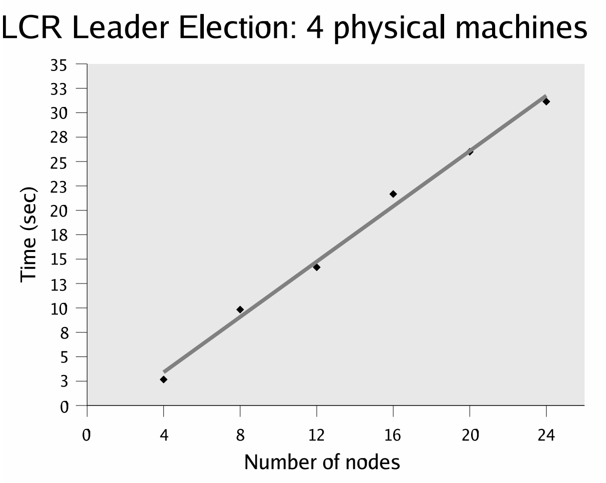
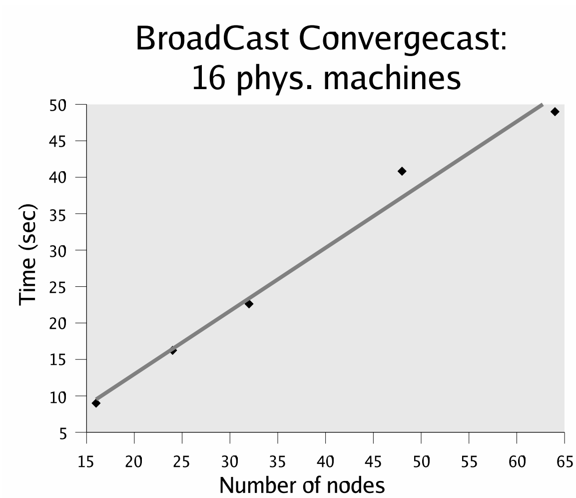


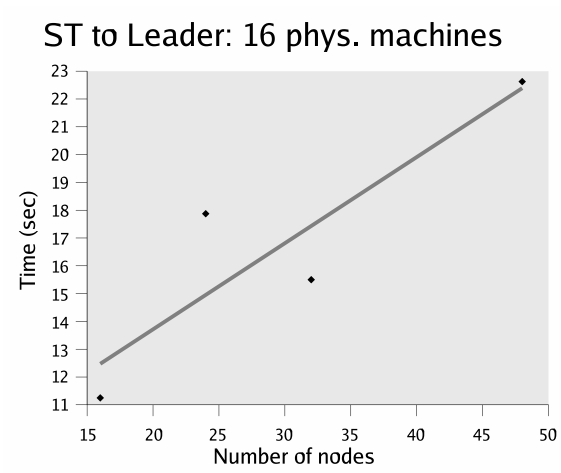
Figure 3.7: (a) to (c) show the time taken to terminate, in regard to the number of physical machines used.



a



b



c

Figure 3.8: (a) to (c) show the time taken to terminate, in regard to the number of nodes.

- Initialization of Map (or Array) entries. The toolkit allows usage of possibly non-initialized map/ array entries. As a result, when the compiled code is run, a NullPointerException is thrown from the Java environment when these variables are accessed. The following example illustrates the problem and demonstrates some possible solutions:

```
type Tup = tuple of a:Int, b: Bool
automaton Test
signature
...
states
 M: Map[Tup]
initially
 (true ⇒ SM[1].a = 3)
 det do
   SM[1].a := 3
...
```

  The user here tries to initialize the tuple before constructing it, which is done using a command like `SM[1] := [3, true]`. One possible solution would be for the toolkit to check for an initialization statement of the type `SM[1] := ...` in the **initially** block, before the accessing statement (of the type `SM[1].a`). If none exists, it could print a warning. Another solution could be to arbitrarily initialize all Map / Array Entries. The toolkit already supports such kind of initialization, but again if it does not occur, a warning message could be printed.

- In GHS, some parts of the IOA code were used more than once. The code given in [2] makes use of a `procedure`, i.e. a block of statements that can be declared and then called as many times as necessary. Given the complexity of GHS, such a feature would be quite useful during the design, coding and debugging process. For GHS, there was no need for parameter passing to the procedure. Therefore, as a first step, a simple procedure support (without parameter passing) from the toolkit would be enough.

- The use of MPI for communication has both advantages and disadvantages. Implementing the Toolkit was probably easier using MPI. No low-level communication programming was necessary. Furthermore, it has been tested to work for a long time now, and indeed, it works. However, it introduces some issues that could have been avoided. Firstly, most of the error messages coming from MPI are far from descriptive. (see Troubleshooting # 4) Moreover, MPI sets up a connection between all pairs of nodes, even if these connections are not necessary. An n-node LCR needs only n connections, while MPI sets up $\Theta(n^2)$ connections. This is probably the reason why on a larger number of nodes, MPI takes up a lot of time to setup. We suggest that the possibility of another communication interface, which gives more control over these issues (e.g. Java RMI) is examined at some time in the future.

- Finally, we have tested the possibility of pausing between consecutive tests for incoming and outgoing messages (MPI's `test` and `Iprobe`). Right now a node might be in an infinite loop probing for messages for tens of seconds and using up all the processing power available to it. Forcing the nodes to sleep for some milliseconds before probing again showed to improve performance when the number of nodes per physical machine is large. We have experimented with some runtimes of LCR Leader election on 20 nodes on a single machine, using different sleep times. The results are shown below:

Sleep time (milliseconds)	LCR on 20 nodes, 1 machine runtime (seconds)
100	40
50	25
25	13
10	8
1	13
0	121

References

[1] Nancy Lynch. *Distributed Algorithms*. Morgan Kaufmann Publishers, San Mateo, CA, 1996.

[2] Lampoft L. Welch J. and Lynch N. A lattice-structured proof of a minimum spanning tree algorithm. In *Proceedings of 7th A CM Symposium on Principles of Distributed Computing*, pages 28–43, August 1988.

A Troubleshooting

1. Sometimes during the composition of the process and mediator automata, two SEND and/or two RECEIVE transitions were produced by the composer. This should be fixed before generating Java code because the code will not compile later. To prevent this one should make sure that the **where** clauses on the SEND and RECEIVE actions in the process automaton match the where clauses for the SendMediator and ReceiveMediator component automata in the node composition.

2. Send/ Receive Convention. In LCR, we have used the convention of [1] for the `Send` and `Receive` transitions: `Send(m, i, j)` and `Receive(m, j, i)`. This means that `i` is always the sender and `j` is always the receiver. This convention sometimes caused problems that were hard to debug. We found that using a different convention made it easier to understand and debug any problems: `Send(m, i, j)` and `Receive(m, i, j)`, meaning that node `i` sends to node `j` and node `i` receives from node `j` respectively.

3. Currenlty the NDR Language, used in the schedule and initialially blocks does not support the **for** `v:T` **in** `S:Set[T]`. The way to create such loops is to use a **while** loop of the form:

```
uses ChoiseSet

...

schedule
states
 tempNbrs: Set[Int],
 k: Int

do
 tempNbrs := P.nbrs;
 while (¬isEmpty(tempNbrs)) do
   k := chooseRandom(tempNbrs);
   tempNbrs := delete(k, tempNbrs);
   \% fire action on neighbor k
 od;
od
```

4. MPI throws a SIGSEV error if the program tries to access a node using a negative number as the rank.

5. Several times when running an algorithm we encountered a `java.lang.NullPointerException` during the initialization or the first transitions of the automata. Almost always, this was due to a wrong initialization of the state variables in IOA.

B Bug Reports

1. In the LCRNode automaton some types such as `Status` and `_States[LCRProcess]` were not declared automatically. Manual declaration of these types was necessary. The latest version

of the toolkit generates these type definitions automatically. [**Fixed**]

2. The transitions that connect to the MPI have different signatures, but the implementation of the toolkit did not support that. (e.g. `Iprobe(i_v1,j_v2)` and `resp_Iprobe(i_v3, j_v4)` were not recognized as an MPI pair). We manually changed them to have exactly the same signature, for example `Iprobe(i_v1, j_v2)` and `resp_Iprobe(i_v1, j_v2)`. The latest version of the toolkit recognizes them as pairs even if they have different names. [**Fixed**]

3. In LCR a statement `(const 0)` was produced that was not recognized by the code generator. We manually changed the IL file produced to `(const v999)`, and declared the variable `v999` to something like `(v999 zero s8 (scope 1))` where `s8` was the sort corresponding to NatSort. [**Pending**]

4. Formal parameters were not translated in Java. We manually declared the field in the generated code, and initialized it to the correct value. The toolkit now translates all formal parameters and automatically initializes three special parameters: rank, size (of type Int or Nat) and hostName (of type String). [**Fixed**]

5. The initialization of the arguments from MPI (the statement `MPI.Init(args);`) had to happen in the *main()* method of the class LCRNode and not ioa.runitime.Automaton. Otherwise, the environment would not recognize the correct number of processes running. The toolkit has been modified so that this will happen automatically from now on. [**Fixed**]

6. The composer tool (incorrectly) removes all the preconditions of internal actions during composition. [**Pending**]

7. In the NDR Language translation, no `break;` statement was produced after a fire block. This caused unexpected termination in some algorithms. [**Fixed**]

8. IntSort's modulo operator is not compatible with its specification. [**Pending**]

9. The syntax of declaring a map is `v: Map[D1, ..., Dn, R]` where $n \geq 1$. If only one type is given, (e.g. `map1: Map[Int]`), the checker tool throws a `java.lang.InternalError` instead of a more descriptive Syntax Error message.

C Automata Definitions and Input Files

C.1 SendMediator and ReceiveMediator

These automata were used as the channel between two nodes and the connection of the automata to the MPI.

SendMediator

```
type sCall = enumeration of idle, Isend, test

automaton SendMediator(Msg, Node:Type, i:Node, j:Node)

  assumes Infinite(Handle)

  signature
    input  SEND(m: Msg, const i, const j)
    output Isend(m: Msg, const i, const j)
    input  resp_Isend(handle:Handle, const i, const j)
    output test(handle:Handle, const i, const j)
    input  resp_test(flag:Bool, const i, const j)

  states
    status: sCall := idle,
    toSend: Seq[Msg] := {},
    sent: Seq[Msg] := {},
    handles: Seq[Handle] := {}

  transitions
    input SEND(m, i, j)
      eff toSend := toSend ⊢ m
    output Isend(m,i,j)
      pre head(toSend) = m;
          status = idle
      eff toSend := tail(toSend);
          sent := sent ⊢ m;
          status := Isend
    input resp_Isend(handle, i, j)
      eff handles := handles ⊢ handle;
          status := idle
    output test(handle, i, j)
      pre status = idle;
          handle = head(handles)
      eff status := test
    input resp_test(flag, i, j)
      eff if (flag = true) then
             handles := tail(handles);
             sent := tail(sent)
          fi;
          status := idle
```

ReceiveMediator

```
type rCall = enumeration of idle, receive, Iprobe
```

```
automaton ReceiveMediator(Msg, Node: Type, i: Node, j:Node)

  assumes Infinite(Handle)

  signature
    output RECEIVE(m:Msg, const i, const j)
    output Iprobe(const i, const j)
    input resp_Iprobe(flag:Bool, const i, const j)
    output receive(const i, const j)
    input resp_receive(m: Msg, const i, const j)

  states
    status: rCall := idle,
    toRecv: Seq[Msg] := {},
    ready: Bool := false

  transitions
    output RECEIVE(m, i, j)
      pre m = head(toRecv)
      eff toRecv := tail(toRecv)
    output Iprobe(i, j)
      pre status = idle;
          ready = false
      eff status := Iprobe
    input resp_Iprobe(flag, i, j)
      eff ready := flag;
          status := idle
    output receive(i, j)
      pre ready = true;
          status = idle
      eff status := receive
    input resp_receive(m, i, j)
      eff toRecv := toRecv ⊢ m;
          ready := false;
          status := idle
```

