Semantics and Analysis of KLAIM Models in Maude*

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IFIP WG 2.2
München, September 2014

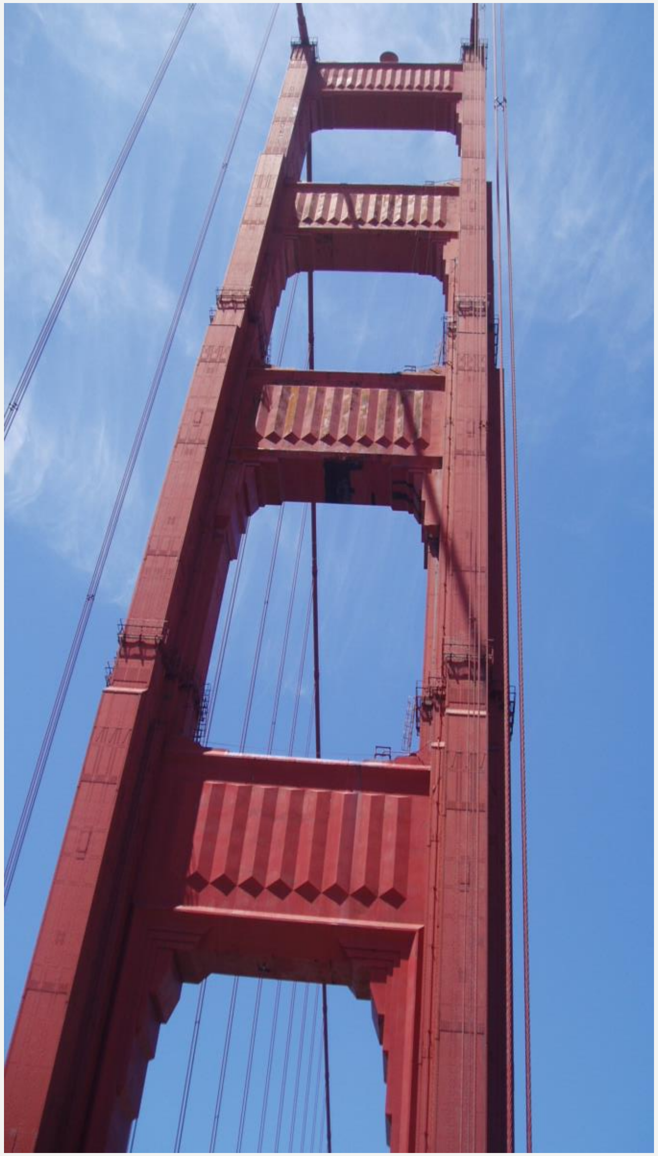
* Partially supported by EU-project ASCENS

Goal and Approach

- **ASCENS Project**
  - Languages, theories and tools for engineering autonomic systems in distributed environments
  - Case studies:
    - Robot swarm, Peer2Peer Cloud, E-mobility

- **Goal of this talk:**
  - Correct simulation and analysis of a specification language for distributed (autonomic) systems

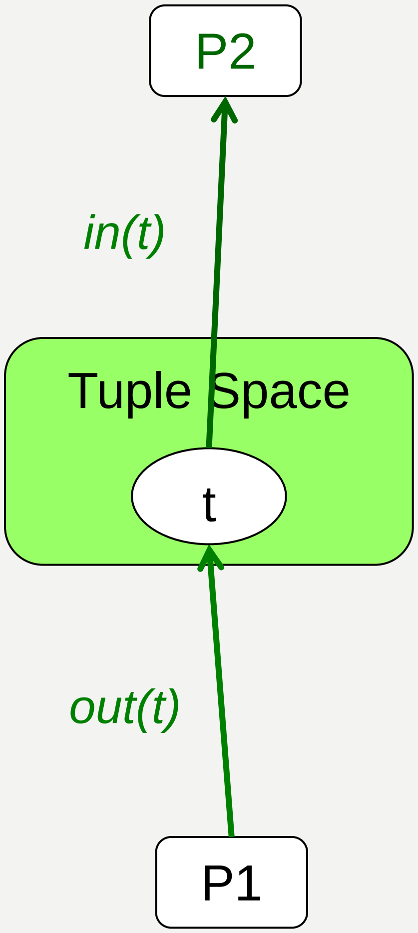
- **Approach:**
  - Choose KLAIM as coordination language
  - Rewriting Logic as a semantic framework
  - Formal analysis using the Maude environment



Why KLAIM?