C.2 LCR

Expanded automaton with initialization and scheduling

```
uses ChoiceSet(Int)

automaton LCR(rank: Int, size: Int)
  signature
    output receive(N6: Int, N7: Int)
      where N7 = rank ∧ N6 = mod((rank+size) -1, size)
    output SEND(m: Int, I2: Int, I3: Int)
      where I3 = mod(rank + 1, size) ∧ I2 = rank
    input resp_Iprobe(flag: Bool, N4: Int, N5: Int)
      where N5 = rank ∧ N4 = mod((rank+size) -1, size)
    input resp_test(flag: Bool, N18: Int, N19: Int)
      where N19 = mod(rank + 1, size) ∧ N18 = rank
    input resp_receive(m: Int, N8: Int, N9: Int)
      where N9 = rank ∧ N8 = mod((rank+size) -1, size)
    input vote
```

```
  output test(handle: Handle, N16: Int, N17: Int)
    where N17 = mod(rank + 1, size) ∧ N16 = rank
  output Iprobe(N2: Int, N3: Int)
    where N3 = rank ∧ N2 = mod((rank+size) -1, size)
  output RECEIVE(m: Int, I0: Int, I1: Int)
    where I1 = rank ∧ I0 = mod((rank+size) -1, size)
  output leader(I4: Int) where I4 = rank
  input resp_Isend(handle: Handle, N14: Int, N15: Int)
    where N15 = mod(rank + 1, size) ∧ N14 = rank
  output Isend(m: Int, N12: Int, N13: Int)
    where N13 = mod(rank + 1, size) ∧ N12 = rank
states
  P: _States[LCRProcess],
  RM: Map[Int, _States[ReceiveMediator, Int, Int]],
  SM: Map[Int, _States[SendMediator, Int, Int]]
   initially
    (true ⇒ P.pending = {rank} ∧ P.status = idle)
      ∧
        ∀ j: Int
           ((j = mod((rank+size) -1, size)
               ⇒
                 RM[j].status = idle
                   ∧ RM[j].toRecv = {}
                   ∧ RM[j].ready = false)
              ∧ (j = mod((rank+size) -1, size) ⇔ defined(RM, j)))
      ∧
        ∀ j: Int
           ((j = mod(rank + 1, size)
               ⇒
                 SM[j].status = idle
                   ∧ SM[j].toSend = {}
                   ∧ SM[j].sent = {}
                   ∧ SM[j].handles = {})
              ∧ (j = mod(rank + 1, size) ⇔ defined(SM, j)))
  det do
    P.pending := {rank};
    P.status := idle;
    RM[mod((rank+size) -1, size)] := [idle, {}, false];
    SM[mod(rank+1, size)] := [idle, {}, {}, {}]
  od
transitions
  output receive(N6, N7)
    pre RM[mod((rank+size) -1, size)].ready = true
         ∧ RM[mod((rank+size) -1, size)].status = idle
    eff RM[mod((rank+size) -1, size)].status := receive
  output SEND(m, I2, I3)
    pre P.status ≠ idle ∧ m ∈ (P.pending)
    eff SM[mod(rank + 1, size)].toSend :=
          (SM[mod(rank + 1, size)].toSend) ⊢ m;
        P.pending := delete(m, P.pending)
  input resp_Iprobe(flag, N4, N5)
    eff RM[mod((rank+size) -1, size)].ready := flag;
        RM[mod((rank+size) -1, size)].status := idle
  input resp_test(flag, N18, N19)
    eff if flag = true then
          SM[mod(rank + 1, size)].handles :=
```

```
              tail(SM[mod(rank + 1, size)].handles);
            SM[mod(rank + 1, size)].sent :=
              tail(SM[mod(rank + 1, size)].sent)
          fi;
          SM[mod(rank + 1, size)].status := idle
    input resp_receive(m, N8, N9)
      eff RM[mod((rank+size) -1, size)].toRecv :=
            (RM[mod((rank+size) -1, size)].toRecv) ⊢ m;
          RM[mod((rank+size) -1, size)].ready := false;
          RM[mod((rank+size) -1, size)].status := idle
    input vote
      eff P.status := voting
    output test(handle, N16, N17)
      pre SM[mod(rank + 1, size)].status = idle
            ∧ handle = head(SM[mod(rank + 1, size)].handles)
      eff SM[mod(rank + 1, size)].status := test
    output Iprobe(N2, N3)
      pre RM[mod((rank+size) -1, size)].status = idle
            ∧ RM[mod((rank+size) -1, size)].ready = false
      eff RM[mod((rank+size) -1, size)].status := Iprobe
    output RECEIVE(m, I0, I1) where m > I1 ∨ m < I1 ∨ m = I1
      pre m = head(RM[mod((rank+size) -1, size)].toRecv)
      eff if m > I1 then P.pending := insert(m, P.pending)
          elseif m = I1 then P.status := elected
          fi;
          RM[mod((rank+size) -1, size)].toRecv :=
            tail(RM[mod((rank+size) -1, size)].toRecv)
    output leader(I4)
      pre P.status = elected
      eff P.status := announced
    input resp_Isend(handle, N14, N15)
      eff SM[mod(rank + 1, size)].handles :=
            (SM[mod(rank + 1, size)].handles) ⊢ handle;
          SM[mod(rank + 1, size)].status := idle
    output Isend(m, N12, N13)
      pre head(SM[mod(rank + 1, size)].toSend) = m
            ∧ SM[mod(rank + 1, size)].status = idle
      eff SM[mod(rank + 1, size)].toSend :=
            tail(SM[mod(rank + 1, size)].toSend);
          SM[mod(rank + 1, size)].sent :=
            (SM[mod(rank + 1, size)].sent) ⊢ m;
          SM[mod(rank + 1, size)].status := Isend
schedule
  do
    fire input vote;
    while (true) do
     if P.pending ≠ {} then
       fire output SEND(chooseRandom(P.pending), rank,  mod(rank+1,size)) fi;
     if SM[mod(rank+1,size)].status = idle
        ∧ SM[mod(rank+1,size)].toSend ≠ {} then
       fire output
         Isend(head(SM[mod(rank+1,size)].toSend), rank, mod(rank+1,size)) fi;
     if SM[mod(rank+1,size)].status = idle
        ∧ SM[mod(rank+1,size)].handles ≠ {} then
       fire output
         test(head(SM[mod(rank+1,size)].handles), rank, mod(rank+1,size)) fi;
```

```
      if RM[mod((rank+size) -1,size)].status = idle
         ∧ RM[mod((rank+size) -1,size)].ready = false then
        fire output Iprobe(rank, mod(rank-1,size)) fi;
      if RM[mod((rank+size) -1,size)].status = idle
         ∧ RM[mod((rank+size) -1,size)].ready = true then
        fire output receive(rank, mod((rank+size) -1, size)) fi;
      if RM[mod((rank+size) -1,size)].toRecv ≠ {} then
        fire output
         RECEIVE(head(RM[mod((rank+size) -1,size)].toRecv),
                 mod((rank+size) -1,size), rank) fi;
      if P.status = elected then
        fire output leader(rank) fi
    od
  od

type Status = enumeration of idle, voting, elected, announced
type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test
type _States[LCRProcess] = tuple of pending: Set[Int], status: Status
type _States[ReceiveMediator, Int, Int] = tuple of status: rCall, toRecv:
  Seq[Int], ready: Bool
type _States[SendMediator, Int, Int] = tuple of status: sCall, toSend:
  Seq[Int], sent: Seq[Int], handles: Seq[Handle]
```

C.3 Asynchronous Spanning Tree

Expanded automaton with initialization and scheduling

```
type Message = enumeration of search, null
type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test
type _States[sTreeProcess] = tuple of parent: Int, reported:
    Bool, send: Map[Int, Message]
type _States[SendMediator, Message, Int] =  tuple of status: sCall, toSend:
    Seq[Message], sent: Seq[Message], handles: Seq[Handle]
type  _States[ReceiveMediator, Message, Int] =  tuple of status: rCall, toRecv:
    Seq[Message], ready: Bool

uses ChoiceSet(Int)

automaton sTree(rank: Int, nbrs: Set[Int])
  signature
    output SEND(m: Message, v10: Int, v11: Int) where v10 = rank
    output RECEIVE(m: Message, v0: Int, v1: Int) where v0 = rank
    output PARENT(j3: Int)
    output test(handle: Handle, v16: Int, v17: Int) where v16 = rank
    input  resp_test(flag: Bool, v18: Int, v19: Int) where v18 = rank
    output receive(v6: Int, v7: Int) where v6 = rank
    input  resp_receive(m: Message, v8: Int, v9: Int) where v8 = rank
    output Iprobe(v2: Int, v3: Int) where v2 = rank
    input  resp_Iprobe(flag: Bool, v4: Int, v5: Int) where v4 = rank
    output Isend(m: Message, v12: Int, v13: Int) where v12 = rank
    input  resp_Isend(handle: Handle, v14: Int, v15: Int) where v14 = rank
  states
    P: _States[sTreeProcess],
```

```
  RM: Map[Int, _States[ReceiveMediator, Message, Int]],
  SM: Map[Int, _States[SendMediator, Message, Int]],
  % Temporary
  tempNbrs: Set[Int], j: Int
initially
  true ⇒ P.parent = -1
det do
  P.parent := -1;
  P.reported := false;
  tempNbrs := nbrs;
  while (¬isEmpty(tempNbrs)) do
    j := chooseRandom(tempNbrs);
    tempNbrs := delete(j, tempNbrs);
    if rank = 0 then
      P.send[j] := search
    else
      P.send[j] := null
    fi;
    RM[j] := [idle, {}, false];
    SM[j] := [idle, {}, {}, {}]
  od
od

transitions
  output SEND(m, v10, v11) where v10 = rank
    pre P.send[v11] = search
    eff SM[v11].toSend := (SM[v11].toSend) ⊢ m;
        P.send[v11] := null
  output RECEIVE(m, v0, v1)
    pre m = head(RM[v1].toRecv)
    eff if rank ≠ 0 ∧ P.parent = -1 then
          P.parent := v1;
          for k: Int in nbrs - {v1} do
            P.send[k] := search
          od
        fi;
        RM[v1].toRecv := tail(RM[v1].toRecv)
  output PARENT(j3)
    pre P.parent = j3 ∧ P.reported = false
    eff P.reported := true
  output receive(v6, v7)
    pre RM[v7].ready = true ∧ RM[v7].status = idle
    eff RM[v7].status := receive
  input resp_receive(m, v6, v7)
    eff RM[v7].toRecv := (RM[v7].toRecv) ⊢ m;
        RM[v7].ready := false;
        RM[v7].status := idle
  output test(handle, v16, v17)
    pre SM[v17].status = idle ∧ handle = head(SM[v17].handles)
    eff SM[v17].status := test
  input resp_test(flag, v18, v19)
    eff if flag = true then
          SM[v19].handles := tail(SM[v19].handles);
          SM[v19].sent := tail(SM[v19].sent)
        fi;
        SM[v19].status := idle
```

```
    output Iprobe(v2, v3)
      pre RM[v3].status = idle ∧ RM[v3].ready = false
      eff RM[v3].status := Iprobe
    input resp_Iprobe(flag, v2, v3)
      eff RM[v3].ready := flag;
          RM[v3].status := idle
    output Isend(m, v12, v13)
      pre head(SM[v13].toSend) = m ∧ SM[v13].status = idle
      eff SM[v13].toSend := tail(SM[v13].toSend);
          SM[v13].sent := (SM[v13].sent) ⊢ m;
          SM[v13].status := Isend
    input resp_Isend(handle, v12, v13)
      eff SM[v13].handles := (SM[v13].handles) ⊢ handle;
          SM[v13].status := idle
schedule
  states
    nb: Set[Int],
    k: Int
  do
   while (true) do
     nb := nbrs;
     while (¬isEmpty(nb)) do
       k := chooseRandom(nb);
       nb := delete(k, nb);
       if P.send[k] = search then
         fire output SEND(search, rank, k) fi;
       if SM[k].status = idle ∧ SM[k].toSend ≠ {} then
         fire output Isend(head(SM[k].toSend), rank, k) fi;
       if SM[k].status = idle ∧ SM[k].handles ≠ {} then
         fire output test(head(SM[k].handles), rank, k) fi;
       if RM[k].status = idle ∧ RM[k].ready = false then
         fire output Iprobe(rank, k) fi;
       if RM[k].status = idle ∧ RM[k].ready = true then
         fire output receive(rank, k) fi;
       if RM[k].toRecv ≠ {} then
         fire output RECEIVE(head(RM[k].toRecv), rank, k) fi;
       if P.parent = k ∧ P.reported = false then
         fire output PARENT(k) fi
     od
   od
  od
```

C.4 Asynchronous Broadcast Convergecast

Expanded automaton with initialization and scheduling

```
type Kind = enumeration of bcast, ack
type BCastMsg = tuple of kind: Kind , w: Int
type Message = union of msg: BCastMsg, kind: Kind
type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test
type _States[bcastProcess] = tuple of val:Int, acked: Set[Int],
    parent: Int, reported:
    Bool, send: Map[Int, Seq[Message]], temp: BCastMsg
type _States[SendMediator, Message, Int] =  tuple of status: sCall, toSend:
```

```
    Seq[Message], sent: Seq[Message], handles: Seq[Handle]
type _States[ReceiveMediator, Message, Int] =  tuple of status: rCall, toRecv:
    Seq[Message], ready: Bool

uses ChoiceSet(Int)

automaton bcast(rank: Int, nbrs: Set[Int])
  assumes bcastNode_Axioms
  assumes P_Axioms
  assumes RM_Axioms
  assumes SM_Axioms
  signature
    output receive(v6: Int, v7: Int) where v6 = rank
    output SEND(m: Message, v10: Int, v11: Int) where v10 = rank
    input resp_Iprobe(flag: Bool, v4: Int, v5: Int) where v4 = rank
    internal report(v2: Int) where v2 = rank
    input resp_test(flag: Bool, v18: Int, v19: Int) where v18 = rank
    input resp_receive(m: Message, v8: Int, v9: Int) where v8 = rank
    output test(handle: Handle, v16: Int, v17: Int) where v16 = rank
    output Iprobe(v2: Int, v3: Int) where v2 = rank
    output RECEIVE(m: Message, v0: Int, v1: Int) where v0 = rank
    input resp_Isend(handle: Handle, v14: Int, v15: Int) where v14 = rank
    output Isend(m: Message, v12: Int, v13: Int) where v12 = rank
  states
    P: _States[bcastProcess],
    RM: Map[Int, _States[ReceiveMediator, Message, Int]],
    SM: Map[Int, _States[SendMediator, Message, Int]],
    %%Temporary variables
    tempNbrs : Set[Int] := {},
    j: Int

  initially
      true ⇒ P.val = 99
      det do
        if rank = 0 then
          P.val := 99;
          (P.temp).kind := bcast;
          (P.temp).w := P.val;
          tempNbrs := nbrs;
          while (¬isEmpty(tempNbrs)) do
            j := chooseRandom(tempNbrs);
            tempNbrs := delete(j, tempNbrs);
            P.send[j] := {} ⊢ msg(P.temp)
          od
        else
          P.val := -1;
          tempNbrs := nbrs;
         while (¬isEmpty(tempNbrs)) do
            j := chooseRandom(tempNbrs);
            tempNbrs := delete(j, tempNbrs);
            P.send[j] := {}
          od
        fi;
        P.parent := -1;
        P.reported := false;
        P.acked := {};
```

```
      tempNbrs := nbrs;
      while (¬isEmpty(tempNbrs)) do
        j := chooseRandom(tempNbrs);
        tempNbrs := delete(j, tempNbrs);
        RM[j] := [idle, {}, false];
        SM[j] := [idle, {}, {}, {}]
      od
  od

transitions
  output receive(v6, v7)
    pre RM[v7].ready = true ∧ RM[v7].status = idle
    eff RM[v7].status := receive
  output SEND(m, v10, v11) where v10 = rank
    pre m = head(P.send[v11])
    eff SM[v11].toSend := (SM[v11].toSend) ⊢ m;
        P.send[v11] := tail(P.send[v11])
  input resp_Iprobe(flag, v4, v5)
    eff RM[v5].ready := flag;
        RM[v5].status := idle
  internal report(v2)
    %% The preconditions were (incorrectly) removed
    eff if rank = 0 then P.reported := true
        elseif rank ≠ 0 then
           P.send[P.parent] := P.send[P.parent] ⊢ kind(ack);
           P.reported := true
        fi
  input resp_test(flag, v18, v19)
    eff if flag = true then
           SM[v19].handles := tail(SM[v19].handles);
           SM[v19].sent := tail(SM[v19].sent)
        fi;
        SM[v19].status := idle
  input resp_receive(m, v8, v9)
    eff RM[v9].toRecv := (RM[v9].toRecv) ⊢ m;
        RM[v9].ready := false;
        RM[v9].status := idle
  output test(handle, v16, v17)
    pre SM[v17].status = idle ∧ handle = head(SM[v17].handles)
    eff SM[v17].status := test
  output Iprobe(v2, v3)
    pre RM[v3].status = idle ∧ RM[v3].ready = false
    eff RM[v3].status := Iprobe
  output RECEIVE(m, v0, v1)
    pre m = head(RM[v1].toRecv)
    eff if m = kind(ack) then P.acked := (P.acked) ∪ {v1}
        else
           if P.val = -1 then
              P.val := (m.msg).w;
              P.parent := v1;
              for k: Int in (nbrs) - {v1} do
                P.send[k] := P.send[k] ⊢ m
                od
           else P.send[v1] := P.send[v1] ⊢ kind(ack)
           fi
        fi;
```

```
          RM[v1].toRecv := tail(RM[v1].toRecv)
    input resp_Isend(handle, v14, v15)
      eff SM[v15].handles := (SM[v15].handles) ⊢ handle;
          SM[v15].status := idle
    output Isend(m, v12, v13)
      pre head(SM[v13].toSend) = m ∧ SM[v13].status = idle
      eff SM[v13].toSend := tail(SM[v13].toSend);
          SM[v13].sent := (SM[v13].sent) ⊢ m;
          SM[v13].status := Isend

schedule
states
 tempNbrs2: Set[Int],
 k: Int
do
  while(true) do
   tempNbrs2 := nbrs;
    while (¬isEmpty(tempNbrs2)) do
      k := chooseRandom(tempNbrs2);
      tempNbrs2 := delete(k, tempNbrs2);
      if P.send[k] ≠ {} then
        fire output SEND(head(P.send[k]), rank, k) fi;
      if SM[k].status = idle ∧ SM[k].toSend ≠ {} then
        fire output Isend(head(SM[k].toSend), rank, k) fi;
      if SM[k].status = idle ∧ SM[k].handles ≠ {} then
        fire output test(head(SM[k].handles), rank, k) fi;
      if RM[k].status = idle ∧ RM[k].ready = false then
        fire output Iprobe(rank, k) fi;
      if RM[k].status = idle ∧ RM[k].ready = true then
        fire output receive(rank, k) fi;
      if RM[k].toRecv ≠ {} then
        fire output RECEIVE(head(RM[k].toRecv), rank, k) fi
    od;
    if rank = 0 ∧ P.acked = nbrs ∧ P.reported = false then
      fire internal report(rank) fi;
    if rank ≠ 0 ∧ P.parent ≠ -1 ∧ P.acked = nbrs - {P.parent} ∧
       P.reported = false then
      fire internal report(rank) fi
  od
od
```

C.5 Leader Election using Asynchronous Broadcast Convergecast

Expanded automaton with initialization and scheduling

```
type Kind = enumeration of bcast, ack
type BCastMsg = tuple of kind: Kind, w: Int
type AckMsg = tuple of kind: Kind, mx: Int
type MSG = union of bmsg: BCastMsg, amsg: AckMsg, kind: Kind
type Message = tuple of msg: MSG, source: Int

type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test

type _States[bcastLeaderProcess] = tuple of val: Map[Int, Int],
```

```
  parent: Map[Int, Int], reported: Map[Int, Bool], acked:
  Map[Int, Set[Int]], send: Map[Int, Int, Seq[Message]], max:
  Map[Int, Int], elected: Bool, announced: Bool

type _States[ReceiveMediator, Message, Int] = tuple of status: rCall, toRecv:
  Seq[Message], ready: Bool

type _States[SendMediator, Message, Int] = tuple of status: sCall, toSend:
  Seq[Message], sent: Seq[Message], handles: Seq[Handle]

type _States[bcastLeaderNode] = tuple of P: _States[bcastLeaderProcess],
  RM: Map[Int, _States[ReceiveMediator, Message, Int]], SM:
  Map[Int, _States[SendMediator, Message, Int]]

uses ChoiceSet(Int)

automaton bcastLeader(rank: Int, size:Int, nbrs:Set[Int])
  signature
    output receive(N6: Int, N7: Int) where N6 = rank
    output SEND(m: Message, N10: Int, N11: Int) where N10 = rank
    input resp_Iprobe(flag: Bool, N4: Int, N5: Int) where N4 = rank
    internal finished
    internal report(I2: Int, source: Int) where I2 = rank
    output LEADER
    input resp_test(flag: Bool, N18: Int, N19: Int) where N18 = rank
    input resp_receive(m: Message, N8: Int, N9: Int) where N8 = rank
    output test(handle: Handle, N16: Int, N17: Int) where N16 = rank
    output Iprobe(N2: Int, N3: Int) where N2 = rank
    output RECEIVE(m: Message, N0: Int, N1: Int) where N0 = rank
    input resp_Isend(handle: Handle, N14: Int, N15: Int) where N14 = rank
    output Isend(m: Message, N12: Int, N13: Int) where N12 = rank
  states
    P: _States[bcastLeaderProcess],
    RM: Map[Int, _States[ReceiveMediator, Message, Int]],
    SM: Map[Int, _States[SendMediator, Message, Int]],
    tempNbrs: Set[Int],
    c: Int,
    j: Int

      initially
       (true
          ⇒
            ∀ j: Int
               (0 ≤ j ∧ j < 16
                  ⇒
                     (rank = j
                        ⇒
                          P.val[j] = rank
                            ∧ (rank ≠ j ⇒ P.val[j] = -1)
                            ∧ P.parent[j] = -1
                            ∧ P.acked[j] = {}
                            ∧ P.max[j] = rank
                            ∧
                              ∀ k: Int
                                 (P.send[j, k] = {}
                                    ∧ k ∈ nbrs
```

```
                               ∧ rank = j
                               ⇒
                                 P.send[j, k]
                                   = {} ⊢ [bmsg([bcast, 99]), j])))
          ∧ P.elected = false)
      ∧
        ∀ j: Int
          (RM[j].status = idle
             ∧ RM[j].toRecv = {}
             ∧ RM[j].ready = false
             ∧ defined(RM, j))
      ∧
        ∀ j: Int
          (SM[j].status = idle
             ∧ SM[j].toSend = {}
             ∧ SM[j].sent = {}
             ∧ SM[j].handles = {}
             ∧ defined(SM, j))
    det do
      c := size;
      while (c > 0) do
        c := c - 1;
        if (rank = c) then
           P.val[c] := rank
        else
           P.val[c] := -1
        fi;
        P.parent[c] := -1;
        P.acked[c] := {};
        P.max[c] := rank;
        P.reported[c] := false;
        P.elected := false;
        P.announced := false;

        tempNbrs := nbrs;
        while (¬isEmpty(tempNbrs)) do
          j := chooseRandom(tempNbrs);
          tempNbrs := delete(j, tempNbrs);
          P.send[c, j] := {};
          if c = rank then
            P.send[c, j] := {} ⊢ [bmsg( [bcast, 99] ), c]
          fi
        od;

        tempNbrs := nbrs;
        while (¬isEmpty(tempNbrs)) do
          j := chooseRandom(tempNbrs);
          tempNbrs := delete(j, tempNbrs);
          RM[j] := [idle, {}, false];
          SM[j] := [idle, {}, {}, {}]
        od
      od
    od

transitions
  output receive(N6, N7)
```

```
  pre RM[N7].ready = true ∧ RM[N7].status = idle
  eff RM[N7].status := receive
output SEND(m, N10, N11) where N10 = rank
  pre m = head(P.send[m.source, N11])
  eff SM[N11].toSend := (SM[N11].toSend) ⊢ m;
      P.send[m.source, N11] := tail(P.send[m.source, N11])
input resp_Iprobe(flag, N4, N5)
  eff RM[N5].ready := flag;
      RM[N5].status := idle

output LEADER
  pre P.elected = true ∧ P.announced = false
  eff P.announced := true

internal finished
  % preconditions didn't pass through
  pre P.acked[rank] = nbrs ∧
      P.reported[rank] = false
  eff P.reported[rank] := true;
      if (P.max[rank] = rank) then
         P.elected := true
      fi;
internal report(I2, source)
  eff P.send[source, P.parent[source]] :=
        P.send[source, P.parent[source]]
          ⊢ [amsg([ack, P.max[source]]), source];
      P.reported[source] := true

input resp_test(flag, N18, N19)
  eff if flag = true then
         SM[N19].handles := tail(SM[N19].handles);
         SM[N19].sent := tail(SM[N19].sent)
      fi;
      SM[N19].status := idle
input resp_receive(m, N8, N9)
  eff RM[N9].toRecv := (RM[N9].toRecv) ⊢ m;
      RM[N9].ready := false;
      RM[N9].status := idle
output test(handle, N16, N17)
  pre SM[N17].status = idle ∧ handle = head(SM[N17].handles)
  eff SM[N17].status := test
output Iprobe(N2, N3)
  pre RM[N3].status = idle ∧ RM[N3].ready = false
  eff RM[N3].status := Iprobe
output RECEIVE(m, N0, N1)
  pre m = head(RM[N1].toRecv)
  eff if m.msg = kind(ack) then
         P.acked[m.source] := P.acked[m.source] ∪ {N1}
      elseif tag(m.msg) = amsg then
         if P.max[m.source] < (((m.msg).amsg).mx) then
            P.max[m.source] := ((m.msg).amsg).mx
         fi;
         P.acked[m.source] := P.acked[m.source] ∪ {N1}
      else
         if P.val[m.source] = -1 then
            P.val[m.source] := ((m.msg).bmsg).w;
```

```
              P.parent[m.source] := N1;
              for k: Int in (nbrs) - {N1} do
                P.send[m.source, k] := P.send[m.source, k] ⊢ m
                od
            else
              P.send[m.source, N1] :=
                P.send[m.source, N1] ⊢ [kind(ack), m.source]
            fi
          fi;
          RM[N1].toRecv := tail(RM[N1].toRecv)
    input resp_Isend(handle, N14, N15)
      eff SM[N15].handles := (SM[N15].handles) ⊢ handle;
          SM[N15].status := idle
    output Isend(m, N12, N13)
      pre head(SM[N13].toSend) = m ∧ SM[N13].status = idle
      eff SM[N13].toSend := tail(SM[N13].toSend);
          SM[N13].sent := (SM[N13].sent) ⊢ m;
          SM[N13].status := Isend


schedule
states
 c2: Int, %% Source
 tempNbrs2: Set[Int],
 k: Int

 do
     while(true) do
          c2 := size;
          while (c2 > 0) do
            c2 := c2 - 1;
            tempNbrs2 := nbrs;
            while (¬isEmpty(tempNbrs2)) do
                k := chooseRandom(tempNbrs2);
                tempNbrs2 := delete(k, tempNbrs2);
                if P.send[c2, k] ≠ {} then
                        fire output SEND(head(P.send[c2, k]), rank, k) fi;
                if SM[k].status = idle ∧ SM[k].toSend ≠ {} then
                        fire output Isend(head(SM[k].toSend), rank, k) fi;
                if SM[k].status = idle ∧ SM[k].handles ≠ {} then
                        fire output test(head(SM[k].handles), rank, k) fi;
                if RM[k].status = idle ∧ RM[k].ready = false then
                        fire output Iprobe(rank, k) fi;
                if RM[k].status = idle ∧ RM[k].ready = true then
                        fire output receive(rank, k) fi;
                if RM[k].toRecv ≠ {} then
                        fire output RECEIVE(head(RM[k].toRecv), rank, k) fi
            od;
            if c2 ≠ rank ∧ P.parent[c2] ≠ -1 ∧
               P.acked[c2] = nbrs - {P.parent[c2]} ∧
               P.reported[c2] = false then
                fire internal report(rank, c2) fi;
            if c2 = rank ∧  P.acked[rank] = nbrs ∧
               P.reported[rank] = false then
                fire internal finished fi;
            if P.elected = true ∧ P.announced = false then
```

```
                fire output LEADER fi
          od
      od
 od
```

C.6 Spanning Tree to Leader Election

Expanded automaton with initialization and scheduling

```
uses ChoiceSet(Int)

automaton sTreeLeader(rank: Int, nbrs: Set[Int])
  signature
    output receive(N6: Int, N7: Int) where N6 = rank
    output SEND(m: Message, N10: Int, N11: Int) where N10 = rank
    input resp_Iprobe(flag: Bool, N4: Int, N5: Int) where N4 = rank
    input resp_test(flag: Bool, N18: Int, N19: Int) where N18 = rank
    input resp_receive(m: Message, N8: Int, N9: Int) where N8 = rank
    output test(handle: Handle, N16: Int, N17: Int) where N16 = rank
    output Iprobe(N2: Int, N3: Int) where N2 = rank
    output RECEIVE(m: Message, N0: Int, N1: Int) where N0 = rank
    output leader
    input resp_Isend(handle: Handle, N14: Int, N15: Int) where N14 = rank
    output Isend(m: Message, N12: Int, N13: Int) where N12 = rank
  states
    P: _States[sTreeLeaderProcess],
    RM: Map[Int, _States[ReceiveMediator, Message, Int]],
    SM: Map[Int, _States[SendMediator, Message, Int]],
    % Temporary storage
    j: Int,
    tempNbrs: Set[Int]
  initially
      (true ⇒
         P.receivedElect = {}
         ∧ P.sentElect = {}
         ∧ P.status = idle
         ∧ (size(nbrs) = 1 ⇒
              P.send[chooseRandom(nbrs)]
                = P.send[chooseRandom(nbrs)] ⊢ elect))
       ∧ ∀ j: Int
           (j ∈ nbrs ⇒
            (RM[j].status = idle
               ∧ RM[j].toRecv = {}
               ∧ RM[j].ready = false
               ∧ defined(RM, j)))
       ∧ ∀ j: Int
           (j ∈ nbrs ⇒
            (SM[j].status = idle
               ∧ SM[j].toSend = {}
               ∧ SM[j].sent = {}
               ∧ SM[j].handles = {}
               ∧ defined(SM, j)))
  det do
    P.receivedElect := {};
    P.sentElect := {};
```

```
    P.status := idle;
    tempNbrs := nbrs;
    while (¬isEmpty(tempNbrs)) do
      j := chooseRandom(tempNbrs);
      tempNbrs := delete(j, tempNbrs);
      P.send[j] := {};
      RM[j] := [idle, {}, false];
      SM[j] := [idle, {}, {}, {}]
    od;
    if size(nbrs) = 1 then
      P.send[chooseRandom(nbrs)] := {} ⊢ elect
    fi
  od
  transitions
    output receive(N6, N7)
      pre RM[N7].ready = true ∧ RM[N7].status = idle
      eff RM[N7].status := receive
    output SEND(m, N10, N11) where N10 = rank
      pre m = head(P.send[N11])
      eff SM[N11].toSend := (SM[N11].toSend) ⊢ m;
          P.send[N11] := tail(P.send[N11])
    input resp_Iprobe(flag, N4, N5)
      eff RM[N5].ready := flag;
          RM[N5].status := idle
    input resp_test(flag, N18, N19)
      eff if flag = true then
             SM[N19].handles := tail(SM[N19].handles);
             SM[N19].sent := tail(SM[N19].sent)
          fi;
          SM[N19].status := idle
    input resp_receive(m, N8, N9)
      eff RM[N9].toRecv := (RM[N9].toRecv) ⊢ m;
          RM[N9].ready := false;
          RM[N9].status := idle
    output test(handle, N16, N17)
      pre SM[N17].status = idle ∧ handle = head(SM[N17].handles)
      eff SM[N17].status := test
    output Iprobe(N2, N3)
      pre RM[N3].status = idle ∧ RM[N3].ready = false
      eff RM[N3].status := Iprobe
    output RECEIVE(m, N0, N1)
      pre m = head(RM[N1].toRecv)
      eff P.receivedElect := insert(N1, P.receivedElect);
          if size(P.receivedElect) = size(nbrs) - 1 then
             P.send[chooseRandom(nbrs - (P.receivedElect))] :=
               P.send[chooseRandom(nbrs - (P.receivedElect))] ⊢ elect;
             P.sentElect :=
               insert
                 (chooseRandom(nbrs - (P.receivedElect)), P.sentElect)
          elseif P.receivedElect = nbrs then
             if N1 ∈ (P.sentElect) then
                if N0 > N1 then P.status := elected fi
             else P.status := elected
             fi
          fi;
          RM[N1].toRecv := tail(RM[N1].toRecv)
```

```
    output leader
      pre P.status = elected
      eff P.status := announced
    input resp_Isend(handle, N14, N15)
      eff SM[N15].handles := (SM[N15].handles) ⊢ handle;
          SM[N15].status := idle
    output Isend(m, N12, N13)
      pre head(SM[N13].toSend) = m ∧ SM[N13].status = idle
      eff SM[N13].toSend := tail(SM[N13].toSend);
          SM[N13].sent := (SM[N13].sent) ⊢ m;
          SM[N13].status := Isend

schedule
  states
    tempNbrs2: Set[Int],
    k: Int
  do
   while(true) do
    tempNbrs2 := nbrs;
    while (¬isEmpty(tempNbrs2)) do
      k := chooseRandom(tempNbrs2);
      tempNbrs2 := delete(k, tempNbrs2);
      if P.send[k] ≠ {} then
        fire output SEND(head(P.send[k]), rank, k) fi;
      if SM[k].status = idle ∧ SM[k].toSend ≠ {} then
        fire output Isend(head(SM[k].toSend), rank, k) fi;
      if SM[k].status = idle ∧ SM[k].handles ≠ {} then
        fire output test(head(SM[k].handles), rank, k) fi;
      if RM[k].status = idle ∧ RM[k].ready = false then
        fire output Iprobe(rank, k) fi;
      if RM[k].status = idle ∧ RM[k].ready = true then
        fire output receive(rank, k) fi;
      if RM[k].toRecv ≠ {} then
        fire output RECEIVE(head(RM[k].toRecv), rank, k) fi
    od;
    if P.status = elected then fire output leader fi
   od
  od

type Status = enumeration of idle, elected, announced
type Message = enumeration of elect
type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test
type _States[sTreeLeaderProcess] = tuple of receivedElect:
  Set[Int], sentElect: Set[Int], status: Status, send:
  Map[Int, Seq[Message]]
type _States[ReceiveMediator, Message, Int] = tuple of status: rCall,
  toRecv: Seq[Message], ready: Bool
type _States[SendMediator, Message, Int] = tuple of status: sCall, toSend:
  Seq[Message], sent: Seq[Message], handles: Seq[Handle]
```