- **Tuple space coordination model**
  - Linda [Gelernter et al 1985]
    - Tuple space concept
  - **KLAIM [De Nicola et al. 1997]**
    - Distributed tuple space, CCS-like computation
  - SCEL [Pugliese, De Nicola et. al. 2011/13]
    - Distributed tuple space, policy-controlled computation

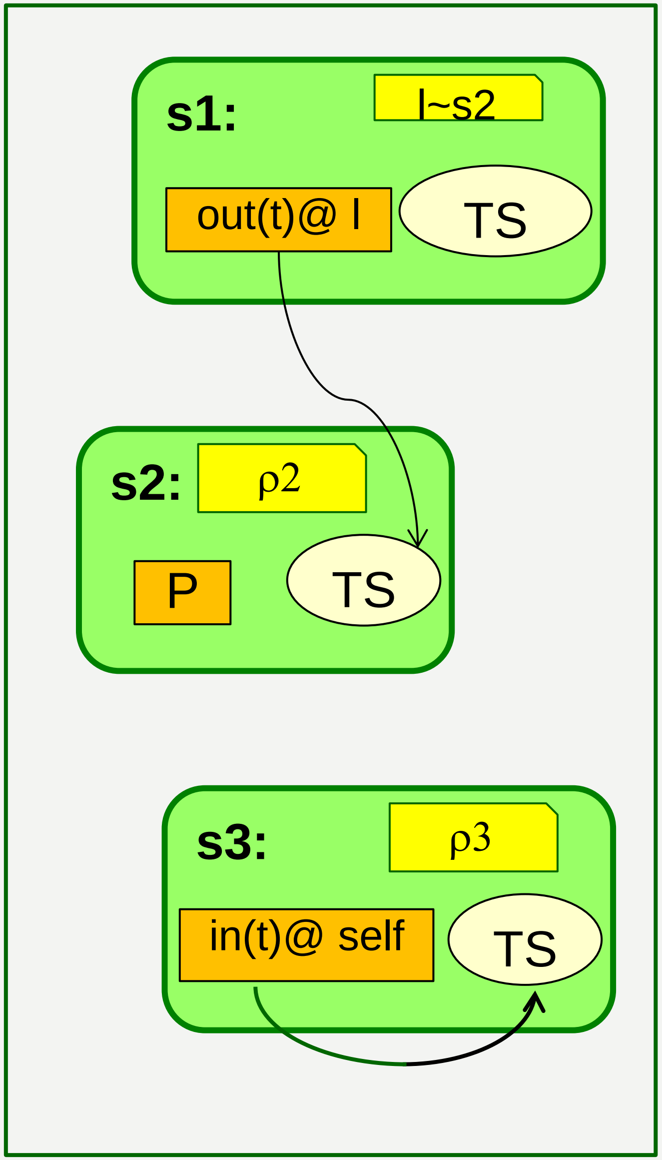
Linda



KLAIM

(**K**ernel **L**anguage for **A**gents **I**nteraction and **M**obility)

- Language for distributed mobile computing
- **KLAIM Structure**
    - Nets are composed of Nodes
    - Nodes have a unique location and contain a CCS-like process
    - Processes reflect the tuple space concept
    - Mobility is modeled by moving processes

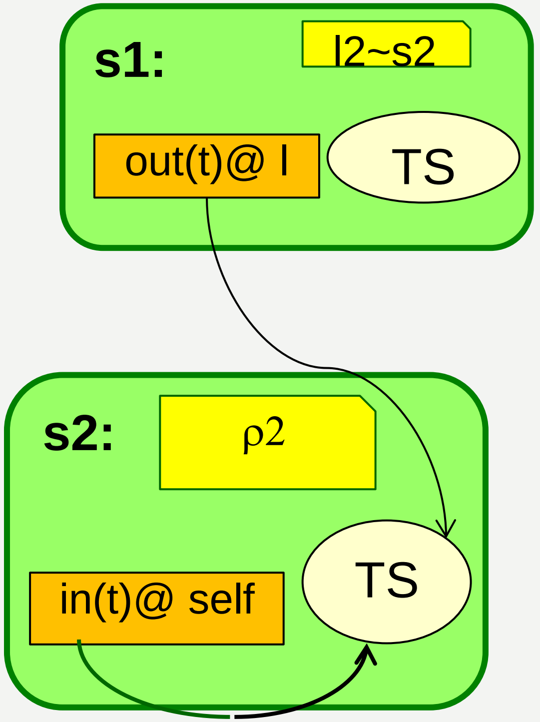


Example

$$s_1 ::_{[s_1/\text{self}]\bullet[s_2/l_2]} out(1)@l_2.nil \parallel s_2 ::_{[s_2/\text{self}]} in(1)@self.nil$$

Syntax

$$
\begin{array}{rll}
\text{Nets:} & N ::= & 0 \mid s ::_\rho C \mid N_1 \parallel N_2 \mid (\nu s)N \\
\text{Components:} & C ::= & \langle t \rangle \mid P \mid C_1|C_2 \\
\text{Processes:} & P ::= & \mathbf{nil} \mid a.P \mid P_1|P_2 \mid X \mid \mathbf{rec}\, X.P \\
\text{Actions:} & a ::= & \mathbf{in}(T)@u \mid \mathbf{out}(t)@u \mid \mathbf{new}(s) \\
\text{Tuples:} & t ::= & u \mid P \mid t_1, t_2 \\
\text{Templates:} & T ::= & u \mid !x \mid !X \mid T_1, T_2
\end{array}
$$



Structured Reduction semantics

- describes the process behavior in a net

$$(\textsc{Red-Out})\ \frac{\rho(u) = s' \qquad \mathcal{E}[\![t]\!]_\rho = t'}{s ::_\rho \mathbf{out}(t)@u.P \parallel s' ::_{\rho'} \mathbf{nil} \ \longmapsto\ s ::_\rho P \parallel s' ::_{\rho'} \langle t' \rangle}$$

- is based on structural equivalence
  - Monoid laws for |, ||
  - α-conversion, ...