C.7 GHS

Expanded automaton with initialization and scheduling

```
uses ChoiceSet(Link)

automaton
  GHS(rank: Int, size: Int, links: Set[Link], weight: Map[Link, Int])
  signature
    input resp_receive(m: Message, N8: Int, N9: Int) where N8 = rank
    internal ReceiveChangeRoot(qp: Link)
    input resp_Iprobe(flag: Bool, N4: Int, N5: Int) where N4 = rank
    output RECEIVE(m: Message, i: Int, j: Int) where i = rank
    input resp_Isend(handle: Handle, N14: Int, N15: Int) where N14 = rank
    output Isend(m: Message, N12: Int, N13: Int) where N12 = rank
    internal ReceiveConnect(qp: Link, l: Int)
    internal ReceiveReport(qp: Link, w: Int)
    internal ReceiveAccept(qp: Link)
    internal ReceiveInitiate(qp: Link, l: Int, c: Null[Edge], st: Status)
    output NotInTree(l: Link)
    output InTree(l: Link)
    output Iprobe(N2: Int, N3: Int) where N2 = rank
    internal ReceiveTest(qp: Link, l: Int, c: Null[Edge])
    input resp_test(flag: Bool, N18: Int, N19: Int) where N18 = rank
    output SEND(m: Message, N10: Int, N11: Int) where N10 = rank
    output receive(N6: Int, N7: Int) where N6 = rank
    output test(handle: Handle, N16: Int, N17: Int) where N16 = rank
    internal ReceiveReject(qp: Link)
    input startP
  states
    P: _States[GHSProcess],
    RM: Map[Int, _States[ReceiveMediator, Message, Int]],
    SM: Map[Int, _States[SendMediator, Message, Int]],
    % Temporary
    tempLinks: Set[Link], tempL: Link
     initially
      (true
         ⇒
           P.nstatus = sleeping
             ∧ P.nfrag = nil
             ∧ P.nlevel = 0
             ∧ P.bestlink = embed(chooseRandom(links))
             ∧ P.bestwt = weight[chooseRandom(links)]
             ∧ P.testlink = nil
             ∧ P.inbranch = chooseRandom(links)
             ∧ P.findcount = 0
             ∧
               ∀ l: Link
                  (l ∈ links
                     ⇒
                       P.lstatus[l] = unknown
                         ∧ P.answered[l] = false
                         ∧ P.queueOut[l] = {}
                         ∧ P.queueIn[l] = {}))
        ∧
          ∀ j: Int
             (RM[j].status = idle
                ∧ RM[j].toRecv = {}
                ∧ RM[j].ready = false
                ∧ defined(RM, j))
```

```
      ∧
        ∀ j: Int
           (SM[j].status = idle
              ∧ SM[j].toSend = {}
              ∧ SM[j].sent = {}
              ∧ SM[j].handles = {}
              ∧ defined(SM, j))
  det do
    P.nstatus := sleeping;
    P.nfrag := nil;
    P.nlevel := 0;
    P.bestlink := embed(chooseRandom(links));
    P.bestwt := weight[chooseRandom(links)];
    P.testlink := nil;
    P.inbranch := chooseRandom(links);
    P.findcount := 0;
    tempLinks := links;
    while (¬isEmpty(tempLinks)) do
      tempL := chooseRandom(tempLinks);
      tempLinks := delete(tempL, tempLinks);
      P.lstatus[tempL] := unknown;
      P.answered[tempL] := false;
      P.queueOut[tempL] := {};
      P.queueIn[[tempL.t, tempL.s]] := {};
      RM[tempL.t] := [idle, {}, false];
      SM[tempL.t] := [idle, {}, {}, {}]
    od
  od

transitions
  input resp_receive(m, N8, N9)
    eff RM[N9].toRecv := (RM[N9].toRecv) ⊢ m;
        RM[N9].ready := false;
        RM[N9].status := idle
  internal ReceiveChangeRoot(qp)
    eff P.queueIn[qp] := tail(P.queueIn[qp]);
        if P.lstatus[(P.bestlink).val] = branch then
           P.queueOut[(P.bestlink).val] :=
             P.queueOut[(P.bestlink).val] ⊢ msg(CHANGEROOT)
        else
           P.queueOut[(P.bestlink).val] :=
             P.queueOut[(P.bestlink).val]
               ⊢ connMsg([CONNECT, P.nlevel]);
           P.lstatus[(P.bestlink).val] := branch
        fi
  input resp_Iprobe(flag, N4, N5)
    eff RM[N5].ready := flag;
        RM[N5].status := idle
  output RECEIVE(m, i, j)
    pre m = head(RM[j].toRecv)
    eff P.queueIn[[j, i]] := P.queueIn[[j, i]] ⊢ m;
        RM[j].toRecv := tail(RM[j].toRecv)
  input resp_Isend(handle, N14, N15)
    eff SM[N15].handles := (SM[N15].handles) ⊢ handle;
        SM[N15].status := idle
  output Isend(m, N12, N13)
```

```
    pre head(SM[N13].toSend) = m ∧ SM[N13].status = idle
    eff SM[N13].toSend := tail(SM[N13].toSend);
        SM[N13].sent := (SM[N13].sent) ⊢ m;
        SM[N13].status := Isend
  internal ReceiveConnect(qp, l)
    pre head(P.queueIn[qp]) = connMsg([CONNECT, l])
    eff P.queueIn[qp] := tail(P.queueIn[qp]);
        if P.nstatus = sleeping then
           P.minL := embed(chooseRandom(links));
           P.min := weight[(P.minL).val];
           for tempL: Link in links do
             if weight[tempL] < (P.min) then
                P.minL := embed(tempL);
                P.min := weight[tempL]
             fi
             od;
           P.lstatus[(P.minL).val] := branch;
           P.nstatus := found;
           P.queueOut[(P.minL).val] :=
             P.queueOut[(P.minL).val] ⊢ connMsg([CONNECT, 0])
        fi;
        if l < (P.nlevel) then
           P.lstatus[[qp.t, qp.s]] := branch;
           if P.testlink ≠ nil then
              P.queueOut[[qp.t, qp.s]] :=
                P.queueOut[[qp.t, qp.s]]
                  ⊢ initMsg([INITIATE, P.nlevel, P.nfrag, find]);
              P.findcount := (P.findcount) + 1
           else
              P.queueOut[[qp.t, qp.s]] :=
                P.queueOut[[qp.t, qp.s]]
                  ⊢ initMsg([INITIATE, P.nlevel, P.nfrag, found])
           fi
        else
           if P.lstatus[[qp.t, qp.s]] = unknown then
              P.queueIn[qp] := P.queueIn[qp] ⊢ connMsg([CONNECT, l])
           else
              P.queueOut[[qp.t, qp.s]] :=
                P.queueOut[[qp.t, qp.s]]
                  ⊢
                    initMsg
                      ([INITIATE,
                        (P.nlevel) + 1,
                        embed([qp.t, qp.s]),
                        find])
           fi
        fi
  internal ReceiveReport(qp, w)
    pre head(P.queueIn[qp]) = reportMsg([REPORT, w])
    eff P.queueIn[qp] := tail(P.queueIn[qp]);
        if [qp.t, qp.s] ≠ P.inbranch then
           P.findcount := (P.findcount) - 1;
           if w < (P.bestwt) then
              P.bestwt := w;
              P.bestlink := embed([qp.t, qp.s])
           fi;
```

```
        if P.findcount = 0 ∧ P.testlink = nil then
           P.nstatus := found;
           P.queueOut[P.inbranch] :=
             P.queueOut[P.inbranch] ⊢ reportMsg([REPORT, P.bestwt])
        fi
     else
        if P.nstatus = find then
           P.queueIn[qp] := P.queueIn[qp] ⊢ reportMsg([REPORT, w])
        elseif w > (P.bestwt) then
           if P.lstatus[(P.bestlink).val] = branch then
              P.queueOut[(P.bestlink).val] :=
                P.queueOut[(P.bestlink).val] ⊢ msg(CHANGEROOT)
           else
              P.queueOut[(P.bestlink).val] :=
                P.queueOut[(P.bestlink).val]
                  ⊢ connMsg([CONNECT, P.nlevel]);
              P.lstatus[(P.bestlink).val] := branch
           fi
        fi
     fi
internal ReceiveAccept(qp)
  pre head(P.queueIn[qp]) = msg(ACCEPT)
  eff P.queueIn[qp] := tail(P.queueIn[qp]);
      P.testlink := nil;
      if weight[[qp.t, qp.s]] < (P.bestwt) then
         P.bestlink := embed([qp.t, qp.s]);
         P.bestwt := weight[[qp.t, qp.s]]
      fi;
      if P.findcount = 0 ∧ P.testlink = nil then
         P.nstatus := found;
         P.queueOut[P.inbranch] :=
           P.queueOut[P.inbranch] ⊢ reportMsg([REPORT, P.bestwt])
      fi
internal ReceiveInitiate(qp, l, c, st)
  pre head(P.queueIn[qp]) = initMsg([INITIATE, l, c, st])
  eff P.queueIn[qp] := tail(P.queueIn[qp]);
      P.nlevel := l;
      P.nfrag := c;
      if st = find then P.nstatus := find else P.nstatus := found fi;
      P.S := {};
      for pr: Link in links do
        if pr.t ≠ qp.s ∧ P.lstatus[pr] = branch then
           P.S := (P.S) ∪ {pr}
        fi
        od;
      for k: Link in P.S do
        P.queueOut[k] := P.queueOut[k] ⊢ initMsg([INITIATE, l, c, st])
        od;
      if st = find then
         P.inbranch := [qp.t, qp.s];
         P.bestlink := nil;
         P.bestwt := 1000;
         P.minL := nil;
         P.min := 1000;
         for tempL: Link in links do
           if weight[tempL] < (P.min) ∧ P.lstatus[tempL] = unknown
```

```
            then
            P.minL := embed(tempL);
            P.min := weight[tempL]
          fi
          od;
        if P.minL ≠ nil then
           P.testlink := P.minL;
           P.queueOut[(P.minL).val] :=
             P.queueOut[(P.minL).val]
               ⊢ testMsg([TEST, P.nlevel, P.nfrag])
        else
           P.testlink := nil;
           if P.findcount = 0 ∧ P.testlink = nil then
              P.nstatus := found;
              P.queueOut[P.inbranch] :=
                P.queueOut[P.inbranch]
                  ⊢ reportMsg([REPORT, P.bestwt])
           fi
        fi;
        P.findcount := size(P.S)
      fi
output NotInTree(l)
  pre P.answered[l] = false ∧ P.lstatus[l] = rejected
  eff P.answered[l] := true
output InTree(l)
  pre P.answered[l] = false ∧ P.lstatus[l] = branch
  eff P.answered[l] := true
output Iprobe(N2, N3)
  pre RM[N3].status = idle ∧ RM[N3].ready = false
  eff RM[N3].status := Iprobe
internal ReceiveTest(qp, l, c)
  pre head(P.queueIn[qp]) = testMsg([TEST, l, c])
  eff P.queueIn[qp] := tail(P.queueIn[qp]);
      if P.nstatus = sleeping then
        P.minL := embed(chooseRandom(links));
        P.min := weight[(P.minL).val];
        for tempL: Link in links do
          if weight[tempL] < (P.min) then
            P.minL := embed(tempL);
            P.min := weight[tempL]
          fi
          od;
        P.lstatus[(P.minL).val] := branch;
        P.nstatus := found;
        P.queueOut[(P.minL).val] :=
          P.queueOut[(P.minL).val] ⊢ connMsg([CONNECT, 0])
      fi;
      if l > (P.nlevel) then
        P.queueIn[qp] := P.queueIn[qp] ⊢ testMsg([TEST, l, c])
      else
        if c ≠ P.nfrag then
           P.queueOut[[qp.t, qp.s]] :=
             P.queueOut[[qp.t, qp.s]] ⊢ msg(ACCEPT)
        else
           if P.lstatus[[qp.t, qp.s]] = unknown then
              P.lstatus[[qp.t, qp.s]] := rejected
```

```
            fi;
            if P.testlink ≠ embed([qp.t, qp.s]) then
               P.queueOut[[qp.t, qp.s]] :=
                 P.queueOut[[qp.t, qp.s]] ⊢ msg(REJECT)
            else
               P.minL := nil;
               P.min := 1000;
               for tempL: Link in links do
                 if weight[tempL] < (P.min)
                      ∧ P.lstatus[tempL] = unknown then
                    P.minL := embed(tempL);
                    P.min := weight[tempL]
                 fi
                 od;
               if P.minL ≠ nil then
                  P.testlink := P.minL;
                  P.queueOut[(P.minL).val] :=
                    P.queueOut[(P.minL).val]
                      ⊢ testMsg([TEST, P.nlevel, P.nfrag])
               else
                  P.testlink := nil;
                  if P.findcount = 0 ∧ P.testlink = nil then
                     P.nstatus := found;
                     P.queueOut[P.inbranch] :=
                       P.queueOut[P.inbranch]
                         ⊢ reportMsg([REPORT, P.bestwt])
                  fi
               fi
            fi
         fi
      fi
input resp_test(flag, N18, N19)
  eff if flag = true then
         SM[N19].handles := tail(SM[N19].handles);
         SM[N19].sent := tail(SM[N19].sent)
      fi;
      SM[N19].status := idle
output SEND(m, N10, N11) where N10 = rank
  pre m = head(P.queueOut[[N10, N11]])
  eff SM[N11].toSend := (SM[N11].toSend) ⊢ m;
      P.queueOut[[N10, N11]] := tail(P.queueOut[[N10, N11]])
output receive(N6, N7)
  pre RM[N7].ready = true ∧ RM[N7].status = idle
  eff RM[N7].status := receive
output test(handle, N16, N17)
  pre SM[N17].status = idle ∧ handle = head(SM[N17].handles)
  eff SM[N17].status := test
internal ReceiveReject(qp)
  pre head(P.queueIn[qp]) = msg(REJECT)
  eff P.queueIn[qp] := tail(P.queueIn[qp]);
      if P.lstatus[[qp.t, qp.s]] = unknown then
         P.lstatus[[qp.t, qp.s]] := rejected
      fi;
      P.minL := nil;
      P.min := 1000;
      for tempL: Link in links do
```

```
            if weight[tempL] < (P.min) ∧ P.lstatus[tempL] = unknown then
               P.minL := embed(tempL);
               P.min := weight[tempL]
            fi
            od;
          if P.minL ≠ nil then
             P.testlink := P.minL;
             P.queueOut[(P.minL).val] :=
               P.queueOut[(P.minL).val]
                 ⊢ testMsg([TEST, P.nlevel, P.nfrag])
          else
             P.testlink := nil;
             if P.findcount = 0 ∧ P.testlink = nil then
                P.nstatus := found;
                P.queueOut[P.inbranch] :=
                  P.queueOut[P.inbranch] ⊢ reportMsg([REPORT, P.bestwt])
             fi
          fi
    input startP
      eff if P.nstatus = sleeping then
             P.minL := embed(chooseRandom(links));
             P.min := weight[(P.minL).val];
             for tempL: Link in links do
               if weight[tempL] < (P.min) then
                  P.minL := embed(tempL);
                  P.min := weight[tempL]
               fi
               od;
             P.lstatus[(P.minL).val] := branch;
             P.nstatus := found;
             P.queueOut[(P.minL).val] :=
               P.queueOut[(P.minL).val] ⊢ connMsg([CONNECT, 0])
          fi

schedule
states
 lnks: Set[Link],
 lnk : Link
do
   fire input startP;
   while(true) do
     lnks := links;
     while (¬isEmpty(lnks)) do
       lnk := chooseRandom(lnks);
       lnks := delete(lnk, lnks);
       if P.queueOut[lnk] ≠ {} then
         fire output SEND(head(P.queueOut[lnk]), rank, lnk.t) fi;
       if SM[lnk.t].status = idle ∧ SM[lnk.t].toSend ≠ {} then
         fire output Isend(head(SM[lnk.t].toSend), rank, lnk.t) fi;
       if SM[lnk.t].status = idle ∧ SM[lnk.t].handles ≠ {} then
         fire output test(head(SM[lnk.t].handles), rank, lnk.t) fi;
       if RM[lnk.t].status = idle ∧ RM[lnk.t].ready = false then
         fire output Iprobe(rank, lnk.t) fi;
       if RM[lnk.t].status = idle ∧ RM[lnk.t].ready = true then
         fire output receive(rank, lnk.t) fi;
       if RM[lnk.t].toRecv ≠ {} then
```

```
        fire output RECEIVE(head(RM[lnk.t].toRecv), rank, lnk.t) fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         tag(head(P.queueIn[[lnk.t, lnk.s]])) = connMsg then
           fire internal ReceiveConnect([lnk.t, lnk.s],
             (head(P.queueIn[[lnk.t, lnk.s]])).connMsg.l)
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         tag(head(P.queueIn[[lnk.t, lnk.s]])) = initMsg then
           fire internal ReceiveInitiate([lnk.t, lnk.s],
             (head(P.queueIn[[lnk.t, lnk.s]])).initMsg.l,
             (head(P.queueIn[[lnk.t, lnk.s]])).initMsg.c,
             (head(P.queueIn[[lnk.t, lnk.s]])).initMsg.st)
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         tag(head(P.queueIn[[lnk.t, lnk.s]])) = testMsg then
         fire internal ReceiveTest([lnk.t, lnk.s],
             (head(P.queueIn[[lnk.t, lnk.s]])).testMsg.l,
             (head(P.queueIn[[lnk.t, lnk.s]])).testMsg.c)
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         head(P.queueIn[[lnk.t, lnk.s]]) = msg(ACCEPT) then
           fire internal ReceiveAccept([lnk.t, lnk.s])
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         head(P.queueIn[[lnk.t, lnk.s]]) = msg(REJECT) then
           fire internal ReceiveReject([lnk.t, lnk.s])
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         tag(head(P.queueIn[[lnk.t, lnk.s]])) = reportMsg then
           fire internal ReceiveReport([lnk.t, lnk.s],
             (head(P.queueIn[[lnk.t, lnk.s]])).reportMsg.w)
      fi;
      if P.queueIn[[lnk.t, lnk.s]] ≠ {} ∧
         head(P.queueIn[[lnk.t, lnk.s]]) = msg(CHANGEROOT) then
           fire internal ReceiveChangeRoot([lnk.t, lnk.s])
      fi;
      if P.answered[lnk] = false ∧ P.lstatus[lnk] = branch then
         fire output InTree(lnk) fi;
      if P.answered[lnk] = false ∧ P.lstatus[lnk] = rejected then
         fire output NotInTree(lnk) fi
    od
  od
od

type Nstatus = enumeration of sleeping, find, found
type Edge = tuple of s: Int, t: Int
type Link = tuple of s: Int, t: Int
type Lstatus = enumeration of unknown, branch, rejected
type Msg = enumeration of CONNECT, INITIATE, TEST, REPORT, ACCEPT, REJECT,
  CHANGEROOT
type ConnMsg = tuple of msg: Msg, l: Int
type Status = enumeration of find, found
type InitMsg = tuple of msg: Msg, l: Int, c: Null[Edge], st: Status
type TestMsg = tuple of msg: Msg, l: Int, c: Null[Edge]
type ReportMsg = tuple of msg: Msg, w: Int
type Message = union of connMsg: ConnMsg, initMsg: InitMsg, testMsg:
```

```
  TestMsg, reportMsg: ReportMsg, msg: Msg
type rCall = enumeration of idle, receive, Iprobe
type sCall = enumeration of idle, Isend, test
type _States[GHSProcess] = tuple of nstatus: Nstatus, nfrag: Null[Edge],
  nlevel: Int, bestlink: Null[Link], bestwt: Int, testlink: Null[Link],
  inbranch: Link, findcount: Int, lstatus: Map[Link, Lstatus], queueOut:
  Map[Link, Seq[Message]], queueIn: Map[Link, Seq[Message]], answered:
  Map[Link, Bool], min: Int, minL: Null[Link], S: Set[Link]
type _States[ReceiveMediator, Message, Int] = tuple of status: rCall,
  toRecv: Seq[Message], ready: Bool
type _States[SendMediator, Message, Int] = tuple of status: sCall, toSend:
  Seq[Message], sent: Seq[Message], handles: Seq[Handle]
```

D RuntimeTables

Physical machines	Nodes	Messages	Run time average (sec)
2	20	39	63
3	20	39	39
4	20	39	26
5	20	39	25
10	20	39	11
15	20	39	13
20	20	39	9
4	4	7	3
4	8	15	10
4	12	23	14
4	16	31	22
4	24	47	31
1	1	1	3
4	4	7	3
8	8	15	5
12	12	23	10
16	16	31	9
20	20	39	9
24	24	47	10

Table D.1: Runtime results of the LCR Leader Election Algorithm

Physical machines	Nodes	Messages	Run time average (sec)
4	4	3	1
8	8	7	3
12	12	11	2

Table D.2: Runtime results of the Asynchronous Spanning Tree algorithm

Physical machines	Nodes	Messages	Run time average (sec)
2	16	66	45
3	16	66	24
4	16	66	23
5	16	66	18
6	16	66	16
9	16	66	13
12	16	66	11
16	16	66	9
16	24	106	16
16	32		23
16	48		41
16	64		49
4	4	6	7
8	8	26	12
12	12	46	10
16	16	66	9
20	20	86	15
24	24	106	16

Table D.3: Runtime results of the Asynchronous Broadcast Convergecast algorithm

Physical machines	Nodes	Messages	Run time average (sec)
4	4	24	8
8	8	208	26
12	12	552	42
16	16	1048	64
20	20	1720	83
24	24	2530	96

Table D.4: Runtime results of the Leader Election using the Asynchronous Broadcast Convergecast Algorithm

Physical machines	Nodes	Messages	Run time average (sec)
2	16	16	29
3	16	16	20
4	16	16	19
6	16	16	16
9	16	16	12
12	16	16	13
16	16	16	11
16	24	24	18
16	32	32	16
16	48	48	23
4	4	4	5
8	8	8	5
12	12	12	7
16	16	16	8
20	20	20	10
24	24	24	9

Table D.5: Runtime results of the Spanning Tree to Leader Election Algorithm

Physical machines	Nodes	Messages	Run time average (sec)
9	9	89	15
16	16	213	30

Table D.6: Runtime results of the GHS Minimum Spanning Tree algorithm

E Traces of runs

E.1 LCR on 8 nodes

Complete trace

```
    Initialization starts (0) on loon.csail.mit.edu at 7:25:29:615
    Modified state variables:
    P → [pending: (), status: idle]
    RM → Map{}
    SM → Map{}
    rank → null
    size → null
    Initialization ends
    transition: input vote() in automaton LCR(0)
         on loon.csail.mit.edu at 7:25:29:625
    Modified state variables:
    P → [pending: (0), status: voting]
    RM → Map{[7 -> [status: idle, toRecv: {}, ready: false]] }
    SM → Map{[1 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
    rank → 0
    size → 8

    transition: output SEND(0, 0, 1) in automaton LCR(0)
         on loon.csail.mit.edu at 7:25:29:629
    Modified state variables:
    P → Tuple, modified fields: {[pending -> ()] }
    SM → Map, modified entries: {[1 -> Tuple, modified fields: {[toSend ->
Sequence, elements added: {0 } Elements removed: {}] }]}

    Initialization starts (2) on parrot.csail.mit.edu at 7:25:29:820
    Modified state variables:
    P → [pending: (), status: idle]
    RM → Map{}
    SM → Map{}
    rank → null
    size → null
    Initialization ends
    Initialization starts (3)  on tui.csail.mit.edu at 7:25:29:927
    transition: input vote() in automaton LCR(2)
         on parrot.csail.mit.edu at 7:25:29:960
    Modified state variables:
    P → [pending: (2), status: voting]
    RM → Map{[1 -> [status: idle, toRecv: {}, ready: false]] }
    SM → Map{[3 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
    rank → 2
    size → 8

    Modified state variables:
    P → [pending: (), status: idle]
    RM → Map{}
    SM → Map{}
    rank → null
    size → null
    Initialization ends
    Initialization starts (7) on tui.csail.mit.edu at 7:25:30:169
```

```
transition: output SEND(2, 2, 3) in automaton LCR(2)
     on parrot.csail.mit.edu at 7:25:30:200
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[3 -> Tuple, modified fields: {[toSend ->
Sequence, elements added: {2 } Elements removed: {}] }]}

Modified state variables:
P → [pending: (), status: idle]
RM → Map{}
SM → Map{}
rank → null
size → null
Initialization ends
Initialization starts (6) on parrot.csail.mit.edu at 7:25:30:247
Modified state variables:
P → [pending: (), status: idle]
RM → Map{}
SM → Map{}
rank → null
size → null
Initialization ends
Initialization starts (5) on condor.csail.mit.edu at 7:25:30:286
transition: input vote() in automaton LCR(6)
     on parrot.csail.mit.edu at 7:25:30:313
Modified state variables:
P → [pending: (6), status: voting]
RM → Map{[5 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[7 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 6
size → 8

Modified state variables:
P → [pending: (), status: idle]
RM → Map{}
SM → Map{}
rank → null
size → null
Initialization ends
transition: input vote() in automaton LCR(5)
     on condor.csail.mit.edu at 7:25:30:426
Modified state variables:
P → [pending: (5), status: voting]
RM → Map{[4 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[6 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 5
size → 8

transition: input vote() in automaton LCR(3)
     on tui.csail.mit.edu at 7:25:30:460
Modified state variables:
P → [pending: (3), status: voting]
RM → Map{[2 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[4 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 3
size → 8
```

```
transition: output SEND(6, 6, 7) in automaton LCR(6)
     on parrot.csail.mit.edu at 7:25:30:497
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[7 -> Tuple, modified fields: {[toSend ->
Sequence, elements added: {6 } Elements removed: {}] }]}

transition: input vote() in automaton LCR(7)
     on tui.csail.mit.edu at 7:25:30:710
Modified state variables:
P → [pending: (7), status: voting]
RM → Map{[6 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[0 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 7
size → 8

transition: output SEND(5, 5, 6) in automaton LCR(5)
     on condor.csail.mit.edu at 7:25:30:737
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {5 } Elements removed: {}] }]}

transition: output SEND(3, 3, 4) in automaton LCR(3)
     on tui.csail.mit.edu at 7:25:30:959
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[4 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {3 } Elements removed: {}] }]}

transition: output SEND(7, 7, 0) in automaton LCR(7)
     on tui.csail.mit.edu at 7:25:30:989
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[0 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}

Initialization starts (1)          on condor.csail.mit.edu at 7:25:31:086
Modified state variables:
P → [pending: (), status: idle]
RM → Map{}
SM → Map{}
rank → null
size → null
Initialization ends
transition: input vote() in automaton LCR(1)
     on condor.csail.mit.edu at 7:25:31:347
Modified state variables:
P → [pending: (1), status: voting]
RM → Map{[0 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[2 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 1
size → 8

transition: output RECEIVE(7, 7, 0) in automaton LCR(0)
```

```
     on loon.csail.mit.edu at 7:25:31:445
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
SM → Map, modified entries: {[1 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {0 }] [sent -> Sequence, elements
   added: {0 } Elements removed: {}] }]}
```

transition: output `SEND(7, 0, 1)` **in automaton** `LCR(0)`

```
     on loon.csail.mit.edu at 7:25:31:448
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[1 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

transition: output `SEND(1, 1, 2)` **in automaton** `LCR(1)`

```
     on condor.csail.mit.edu at 7:25:31:489
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[2 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {1 } Elements removed: {}] }]}
```

transition: output `RECEIVE(0, 0, 1)` **in automaton** `LCR(1)`

```
     on condor.csail.mit.edu at 7:25:32:205
Modified state variables:
SM → Map, modified entries: {[2 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {1 }] [sent -> Sequence, elements
   added: {1 } Elements removed: {}] }]}
```

transition: output `RECEIVE(1, 1, 2)` **in automaton** `LCR(2)`