We developed three Maude-based implementations of KLAIM:

- **M-KLAIM**

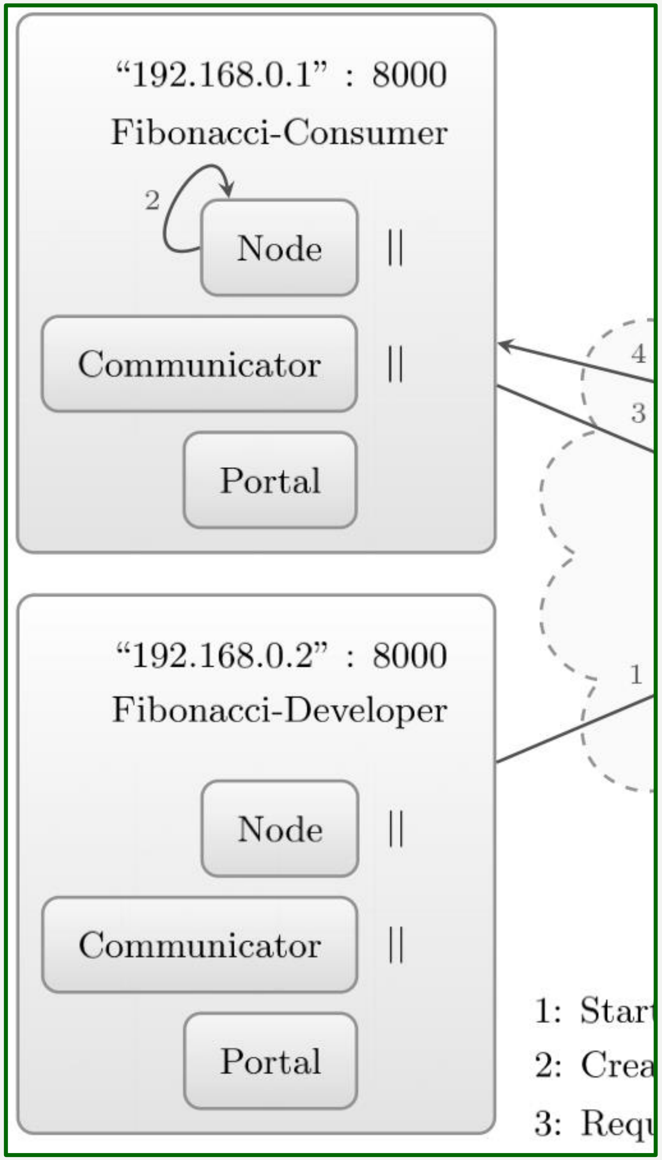
  a formal executable specification of KLAIM

- **MP-KLAIM**

  an refinement of **M-KLAIM** for asynchronous message-passing specification

- **D-KLAIM**

  an extension of **MP-KLAIM** for distributed execution (communication through sockets)



Questions

We used the *-KLAIM implementations for simulation and analysis with the Maude tools such as

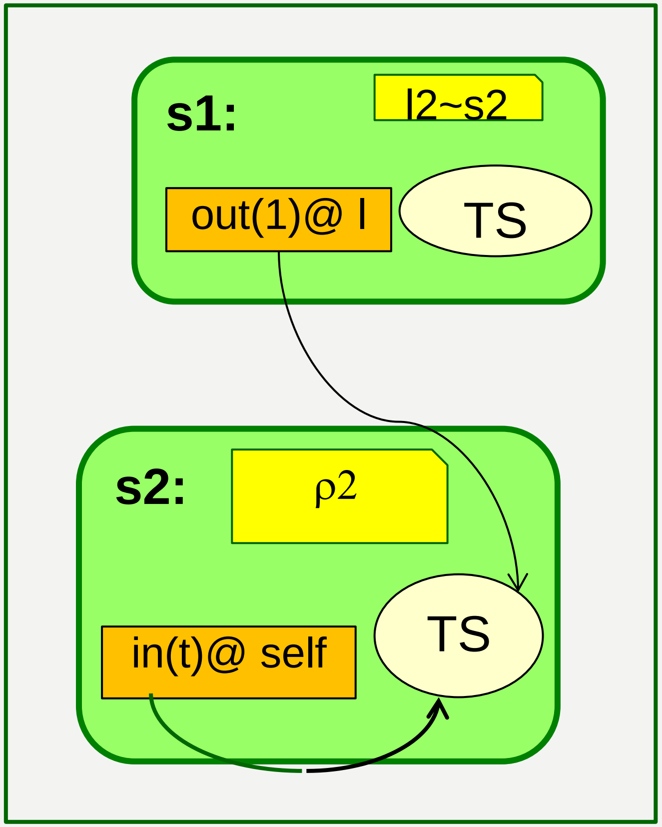
- Distributing a cloud service over a several Maude runtimes
- LTL-model checking of a mutual exclusion algorithm
- State space analysis of a load balancer using the Maude search command

but

- **What are the semantic relationships of** *-KLAIM **with KLAIM?**
- **Which properties are preserved?**