```
     on parrot.csail.mit.edu at 7:25:32:243
Modified state variables:
SM → Map, modified entries: {[3 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {2 }] [sent -> Sequence, elements
   added: {2 } Elements removed: {}] }]}
```

transition: output `RECEIVE(6, 6, 7)` **in automaton** `LCR(7)`

```
     on tui.csail.mit.edu at 7:25:32:274
Modified state variables:
SM → Map, modified entries: {[0 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {7 }] [sent -> Sequence, elements
   added: {7 } Elements removed: {}] }]}
```

transition: output `RECEIVE(7, 0, 1)` **in automaton** `LCR(1)`

```
     on condor.csail.mit.edu at 7:25:32:325
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output `RECEIVE(5, 5, 6)` **in automaton** `LCR(6)`

```
     on parrot.csail.mit.edu at 7:25:32:437
```

transition: output `SEND(7, 1, 2)` **in automaton** `LCR(1)`

```
     on condor.csail.mit.edu at 7:25:32:466
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[2 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

```
Modified state variables:
SM → Map, modified entries: {[7 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {6 }] [sent -> Sequence, elements
   added: {6 } Elements removed: {}] }]}
```

transition: output `RECEIVE(2, 2, 3)` **in automaton** `LCR(3)`

```
     on tui.csail.mit.edu at 7:25:32:584
Modified state variables:
SM → Map, modified entries: {[4 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {3 }] [sent -> Sequence, elements
   added: {3 } Elements removed: {}] }]}
```

transition: output `RECEIVE(7, 1, 2)` **in automaton** `LCR(2)`

```
     on parrot.csail.mit.edu at 7:25:32:777
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output `SEND(7, 2, 3)` **in automaton** `LCR(2)`

```
     on parrot.csail.mit.edu at 7:25:32:997
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[3 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

transition: output `RECEIVE(7, 2, 3)` **in automaton** `LCR(3)`

```
     on tui.csail.mit.edu at 7:25:33:121
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output `SEND(7, 3, 4)` **in automaton** `LCR(3)`

```
     on tui.csail.mit.edu at 7:25:33:135
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[4 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}

Initialization starts (4)          on loon.csail.mit.edu at 7:25:36:355
Modified state variables:
P → [pending: (), status: idle]
RM → Map{}
SM → Map{}
rank → null
size → null
Initialization ends
```

transition: input `vote()` **in automaton** `LCR(4)`

```
     on loon.csail.mit.edu at 7:25:36:365
Modified state variables:
P → [pending: (4), status: voting]
RM → Map{[3 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[5 -> [status: idle, toSend: {}, sent: {}, handles: {}]] }
rank → 4
size → 8
```

transition: output `SEND(4, 4, 5)` **in automaton** `LCR(4)`

```
     on loon.csail.mit.edu at 7:25:36:369
Modified state variables:
```

```
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {4 } Elements removed: {}] }]}
```

transition: output RECEIVE(3, 3, 4) **in automaton** LCR(4)

```
     on loon.csail.mit.edu at 7:25:36:553
Modified state variables:
SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend ->
Sequence, elements added: {} Elements removed: {4 }] [sent -> Sequence, elements
added: {4 } Elements removed: {}] }]}
```

transition: output RECEIVE(7, 3, 4) **in automaton** LCR(4)

```
     on loon.csail.mit.edu at 7:25:36:557
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output SEND(7, 4, 5) **in automaton** LCR(4)

```
     on loon.csail.mit.edu at 7:25:36:559
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

transition: output RECEIVE(4, 4, 5) **in automaton** LCR(5)

```
     on condor.csail.mit.edu at 7:25:37:074
Modified state variables:
SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {} Elements removed: {5 }] [sent -> Sequence, elements
   added: {5 } Elements removed: {}] }]}
```

transition: output RECEIVE(7, 4, 5) **in automaton** LCR(5)

```
     on condor.csail.mit.edu at 7:25:37:274
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output SEND(7, 5, 6) **in automaton** LCR(5)

```
     on condor.csail.mit.edu at 7:25:37:280
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

transition: output RECEIVE(7, 5, 6) **in automaton** LCR(6)

```
     on parrot.csail.mit.edu at 7:25:37:755
Modified state variables:
P → Tuple, modified fields: {[pending -> (7)] }
```

transition: output SEND(7, 6, 7) **in automaton** LCR(6)

```
     on parrot.csail.mit.edu at 7:25:37:770
Modified state variables:
P → Tuple, modified fields: {[pending -> ()] }
SM → Map, modified entries: {[7 -> Tuple, modified fields: {[toSend ->
   Sequence, elements added: {7 } Elements removed: {}] }]}
```

transition: output RECEIVE(7, 6, 7) **in automaton** LCR(7)

```
     on tui.csail.mit.edu at 7:25:37:872
```

```
Modified state variables:
P → Tuple, modified fields: {[status -> elected] }

transition: output leader(7) in automaton LCR(7)
     on tui.csail.mit.edu at 7:25:37:874
Modified state variables:
P → Tuple, modified fields: {[status -> announced] }
```

E.2 Asynchronous Spanning Tree on 16 nodes

Complete trace

```
     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: input initialize() in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 6

     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: input initialize() in automaton sTreeNode(0) on
loon.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 0

     transition: output SEND(search, 0, 4) in automaton sTreeNode(0) on
loon.csail.mit.edu
     Modified state variables:
```

```
     P → [nbrs: (1 4), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: output SEND(search, 0, 1) in automaton sTreeNode(0) on
loon.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: input initialize() in automaton sTreeNode(11) on
parrot.csail.mit.edu
     Begin initialization
     Modified state variables:
     Modified state variables:
     P → [nbrs: (10 15 7), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 11

     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: input initialize() in automaton sTreeNode(12) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (13 8), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 12

     transition: input initialize() in automaton sTreeNode(10) on
nene.csail.mit.edu
     transition: input initialize() in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Begin initialization          Begin initialization
```

```
    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort
    i → null
    End initialization
    transition: input initialize() in automaton sTreeNode(1) on
blackbird.csail.mit.edu
    Begin initialization
    Modified state variables:
    P → [nbrs: (0 2 5), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort
    i → null
    End initialization
    Begin initialization
    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort

    RM → ioa.runtime.adt.MapSort     Begin initialization
    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort
    i → null
    End initialization

    SM → ioa.runtime.adt.MapSort
    i → 1


    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort
    i → null
    End initialization
    Begin initialization
    transition: input initialize() in automaton sTreeNode(4) on
parrot.csail.mit.edu
    transition: input initialize() in automaton sTreeNode(7) on
blackbird.csail.mit.edu
    Modified state variables:
    P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort
    i → null
    End initialization
    Modified state variables:
    P → [nbrs: (11 3 6), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
    RM → ioa.runtime.adt.MapSort
```

```
     SM → ioa.runtime.adt.MapSort
     i → 7

     transition: input initialize() in automaton sTreeNode(13) on
tui.csail.mit.edu
     transition: input initialize() in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 14 9), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 13

     Begin initialization
     Modified state variables:
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]

     SM → ioa.runtime.adt.MapSort

     RM → ioa.runtime.adt.MapSort
     i → 9     SM → ioa.runtime.adt.MapSort

         i → null

     End initialization
     transition: input initialize() in automaton sTreeNode(15) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 15

     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 5

     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: input initialize() in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 15), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

```
     i → 14

     Modified state variables:
     P → [nbrs: (0 5 8), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 4
```

Begin initialization

```
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
```

End initialization

```
     transition: input initialize() in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     transition: output RECEIVE(search, 4, 0) in automaton sTreeNode(4) on
parrot.csail.mit.edu
     transition: output RECEIVE(search, 1, 0) in automaton sTreeNode(1) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 2 5), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
         Modified state variables:
     P → [nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(0) in automaton sTreeNode(4) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 5 8), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]
     transition: output PARENT(0) in automaton sTreeNode(1) on
blackbird.csail.mit.edu
     Modified state variables:


     transition: output SEND(search, 4, 8) in automaton sTreeNode(4) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 2 5), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 1, 2) in automaton sTreeNode(1) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 2 5), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     P → [nbrs: (0 5 8), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]
```

```
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [nbrs: (12 4 9), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 8

     transition: output SEND(search, 1, 5) in automaton sTreeNode(1) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 2 5), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 4, 5) in automaton sTreeNode(4) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (0 5 8), parent: 0, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 5, 1) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: 1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(1) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 5, 4) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 10

     transition: output RECEIVE(search, 5, 4) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
```

```
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 5, 9) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 5, 6) in automaton sTreeNode(5) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 4 6 9), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 9, 5) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: 5, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(5) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 9, 13) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 9, 8) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 9, 10) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 5 8), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 8, 4) in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     transition: output RECEIVE(search, 4, 5) in automaton sTreeNode(4) on
```

```
parrot.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [nbrs: (12 4 9), parent: 4, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(4) in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 4 9), parent: 4, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 8, 9) in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 4 9), parent: 4, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 8, 9) in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 8, 12) in automaton sTreeNode(8) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 4 9), parent: 4, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 9, 8) in automaton sTreeNode(9) on
condor.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 10, 9) in automaton sTreeNode(10) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: 9, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(9) in automaton sTreeNode(10) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 10, 6) in automaton sTreeNode(10) on
```

```
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 10, 11) in automaton sTreeNode(10) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 10, 14) in automaton sTreeNode(10) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14 6 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 6, 5) in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: 5, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(5) in automaton sTreeNode(6) on tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 6, 2) in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 6, 7) in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 6, 10) in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 2 5 7), parent: 5, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

```
     transition: output RECEIVE(search, 6, 10) in automaton sTreeNode(6) on
tui.csail.mit.edu
     transition: output RECEIVE(search, 10, 6) in automaton sTreeNode(10) on
nene.csail.mit.edu

     Modified state variables:
     Modified state variables:     RM → ioa.runtime.adt.MapSort

     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort     SM → ioa.runtime.adt.MapSort



     transition: output RECEIVE(search, 13, 9) in automaton sTreeNode(13) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 14 9), parent: 9, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(9) in automaton sTreeNode(13) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 14 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 13, 14) in automaton sTreeNode(13) on
tui.csail.mit.edu
     Modified state variables:
     P → [nbrs: (12 14 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 12, 8) in automaton sTreeNode(12) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (13 8), parent: 8, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(8) in automaton sTreeNode(12) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (13 8), parent: 8, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 12, 13) in automaton sTreeNode(12) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (13 8), parent: 8, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort
         transition: output SEND(search, 13, 12) in automaton sTreeNode(13) on
tui.csail.mit.edu
     Modified state variables:
```

```
     P → [nbrs: (12 14 9), parent: 9, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

transition: output RECEIVE(search, 13, 12) **in automaton** sTreeNode(13) on tui.csail.mit.edu

```
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

transition: output RECEIVE(search, 12, 13) **in automaton** sTreeNode(12) on parrot.csail.mit.edu

```
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

transition: output RECEIVE(search, 11, 10) **in automaton** sTreeNode(11) on parrot.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (10 15 7), parent: 10, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
```

transition: output PARENT(10) **in automaton** sTreeNode(11) on parrot.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (10 15 7), parent: 10, reported: true, send:
ioa.runtime.adt.MapSort]
```

transition: output SEND(search, 11, 15) **in automaton** sTreeNode(11) on parrot.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (10 15 7), parent: 10, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort
```

transition: output RECEIVE(search, 7, 6) **in automaton** sTreeNode(7) on blackbird.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (11 3 6), parent: 6, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
```

transition: output PARENT(6) **in automaton** sTreeNode(7) on blackbird.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (11 3 6), parent: 6, reported: true, send:
ioa.runtime.adt.MapSort]
```

transition: output SEND(search, 7, 3) **in automaton** sTreeNode(7) on blackbird.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (11 3 6), parent: 6, reported: true, send:
ioa.runtime.adt.MapSort]
```

```
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 7, 11) in automaton sTreeNode(7) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 3 6), parent: 6, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Begin initialization
     Modified state variables:
     P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → null
     End initialization
     transition: input initialize() in automaton sTreeNode(3) on
nene.csail.mit.edu
     transition: output SEND(search, 11, 7) in automaton sTreeNode(11) on
parrot.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 15 7), parent: 10, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 11, 7) in automaton sTreeNode(11) on
parrot.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 7, 11) in automaton sTreeNode(7) on
blackbird.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 14, 10) in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 15), parent: 10, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(10) in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 15), parent: 10, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 14, 15) in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 15), parent: 10, reported: true, send:
```

```
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [nbrs: (2 7), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 3

     transition: output RECEIVE(search, 3, 7) in automaton sTreeNode(3) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (2 7), parent: 7, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort

     transition: output PARENT(7) in automaton sTreeNode(3) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (2 7), parent: 7, reported: true, send:
ioa.runtime.adt.MapSort]

     transition: output SEND(search, 3, 2) in automaton sTreeNode(3) on
nene.csail.mit.edu
     Modified state variables:
     P → [nbrs: (2 7), parent: 7, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 14, 13) in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (10 13 15), parent: 10, reported: true, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 14, 13) in automaton sTreeNode(14) on
blackbird.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 13, 14) in automaton sTreeNode(13) on
tui.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 15, 11) in automaton sTreeNode(15) on
blackbird.csail.mit.edu
     Modified state variables:
     P → [nbrs: (11 14), parent: 11, reported: false, send:
ioa.runtime.adt.MapSort]
     RM → ioa.runtime.adt.MapSort
```

transition: **output** PARENT(11) **in** **automaton** sTreeNode(15) on
blackbird.csail.mit.edu
Modified state variables:
P → [nbrs: (11 14), parent: 11, reported: true, send:
ioa.runtime.adt.MapSort]

transition: **output** SEND(search, 15, 14) **in** **automaton** sTreeNode(15) on
blackbird.csail.mit.edu
Modified state variables:
P → [nbrs: (11 14), parent: 11, reported: true, send:
ioa.runtime.adt.MapSort]
SM → ioa.runtime.adt.MapSort

transition: **output** RECEIVE(search, 15, 14) **in** **automaton** sTreeNode(15) on
blackbird.csail.mit.edu
Modified state variables:
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort
transition: **output** RECEIVE(search, 14, 15) **in** **automaton** sTreeNode(14) on
blackbird.csail.mit.edu

Modified state variables:
RM → ioa.runtime.adt.MapSort

Begin initialization
Modified state variables:
P → [nbrs: (), parent: 87, reported: true, send: ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort
i → null
End initialization
transition: **input** initialize() **in** **automaton** sTreeNode(2) on
condor.csail.mit.edu
Modified state variables:
P → [nbrs: (1 3 6), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort
i → 2

transition: **output** RECEIVE(search, 2, 1) **in** **automaton** sTreeNode(2) on
condor.csail.mit.edu
Modified state variables:
P → [nbrs: (1 3 6), parent: 1, reported: false, send:
ioa.runtime.adt.MapSort]
RM → ioa.runtime.adt.MapSort

transition: **output** PARENT(1) **in** **automaton** sTreeNode(2) on
condor.csail.mit.edu
Modified state variables:
P → [nbrs: (1 3 6), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]

transition: **output** SEND(search, 2, 3) **in** **automaton** sTreeNode(2) on
condor.csail.mit.edu

```
     Modified state variables:
     P → [nbrs: (1 3 6), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 2, 3) in automaton sTreeNode(2) on
condor.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(search, 2, 6) in automaton sTreeNode(2) on
condor.csail.mit.edu
     Modified state variables:
     P → [nbrs: (1 3 6), parent: 1, reported: true, send:
ioa.runtime.adt.MapSort]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 6, 2) in automaton sTreeNode(6) on
tui.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 2, 6) in automaton sTreeNode(2) on
condor.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(search, 3, 2) in automaton sTreeNode(3) on
nene.csail.mit.edu
     Modified state variables:
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

E.3 Asynchronous Broadcast Convergecast on 16 nodes

Complete trace

```
     Begin initialization
     Modified state variables:
     P → [val: 87, acked: (), nbrs: (), parent: 87, reported: true, send:
ioa.runtime.adt.MapSort,
      temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 0
     End initialization
     transition: input initialize() in automaton bcastNode
     Modified state variables:
     transition: output RECEIVE(msg([kind: bcast, w: 99]), 1, 0) in automaton
bcastNode

     P → [val: -1, acked: (), nbrs: (0 5 8), parent: -1, reported: false,
```

```
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 4

     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 2 5), parent: 0, reported: false,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 1, 2) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 2 5), parent: 0, reported: false,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 1, 5) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 2 5), parent: 0, reported: false,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Begin initialization
     Modified state variables:
     P → [val: 87, acked: (), nbrs: (), parent: 87, reported: true,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 0
     End initialization
     transition: input initialize() in automaton bcastNode
     Modified state variables:
     P → [val: -1, acked: (), nbrs: (10 13 15), parent: -1, reported: false,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 14

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 4, 0) in automaton
bcastNode
     transition: output RECEIVE(msg([kind: bcast, w: 99]), 5, 1) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
     send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 5, 4) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort
```

```
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 4, 8) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 5, 9) in automaton
bcastNode
     transition: output SEND(msg([kind: bcast, w: 99]), 4, 5) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 4, 5) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 4, 5) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (0 5 8), parent: 0, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 5, 6) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 5, 4) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
```

```
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 5, 4) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 5, 4) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (4), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 8, 4) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 8, 9) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 4, 5) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5), nbrs: (0 5 8), parent: 0, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 2, 1) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 3 6), parent: 1, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 2, 3) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 3 6), parent: 1, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 8, 12) in automaton
bcastNode
     Modified state variables:
```

```
     P → [val: 99, acked: (), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Begin initialization
     Modified state variables:
     P → [val: 87, acked: (), nbrs: (), parent: 87, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 0
     End initialization
     transition: input initialize() in automaton bcastNode
     transition: output SEND(msg([kind: bcast, w: 99]), 2, 6) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (1 3 6), parent: 1, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [val: -1, acked: (), nbrs: (10 2 5 7), parent: -1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
     i → 6

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 6, 2) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 6, 10) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 3, 2) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (2 7), parent: 2, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 3, 7) in automaton
bcastNode
     transition: output SEND(msg([kind: bcast, w: 99]), 6, 7) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
```

```
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 6, 5) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 6, 5) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 6, 5) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 12, 8) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (13 8), parent: 8, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 12, 13) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (13 8), parent: 8, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 5, 6) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (4), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 5, 6) in automaton bcastNode
     Modified state variables:
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (2 7), parent: 2, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort
     P → [val: 99, acked: (4), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87    ]]
```

```
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 5, 6) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (4 6), nbrs: (1 4 6 9), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 6, 5) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 13, 12) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 14 9), parent: 12, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 13, 9) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 14 9), parent: 12, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 13, 14) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 14 9), parent: 12, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 7, 3) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 7, 11) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 7, 6) in automaton
bcastNode
```

```
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 7, 6) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 7, 6) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 6, 7) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (5), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 6, 7) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 6, 7) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5 7), nbrs: (10 2 5 7), parent: 2, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 7, 6) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (6), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 11, 7) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
```

```
     transition: output SEND(msg([kind: bcast, w: 99]), 11, 10) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 14, 13) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 14, 10) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 11, 15) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 14, 15) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 11, 10) in automaton
bcastNode
     transition: output RECEIVE(msg([kind: bcast, w: 99]), 10, 6) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 10, 11) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 10, 11) in automaton
bcastNode
     Modified state variables:
```

```
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 10, 14) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 10, 14) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 10, 9) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort


     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 11, 10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 14, 10) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 14, 10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort
```

```
    transition: output SEND(kind(ack), 10, 11) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 11, 10) in automaton bcastNode
    transition: output RECEIVE(msg([kind: bcast, w: 99]), 15, 11) in automaton
bcastNode
    Modified state variables:
    P → [val: 99, acked: (), nbrs: (11 14), parent: 11, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort

    transition: output SEND(msg([kind: bcast, w: 99]), 15, 14) in automaton
bcastNode
    Modified state variables:
    P → [val: 99, acked: (), nbrs: (11 14), parent: 11, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    SM → ioa.runtime.adt.MapSort


    transition: output RECEIVE(msg([kind: bcast, w: 99]), 15, 14) in automaton
bcastNode
    Modified state variables:
    P → [val: 99, acked: (), nbrs: (11 14), parent: 11, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output SEND(kind(ack), 15, 14) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (), nbrs: (11 14), parent: 11, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    Modified state variables:
    P → [val: 99, acked: (10), nbrs: (10 15 7), parent: 7, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 10, 11) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (11), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output SEND(kind(ack), 10, 14) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (11), nbrs: (11 14 6 9), parent: 6, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    SM → ioa.runtime.adt.MapSort
```

```
transition: output RECEIVE(kind(ack), 10, 14) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (11 14), nbrs: (11 14 6 9), parent: 6, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 14, 10) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(msg([kind: bcast, w: 99]), 14, 15) in automaton
bcastNode
Modified state variables:
P → [val: 99, acked: (10), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort

transition: output SEND(kind(ack), 14, 15) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10), nbrs: (10 13 15), parent: 13, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 14, 15) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 13 15), parent: 13, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

Begin initialization
Modified state variables:
P → [val: 87, acked: (), nbrs: (), parent: 87, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort
i → 0
End initialization
transition: input initialize() in automaton bcastNode
Modified state variables:
P → [val: -1, acked: (), nbrs: (10 13 5 8), parent: -1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort
i → 9

transition: internal report(14) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 13 15), parent: 13, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
```

```
transition: output SEND(kind(ack), 14, 13) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 13 15), parent: 13, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 13, 14) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (12 14 9), parent: 12, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 15, 14) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (11 14), parent: 11, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: internal report(15) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (11 14), parent: 11, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

transition: output SEND(kind(ack), 15, 11) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (11 14), parent: 11, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 11, 15) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 15 7), parent: 7, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort

transition: internal report(11) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 15 7), parent: 7, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

transition: output SEND(kind(ack), 11, 7) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 15), nbrs: (10 15 7), parent: 7, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 7, 11) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (11 6), nbrs: (11 3 6), parent: 3, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort

transition: internal report(7) in automaton bcastNode
```

```
     Modified state variables:
     P → [val: 99, acked: (11 6), nbrs: (11 3 6), parent: 3, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 7, 3) in automaton bcastNode
     transition: output RECEIVE(kind(ack), 3, 7) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (7), nbrs: (2 7), parent: 2, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: internal report(3) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (7), nbrs: (2 7), parent: 2, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 3, 2) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (7), nbrs: (2 7), parent: 2, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     Modified state variables:
     P → [val: 99, acked: (11 6), nbrs: (11 3 6), parent: 3, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 2, 3) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (3), nbrs: (1 3 6), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort      transition: output RECEIVE(msg([kind:
bcast, w: 99]), 9, 5) in automaton bcastNode


     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 9, 13) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(msg([kind: bcast, w: 99]), 9, 8) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
```

SM → ioa.runtime.adt.MapSort

transition: **output** RECEIVE(msg([kind: bcast, w: 99]), 13, 9) **in automaton** bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (12 14 9), parent: 12, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort

transition: **output** SEND(kind(ack), 13, 9) **in automaton** bcastNode
Modified state variables:
P → [val: 99, acked: (14), nbrs: (12 14 9), parent: 12, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: **output** RECEIVE(msg([kind: bcast, w: 99]), 9, 8) **in automaton** bcastNode
Modified state variables:
P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: **output** SEND(msg([kind: bcast, w: 99]), 9, 10) **in automaton** bcastNode
Modified state variables:
P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
SM → ioa.runtime.adt.MapSort

transition: **output** RECEIVE(msg([kind: bcast, w: 99]), 10, 9) **in automaton** bcastNode
Modified state variables:
P → [val: 99, acked: (11 14), nbrs: (11 14 6 9), parent: 6, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
transition: **output** RECEIVE(msg([kind: bcast, w: 99]), 9, 10) **in automaton** bcastNode

Modified state variables:
transition: **output** SEND(kind(ack), 10, 9) **in automaton** bcastNode
P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
Modified state variables:
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort P → [val: 99, acked: (11 14), nbrs: (11 14 6 9), parent: 6, reported: false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

RM → ioa.runtime.adt.MapSort

SM → ioa.runtime.adt.MapSort

transition: **output** RECEIVE(msg([kind: bcast, w: 99]), 9, 13) **in automaton**

```
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 9, 8) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 9, 10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 10, 9) in automaton bcastNode
     Modified state variables:
     transition: output RECEIVE(kind(ack), 9, 10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (10), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     P → [val: 99, acked: (11 14 9), nbrs: (11 14 6 9), parent: 6, reported:
false, send: ioa.runtime.adt.MapSort,
     temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort     RM → ioa.runtime.adt.MapSort

     SM → ioa.runtime.adt.MapSort     SM → ioa.runtime.adt.MapSort



     transition: internal report(10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (11 14 9), nbrs: (11 14 6 9), parent: 6, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 10, 6) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (11 14 9), nbrs: (11 14 6 9), parent: 6, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort
     transition: output SEND(kind(ack), 9, 13) in automaton bcastNode

     Modified state variables:
     P → [val: 99, acked: (10), nbrs: (10 13 5 8), parent: 5, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 9, 13) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (10 13), nbrs: (10 13 5 8), parent: 5, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
```

```
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 13, 9) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (14 9), nbrs: (12 14 9), parent: 12, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: internal report(13) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (14 9), nbrs: (12 14 9), parent: 12, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 13, 12) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (14 9), nbrs: (12 14 9), parent: 12, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 12, 13) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (13), nbrs: (13 8), parent: 8, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: internal report(12) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (13), nbrs: (13 8), parent: 8, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 12, 8) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (13), nbrs: (13 8), parent: 8, reported: true, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(msg([kind: bcast, w: 99]), 8, 9) in automaton
bcastNode
     Modified state variables:
     P → [val: 99, acked: (), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output SEND(kind(ack), 8, 9) in automaton bcastNode
     Modified state variables:
     transition: output RECEIVE(kind(ack), 6, 10) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (10 5 7), nbrs: (10 2 5 7), parent: 2, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
```

```
transition: internal report(6) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 5 7), nbrs: (10 2 5 7), parent: 2, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

transition: output SEND(kind(ack), 6, 2) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (10 5 7), nbrs: (10 2 5 7), parent: 2, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 2, 6) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (3 6), nbrs: (1 3 6), parent: 1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort

transition: internal report(2) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (3 6), nbrs: (1 3 6), parent: 1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

transition: output SEND(kind(ack), 2, 1) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (3 6), nbrs: (1 3 6), parent: 1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 1, 2) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (2), nbrs: (0 2 5), parent: 0, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

P → [val: 99, acked: (), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
SM → ioa.runtime.adt.MapSort

transition: output RECEIVE(kind(ack), 9, 8) in automaton bcastNode
Modified state variables:
transition: output RECEIVE(kind(ack), 8, 9) in automaton bcastNode
P → [val: 99, acked: (10 13 8), nbrs: (10 13 5 8), parent: 5, reported:
false, send: ioa.runtime.adt.MapSort,
temp: [kind: bcast, w: 87]]

RM → ioa.runtime.adt.MapSort

Modified state variables:
transition: internal report(9) in automaton bcastNode
Modified state variables:
P → [val: 99, acked: (9), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
RM → ioa.runtime.adt.MapSort
```

```
    SM → ioa.runtime.adt.MapSort
    P → [val: 99, acked: (10 13 8), nbrs: (10 13 5 8), parent: 5, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]


    transition: output SEND(kind(ack), 9, 5) in automaton bcastNode

    Modified state variables:
    P → [val: 99, acked: (10 13 8), nbrs: (10 13 5 8), parent: 5, reported:
true, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 8, 12) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (12 9), nbrs: (12 4 9), parent: 4, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort

    transition: internal report(8) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (12 9), nbrs: (12 4 9), parent: 4, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

    transition: output SEND(kind(ack), 8, 4) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (12 9), nbrs: (12 4 9), parent: 4, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 5, 9) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (4 6 9), nbrs: (1 4 6 9), parent: 1, reported:
false, send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort

    transition: internal report(5) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (4 6 9), nbrs: (1 4 6 9), parent: 1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

    transition: output SEND(kind(ack), 5, 1) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (4 6 9), nbrs: (1 4 6 9), parent: 1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort
    SM → ioa.runtime.adt.MapSort

    transition: output RECEIVE(kind(ack), 1, 5) in automaton bcastNode
    Modified state variables:
    P → [val: 99, acked: (2 5), nbrs: (0 2 5), parent: 0, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
    RM → ioa.runtime.adt.MapSort

    transition: internal report(1) in automaton bcastNode
    Modified state variables:
```

```
     P → [val: 99, acked: (2 5), nbrs: (0 2 5), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 1, 0) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (2 5), nbrs: (0 2 5), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 4, 8) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort

     transition: internal report(4) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]

     transition: output SEND(kind(ack), 4, 0) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (5 8), nbrs: (0 5 8), parent: 0, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 87]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 0, 1) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (1), nbrs: (1 4), parent: -1, reported: false, send:
ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
     RM → ioa.runtime.adt.MapSort
     SM → ioa.runtime.adt.MapSort

     transition: output RECEIVE(kind(ack), 0, 4) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (1 4), nbrs: (1 4), parent: -1, reported: false,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
     RM → ioa.runtime.adt.MapSort

     transition: internal report(0) in automaton bcastNode
     Modified state variables:
     P → [val: 99, acked: (1 4), nbrs: (1 4), parent: -1, reported: true,
send: ioa.runtime.adt.MapSort, temp: [kind: bcast, w: 99]]
```