M-KLAIM syntax

- Direct correspondence to KLAIM syntax



KLAIM:

$$s_1 ::_{[s_1/\mathrm{self}]\bullet[s_2/l_2]} out(1)@l_2.nil \parallel s_2 ::_{[s_2/\mathrm{self}]} in(1)@self.nil$$

M-KLAIM:

```
(site('1)::{[site('1)/self]*[site('2)/'l2]} out(1)@'l2.nil) ||
(site('2)::{[site('2)/self]} in(1)@self.nil)
```

Rewriting semantics of KLAIM:

- Reduction semantics can be naturally expressed in rewriting logic

KLAIM:

$$(\textsc{Red-Out})\ \frac{\rho(u) = s' \qquad \mathcal{E}[\![t]\!]_\rho = t'}{s ::_\rho \mathbf{out}(t)@u.P \parallel s' ::_{\rho'} \mathbf{nil} \longmapsto s ::_\rho P \parallel s' ::_{\rho'} \langle t' \rangle}$$

M-KLAIM:

```
crl [out-remote] :
   (S1::{RHO1} (out(T) @ L) . SP | PP) || (S2::{RHO2} P)
=>
   (S1::{RHO1} SP | PP) || (S2::{RHO2} P | <T[| T |]RHO> )
if S2 := RHO1(L) .
```

Rewriting semantics of KLAIM:

- Reduction semantics can be naturally expressed in rewriting logic

KLAIM:

$$(\textsc{Red-New})\ \frac{}{s ::_\rho \mathbf{new}(s').P \ \longmapsto\ (\nu s')(s ::_\rho P \parallel s' ::_{\rho[s'/self]} \mathbf{nil})}\ s' \notin s, \rho$$

M-KLAIM:

```
crl [newloc]: (site ID {COUNT}::{RHO} (newloc(LVN)) . SP | PP)
  => (site ID {s(COUNT)}::{RHO} (SP [ NEWSITE / LVN ]) | PP)
  || (NEWSITE {0}::{[NEWSITE / self] * RHO} nil)
if NEWSITE := site(qid(string(ID) + "." + string(COUNT, 10))).
```

where NEWSITE is fresh (assuming initial sites to have “basic” ids)

Definitions and Notations

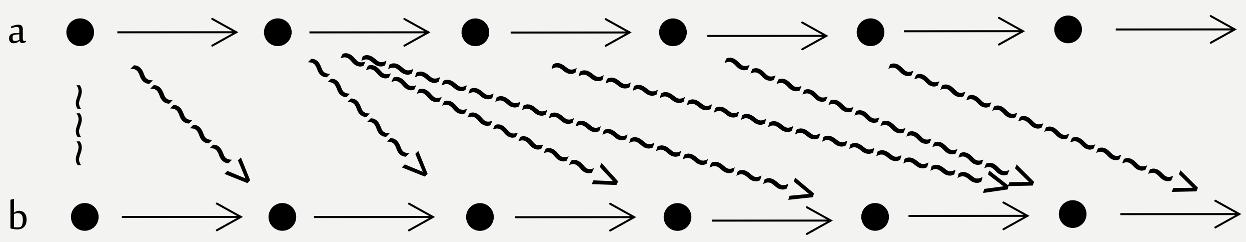
- (A, –>) (Unlabelled) transition system
- (A, –>, L) Kripke structure where
  - L: A –> P(AP) labeling function,
  - AP set of atomic propositions
- Logic CTL*(AP)

$$\begin{array}{ll}\text{state formulas:} & \varphi ::= p \in AP \mid \top \mid \bot \mid \neg\varphi \mid \varphi \vee \varphi \mid \varphi \wedge \varphi \mid \mathbf{A}\psi \mid \mathbf{E}\psi \\ \text{path formulas:} & \psi ::= \varphi \mid \neg\psi \mid \psi \vee \psi \mid \psi \wedge \psi \mid \mathbf{X}\psi \mid \psi\mathbf{U}\psi \mid \psi\mathbf{R}\psi \mid \mathbf{G}\psi \mid \mathbf{F}\psi\,.\end{array}$$

  - CTL* \ X(AP): CTL* formulas without next-operator

Stuttering Bisimulation

- **Matching path**



- **Stuttering Simulation of tss** $(A, \rightarrow_A)$ by $(B, \rightarrow_B)$ is a binary relation ~ s.th.

  if for each a ~ b and each path starting at a there is a matching path starting at b

- **Stuttering bisimulation as usual**

- **AP-bisimulation** ~ of $(A, \rightarrow_A, L_A)$ by $(A, \rightarrow_B, L_B)$ is a

  bisimulation of tss s.th. a ~ b implies $L_B(b) = L_A(a)$

- **Theorem (Meseguer, Palomino, Marti-Oliet 2010)**

  Stuttering AP-bisimulations satisfy the same CTL*\ X(AP) formulas:

  For any bisimulation ~ in $A \times B$, any a,b with a~b and any such formula ϕ,

  $B,b \models \phi$ iff $A,a \models \phi$

KLAIM and M-KLAIM are Stuttering Bisimilar

- The KLAIM and M-KLAIM semantics are transition systems:

$$TS_{\text{KLAIM}} = (\text{KLAIM-NET}, \longmapsto)$$

$$TS_{\text{M-KLAIM}} = (\mathcal{T}(\text{M-KLAIM})_{net}, \Rightarrow_1)$$

where KLAIM-Net denotes all ground KLAIM terms of sort net,

$\mathcal{T}$(M-KLAIM)$_{net}$ all ground valid M-KLAIM terms of sort Net and $=>_1$ the one-step rewrite relation.

- Theorem 1

TS_{KLAIM} and $TS_{M\text{-}KLAIM}$ are stuttering bisimilar w.r.t.

N ~ M if N $\underline{\equiv}$ $\nu s_1 \dots \nu s_k$. m2k(M)

where m2k translates M-KLAIM terms into KLAIM:

$$m2k(s\,\{c\} :: \{\rho\}\; P) = s ::_{m2k(\rho)} m2k(P)$$

$$m2k(N_1 \,||\, N_2) = m2k(N_1) \,||\, m2k(N_2)$$

KLAIM and M-KLAIM are Bisimilar

- Extend TS_{KLAIM} and $TS_{M\text{-}KLAIM}$ to Kripke structures by choosing

  AP to be a set of atomic propositions p such that the validity of p in N depends only on the binding-free part of (the prefix normal form of) N:

  $N \models p_t$ iff $M \models p_t$ and $N \equiv \nu s_1 \ldots \nu s_k.\ m2k(M)$

- Example: $M \models p_{\text{"s contains t1"}}$ iff $N \equiv \nu s_1 \ldots \nu s_k.\ (s ::_\rho \langle t1 \rangle \mid P) \parallel R$