E.4 Spanning Tree to Leader Election on 16 nodes

Complete trace

```
Trace of sTreeLeader
====================================
Number of machines: 5
Number of nodes: 16
Duration: 9 sec
```

```
Number of messages exchanged: 16
====================================

     Initialization starts (15) on loon.csail.mit.edu at 9:29:05:372
     Modified state variables:
     P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
     RM → Map{}
     SM → Map{}
     j → 87
     k → 87
     rank → null
     tempNbrs → ()
     tempNbrs2 → ()
     Initialization ends
     transition: output SEND(elect, 15, 11) in automaton sTreeLeader(15)
 on loon.csail.mit.edu at 9:29:05:388
     Modified state variables:
     P → [nbrs: (11), receivedElect: (), sentElect: (), status: idle, send: Map{[11 -> {}] }
     RM → Map{[11 -> [status: idle, toRecv: {}, ready: false]] }
     SM → Map{[11 -> [status: idle, toSend: {elect}, sent: {}, handles: {}]] }
     j → 11
     k → 11
     rank → 15
     tempNbrs → ()
     tempNbrs2 → ()

     Initialization starts (0) on loon.csail.mit.edu at 9:29:05:847
     Modified state variables:
     P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
     RM → Map{}
     SM → Map{}
     j → 87
     k → 87
     rank → null
     tempNbrs → ()
     tempNbrs2 → ()
     Initialization ends
     transition: output SEND(elect, 0, 1) in automaton sTreeLeader(0)
 on loon.csail.mit.edu at 9:29:05:860
     Modified state variables:
     P → [nbrs: (1), receivedElect: (), sentElect: (), status: idle, send: Map{[1 -> {}] }]
     RM → Map{[1 -> [status: idle, toRecv: {}, ready: false]] }
     SM → Map{[1 -> [status: idle, toSend: {elect}, sent: {}, handles: {}]] }
     j → 1
     k → 1
     rank → 0
     tempNbrs → ()
     tempNbrs2 → ()

     Initialization starts (14) on tui.csail.mit.edu at 9:29:05:977
     Initialization starts (3) on parrot.csail.mit.edu at 9:29:05:978
     Modified state variables:
     Modified state variables:
     P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
     RM → Map{}
     SM → Map{}
```

```
j → 87     P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]

k → 87
RM → Map{}     rank → null

tempNbrs → ()
tempNbrs2 → ()
SM → Map{}     Initialization ends

j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
Initialization starts (13) on parrot.csail.mit.edu at 9:29:06:210
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
Initialization starts (8) on parrot.csail.mit.edu at 9:29:06:475
Initialization starts (11) on drake.csail.mit.edu at 9:29:06:477
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
transition: output SEND(elect, 13, 14) in automaton sTreeLeader(13)
on parrot.csail.mit.edu at 9:29:06:796
Modified state variables:
P → [nbrs: (14), receivedElect: (), sentElect: (), status: idle, send: Map{[14 -> {}] }
RM → Map{[14 -> [status: idle, toRecv: {}, ready: false]] }
SM → Map{[14 -> [status: idle, toSend: {elect}, sent: {}, handles: {}]] }
j → 14
k → 14
```

```
    rank → 13
    tempNbrs → ()
    tempNbrs2 → ()

    Initialization starts (1) on drake.csail.mit.edu at 9:29:07:059
    Initialization starts (2) on condor.csail.mit.edu at 9:29:07:062
    Modified state variables:
    Initialization starts (4) on tui.csail.mit.edu at 9:29:07:150
    Modified state variables:
    P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
    RM → Map{}
    SM → Map{}
    j → 87
    k → 87
    rank → null
    tempNbrs → ()
    tempNbrs2 → ()
    Initialization ends
    transition: output RECEIVE(elect, 11, 15) in automaton sTreeLeader(11)
on drake.csail.mit.edu at 9:29:07:180
    Modified state variables:
    P → [nbrs: (15 7), receivedElect: (15), sentElect: (7), status: idle, send: Map{[15 ->
    RM → Map{[15 -> [status: idle, toRecv: {}, ready: false]] [7 -> [status: idle, toRecv:
    SM → Map{[15 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [7 -> [status: idle,
    j → 7
    k → 15
    rank → 11
    tempNbrs → ()
    tempNbrs2 → ()

    Initialization starts (6) on drake.csail.mit.edu at 9:29:07:304
    Modified state variables:
    transition: output SEND(elect, 4, 5) in automaton sTreeLeader(4)
on tui.csail.mit.edu at 9:29:07:401
    Modified state variables:
    P → [nbrs: (5), receivedElect: (), sentElect: (), status: idle, send: Map{[5 -> {}] }]
    RM → Map{[5 -> [status: idle, toRecv: {}, ready: false]] }
    SM → Map{[5 -> [status: idle, toSend: {elect}, sent: {}, handles: {}]] }
    j → 5
    k → 5
    rank → 4
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 11, 7) in automaton sTreeLeader(11)
on drake.csail.mit.edu at 9:29:07:485
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[7 -> Sequence, elements
    SM → Map, modified entries: {[7 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 7

    Initialization starts (7) on condor.csail.mit.edu at 9:29:07:260
    Modified state variables:
    P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
    RM → Map{}
    SM → Map{}
```

```
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
Initialization starts (12) on condor.csail.mit.edu at 9:29:07:712
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
Initialization starts (10) on loon.csail.mit.edu at 9:29:07:954
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
Initialization ends
Initialization starts (9) on tui.csail.mit.edu at 9:29:08:081
Modified state variables:
P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
RM → Map{}
SM → Map{}
j → 87
k → 87
rank → null
tempNbrs → ()
tempNbrs2 → ()
```

```
    Initialization ends
    Modified state variables:
    P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
    RM → Map{}
    SM → Map{}
    j → 87
    k → 87
    rank → null
    tempNbrs → ()
    tempNbrs2 → ()
    Initialization ends
    transition: output SEND(elect, 12, 8) in automaton sTreeLeader(12)
on condor.csail.mit.edu at 9:29:08:395
    Modified state variables:
    P → [nbrs: (8), receivedElect: (), sentElect: (), status: idle, send: Map{[8 -> {}] }]
    RM → Map{[8 -> [status: idle, toRecv: {}, ready: false]] }
    SM → Map{[8 -> [status: idle, toSend: {elect}, sent: {}, handles: {}]] }
    j → 8
    k → 8
    rank → 12
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output RECEIVE(elect, 1, 0) in automaton sTreeLeader(1)
on drake.csail.mit.edu at 9:29:08:496
    transition: output RECEIVE(elect, 14, 13) in automaton sTreeLeader(14)
on tui.csail.mit.edu at 9:29:08:528
    Modified state variables:
    P → [nbrs: (10 13), receivedElect: (13), sentElect: (10), status: idle, send: Map{[10 -
    RM → Map{[10 -> [status: idle, toRecv: {}, ready: false]] [13 -> [status: idle, toRecv:
    SM → Map{[10 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [13 -> [status: idle
    j → 10
    k → 13
    rank → 14
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 14, 10) in automaton sTreeLeader(14)
on tui.csail.mit.edu at 9:29:08:536
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[10 -> Sequence, elements
    SM → Map, modified entries: {[10 -> Tuple, modified fields: {[toSend -> Sequence, eleme
    k → 10
    tempNbrs2 → (13)

    Modified state variables:
    P → [nbrs: (0 5), receivedElect: (0), sentElect: (5), status: idle, send: Map{[0 -> {}]
    RM → Map{[0 -> [status: idle, toRecv: {}, ready: false]] [5 -> [status: idle, toRecv: {
    SM → Map{[0 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [5 -> [status: idle,
    j → 0
    k → 0
    rank → 1
    tempNbrs → ()
    tempNbrs2 → (5)

    transition: output SEND(elect, 1, 5) in automaton sTreeLeader(1)
```

```
on drake.csail.mit.edu at 9:29:08:965
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[5 -> Sequence, elements
    SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 5
    tempNbrs2 → (0)

    transition: output RECEIVE(elect, 7, 11) in automaton sTreeLeader(7)
on condor.csail.mit.edu at 9:29:09:760
    Modified state variables:
    P → [nbrs: (11 3), receivedElect: (11), sentElect: (3), status: idle, send: Map{[11 ->
    RM → Map{[11 -> [status: idle, toRecv: {}, ready: false]] [3 -> [status: idle, toRecv:
    SM → Map{[11 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [3 -> [status: idle,
    j → 3
    k → 11
    rank → 7
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 7, 3) in automaton sTreeLeader(7)
on condor.csail.mit.edu at 9:29:09:780
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[3 -> Sequence, elements
    SM → Map, modified entries: {[3 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 3

    transition: output RECEIVE(elect, 10, 14) in automaton sTreeLeader(10)
on loon.csail.mit.edu at 9:29:10:113
    Modified state variables:
    P → [nbrs: (14 6), receivedElect: (14), sentElect: (6), status: idle, send: Map{[14 ->
    RM → Map{[14 -> [status: idle, toRecv: {}, ready: false]] [6 -> [status: idle, toRecv:
    SM → Map{[14 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [6 -> [status: idle,
    j → 14
    k → 14
    rank → 10
    tempNbrs → ()
    tempNbrs2 → (6)

    transition: output SEND(elect, 10, 6) in automaton sTreeLeader(10)
on loon.csail.mit.edu at 9:29:10:119
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[6 -> Sequence, elements
    SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 6
    tempNbrs2 → ()

    transition: output RECEIVE(elect, 6, 10) in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:10:522
    Modified state variables:
    P → [nbrs: (10 2 5), receivedElect: (10), sentElect: (), status: idle, send: Map{[10 ->
    RM → Map{[10 -> [status: idle, toRecv: {}, ready: false]] [2 -> [status: idle, toRecv:
    SM → Map{[10 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [2 -> [status: idle,
    j → 10
    k → 10
    rank → 6
    tempNbrs → ()
```

```
    tempNbrs2 → ()

    transition: output RECEIVE(elect, 8, 12) in automaton sTreeLeader(8)
on parrot.csail.mit.edu at 9:29:11:670
    Modified state variables:
    P → [nbrs: (12 9), receivedElect: (12), sentElect: (9), status: idle, send: Map{[12 ->
    RM → Map{[12 -> [status: idle, toRecv: {}, ready: false]] [9 -> [status: idle, toRecv:
    SM → Map{[12 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [9 -> [status: idle,
    j → 12
    k → 12
    rank → 8
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 8, 9) in automaton sTreeLeader(8)
on parrot.csail.mit.edu at 9:29:11:684
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[9 -> Sequence, elements
    SM → Map, modified entries: {[9 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 9
    tempNbrs2 → (12)

    transition: output RECEIVE(elect, 3, 7) in automaton sTreeLeader(3)
on parrot.csail.mit.edu at 9:29:12:228
    Modified state variables:
    P → [nbrs: (2 7), receivedElect: (7), sentElect: (2), status: idle, send: Map{[2 -> {el
    RM → Map{[2 -> [status: idle, toRecv: {}, ready: false]] [7 -> [status: idle, toRecv: {
    SM → Map{[2 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [7 -> [status: idle,
    j → 7
    k → 7
    rank → 3
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 3, 2) in automaton sTreeLeader(3)
on parrot.csail.mit.edu at 9:29:12:262
    transition: output RECEIVE(elect, 9, 8) in automaton sTreeLeader(9)
on tui.csail.mit.edu at 9:29:12:573
    Modified state variables:
    P → [nbrs: (5 8), receivedElect: (8), sentElect: (5), status: idle, send: Map{[5 -> {el
    RM → Map{[5 -> [status: idle, toRecv: {}, ready: false]] [8 -> [status: idle, toRecv: {
    SM → Map{[5 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [8 -> [status: idle,
    j → 5
    k → 8
    rank → 9
    tempNbrs → ()
    tempNbrs2 → ()

    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[2 -> Sequence, elements
    SM → Map, modified entries: {[2 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 2
    tempNbrs2 → (7)

    transition: output SEND(elect, 9, 5) in automaton sTreeLeader(9)
on tui.csail.mit.edu at 9:29:12:730
```

```
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[5 -> Sequence, elements
    SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 5
    tempNbrs2 → (8)

    Initialization starts (5) on loon.csail.mit.edu at 9:29:12:852
    Modified state variables:
    P → [nbrs: (), receivedElect: (), sentElect: (), status: idle, send: Map{}]
    RM → Map{}
    SM → Map{}
    j → 87
    k → 87
    rank → null
    tempNbrs → ()
    tempNbrs2 → ()
    Initialization ends
    transition: output RECEIVE(elect, 2, 3) in automaton sTreeLeader(2)
on condor.csail.mit.edu at 9:29:14:748
    Modified state variables:
    P → [nbrs: (3 6), receivedElect: (3), sentElect: (6), status: idle, send: Map{[3 -> {}]
    RM → Map{[3 -> [status: idle, toRecv: {}, ready: false]] [6 -> [status: idle, toRecv: {
    SM → Map{[3 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [6 -> [status: idle,
    j → 3
    k → 3
    rank → 2
    tempNbrs → ()
    tempNbrs2 → ()

    transition: output SEND(elect, 2, 6) in automaton sTreeLeader(2)
on condor.csail.mit.edu at 9:29:14:759
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[6 -> Sequence, elements
    SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 6

    transition: output RECEIVE(elect, 6, 2) in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:15:104
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (10 2)] [sentElect -> (5)] [send -> Map,
    k → 2
    tempNbrs2 → (10)

    transition: output SEND(elect, 6, 5) in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:15:112
    transition: output RECEIVE(elect, 5, 1) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:15:145
    Modified state variables:
    P → [nbrs: (1 4 6 9), receivedElect: (1), sentElect: (), status: idle, send: Map{[1 ->
    RM → Map{[1 -> [status: idle, toRecv: {}, ready: false]] [4 -> [status: idle, toRecv: {
    SM → Map{[1 -> [status: idle, toSend: {}, sent: {}, handles: {}]] [4 -> [status: idle,
    j → 6
    k → 1
    rank → 5
    tempNbrs → ()
    tempNbrs2 → (6 9)
```

```
    transition: output RECEIVE(elect, 5, 4) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:15:492
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (1 4)] }
    k → 4
    tempNbrs2 → ()

    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[5 -> Sequence, elements
    SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 5
    tempNbrs2 → (10 2)

    transition: output RECEIVE(elect, 5, 9) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:15:836
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (1 4 9)] [sentElect -> (6)] [send -> Map
    k → 9

    transition: output SEND(elect, 5, 6) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:16:182
    Modified state variables:
    P → Tuple, modified fields: {[send -> Map, modified entries: {[6 -> Sequence, elements
    SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend -> Sequence, elemen
    k → 6
    tempNbrs2 → (1 4 9)

    transition: output RECEIVE(elect, 5, 6) in automaton sTreeLeader(5)
on loon.csail.mit.edu at 9:29:16:494
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (1 4 6 9)] }
    SM → Map, modified entries: {[6 -> Tuple, modified fields: {[toSend -> Sequence, elemen

    transition: output RECEIVE(elect, 6, 5) in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:16:554
    Modified state variables:
    P → Tuple, modified fields: {[receivedElect -> (10 2 5)] [status -> elected] }
    SM → Map, modified entries: {[5 -> Tuple, modified fields: {[toSend -> Sequence, elemen

    transition: output leader() in automaton sTreeLeader(6)
on drake.csail.mit.edu at 9:29:16:559
    Modified state variables:
    P → Tuple, modified fields: {[status -> announced] }
```