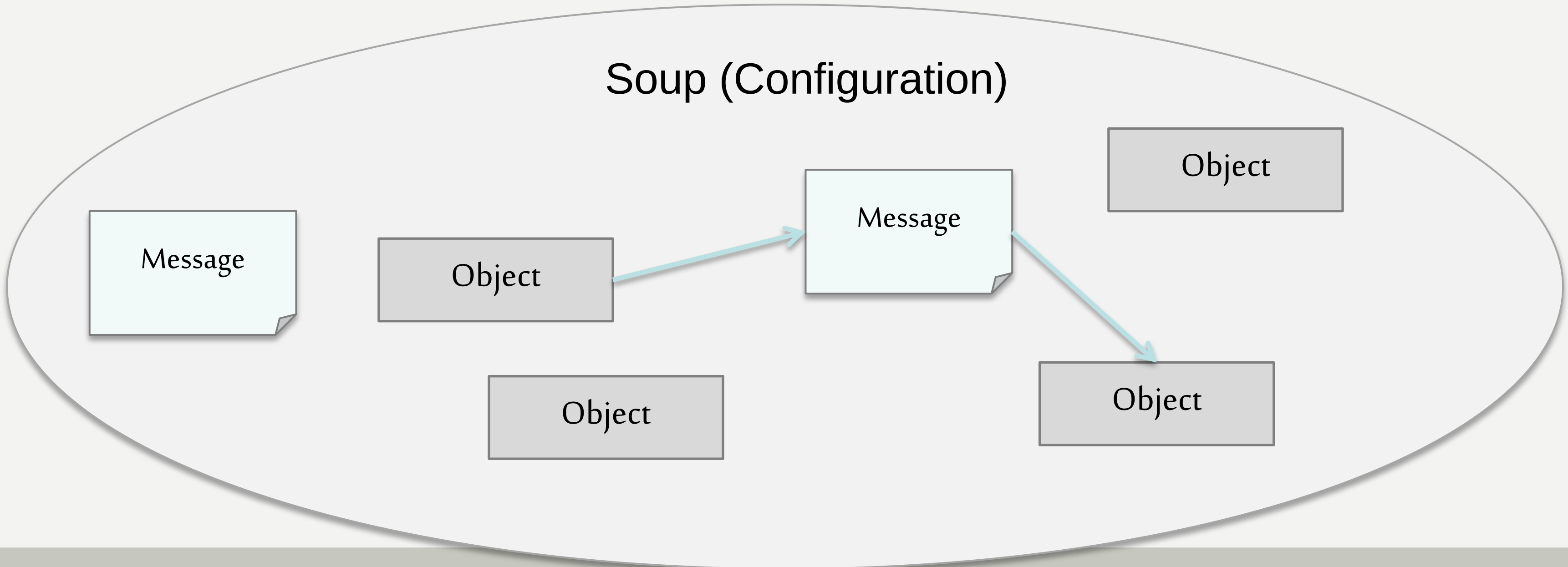
- Corollary 1

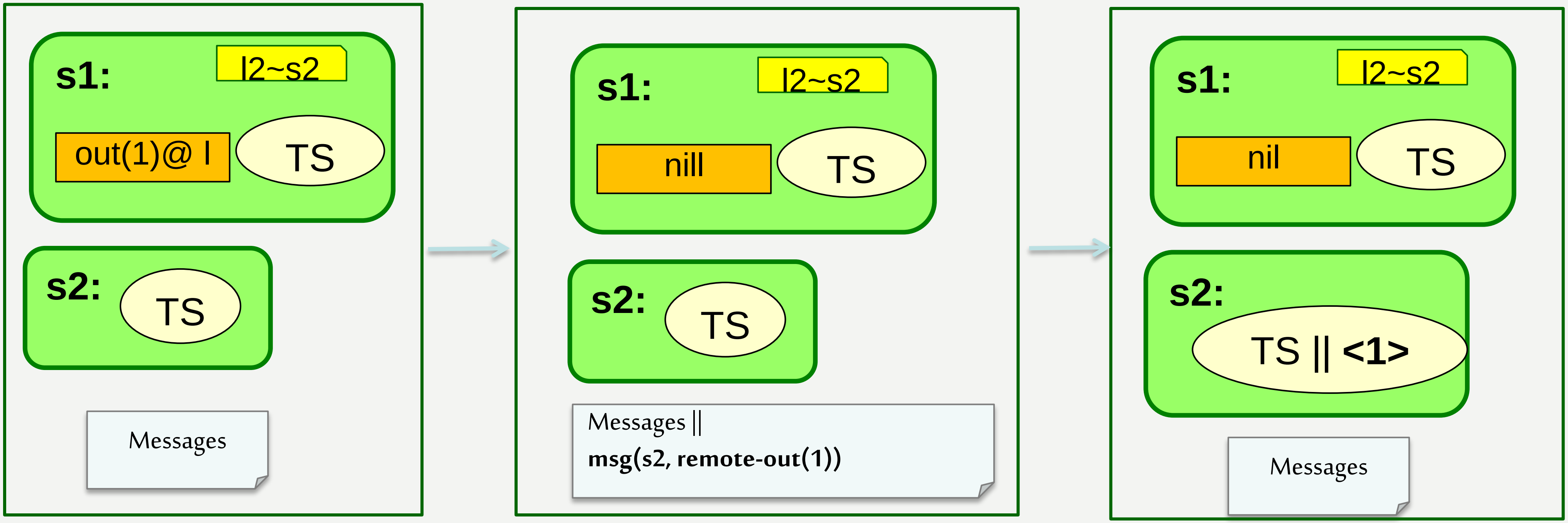
  TS_{KLAIM} and $TS_{M\text{-}KLAIM}$ are stuttering AP-bisimilar and

  satisfy the same CTL*(AP) \ X formulas.

Maude supports modeling of distributed **object-based systems** in which objects communicate asynchronously via message passing

- Message passing is a natural way of expressing communication in distributed systems
- We alter the KLAIM semantics by introducing asynchronous inter-node communication





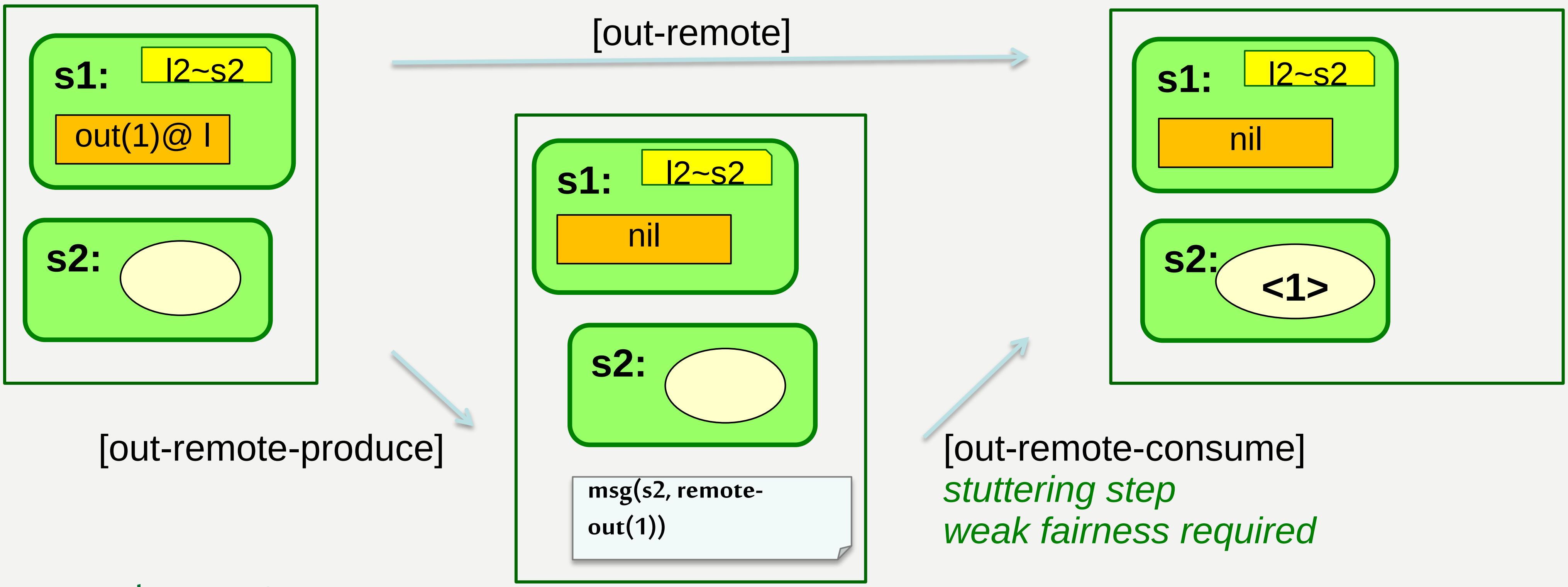
- An out-action is split into two steps:
  - Producing an out-message an sending it into the "soup"
  - Consuming the out-message by inserting the contents into the tuple space

Out-rules formally:

```
crl [out-remote-produce] :
   (S1::{RHO} (out(T) @ L) . SP | PP)
=>
   (S1::{RHO} SP | PP) || msg(S2, remote-out(T[| T |]RHO))
if S2 := RHO(L) /\ S2 =/= S1 .
```

```
rl [out-remote-consume] :
   (S::{RHO} PP) || msg(S, remote-out(ET))
=>
   (S::{RHO} PP | <ET>) .
```

Weak Fair MP-KLAIM is a Stuttering Bisimulation of M-KLAIM



- Theorem 2

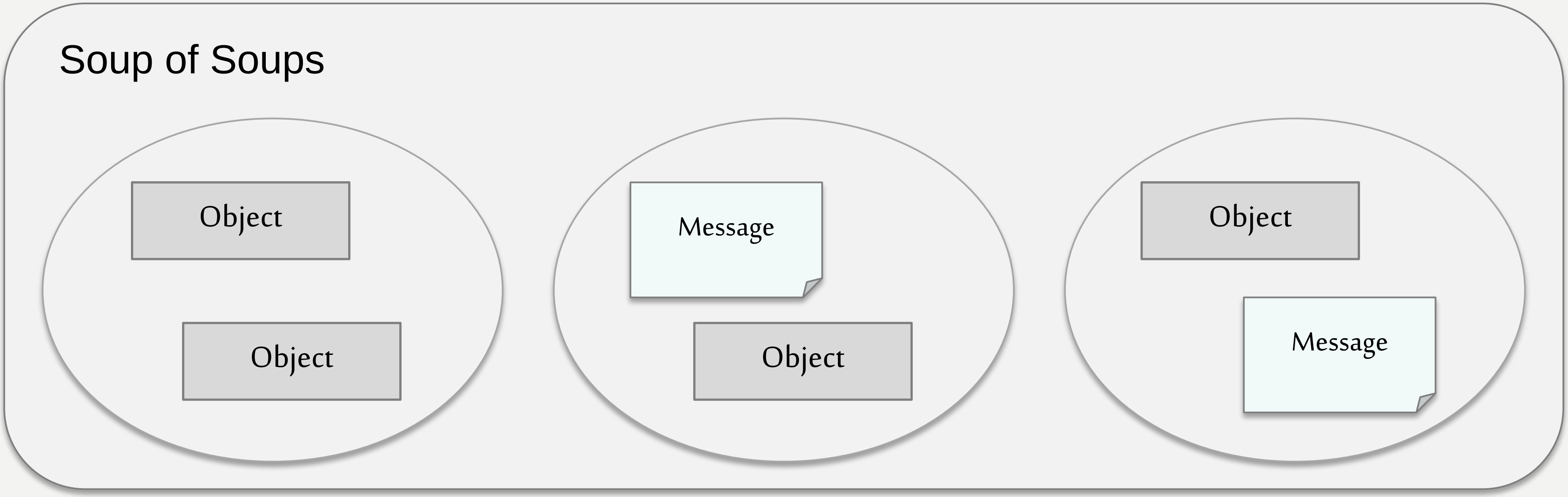
Weak fair $TS_{MP\text{-}KLAIM}$ is a stuttering AP-bisimulation of $TS_{M\text{-}KLAIM}$ and thus satisfies the same CTL*(AP) \ X formulas.

- But satisfaction of atomic props is often nonstandard:

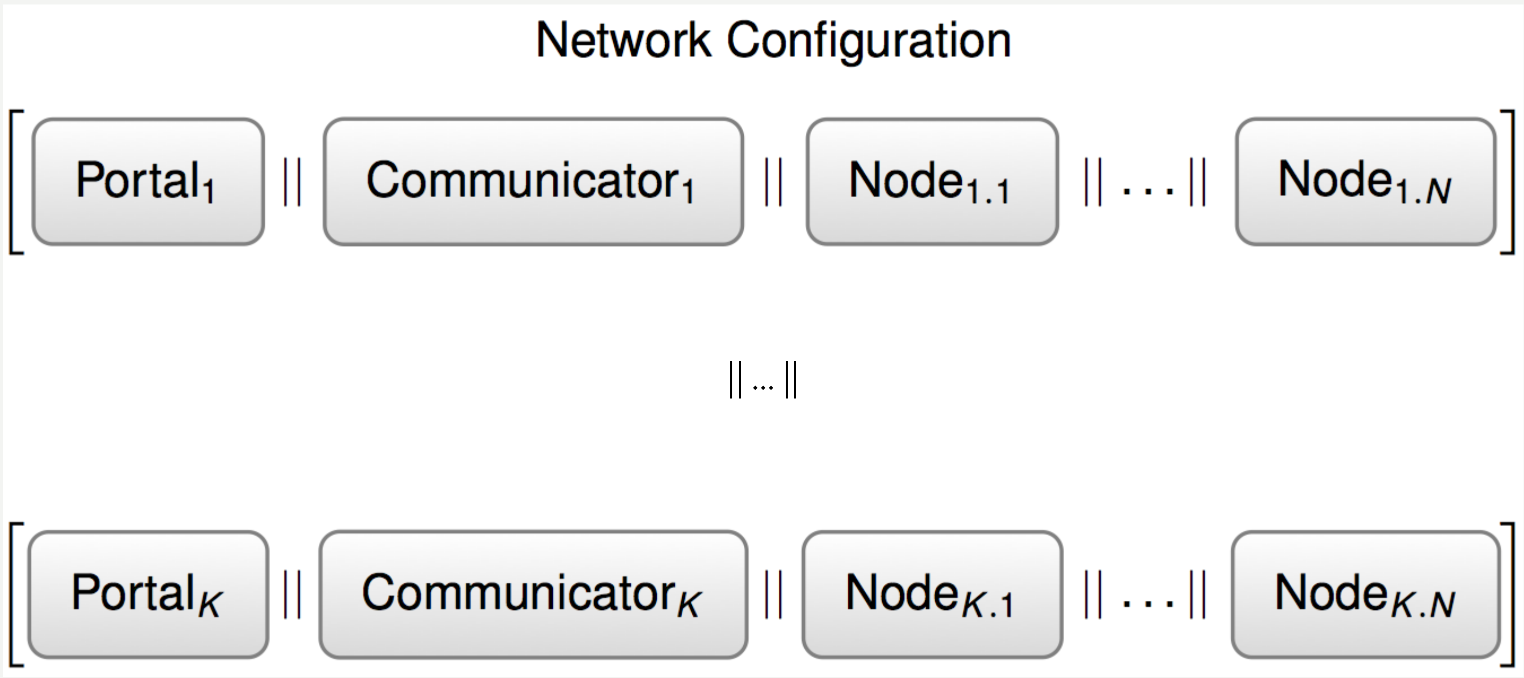
$$M \models p_{s,t} \quad \text{iff} \quad M = (s ::_{\rho} \langle t \rangle \mid P) \parallel R \ \text{ or } \ M = (s ::_{\rho} P) \parallel \langle t \rangle \parallel R$$

The **D-KLAIM** extension allows multiple instances of Maude to execute specifications based on MP-KLAIM.

- Instances communicate through sockets
- Socket communication is supported by rewriting with external objects in Maude
- D-KLAIM introduces objects to handle the socket communication
- D-KLAIM uses a buffered approach for reliable communication



- For formal analysis we developed a **socket abstraction** that captures the **behavior of Maude's socket capabilities** inside a Maude specification.



- The communicator wraps a message addressed to another instance in a (stuttering) transfer message:

```
crl [transfer-send] :
  (communicator(IP1 : PORT1) :: ATTS)
    || msg(IP2 : PORT2 # ID, MSG)
=>
  (communicator(IP1 : PORT) :: ATTS)
    || transfer-send(msg(IP2 : PORT2 # ID, MSG))
if otherPhysicalNode(IP1, PORT1, IP2, PORT2) .
```

- The comm

```
rl [portal-transfer] :
  [ < portal :: ip : IP1, port : PORT1 >
    || transfer-send(msg(IP2 : PORT2 # ID, MSG)) || N1 ]
  || [ < portal :: ip : IP2, port : PORT2 > || N2 ]
=>
  [ < portal :: ip : IP1, port : PORT1 > || N1 ]
  || [ < portal :: ip : IP2, port : PORT2 >
    || transfer-receive(msg(IP2 : PORT2 # ID, MSG)) || N2 ] .
```

- Then it is

D-KLAIM and MP-KLAIM are Stuttering Bisimilar

- Stuttering bisimulation:
  - Self-actions are the same in MP-KLAIM and D-KLAIM
  - Transfer-actions are stuttering actions and complement the actions communicating with nodes of another site.
- Require weak fairness of transfer actions

- Theorem 3

$TS_{MP\text{-}KLAIM}$ and weak fair $TS_{D\text{-}KLAIM}$ are stuttering bisimilar and thus satisfy the same CTL*(AP) \ X formulas.

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Concluding Remarks

- *-KLAIM provides

  provably correct implementations of KLAIM

  - Related with KLAIM by stuttering bisimulation
  - Satisfying the same CTL*(AP)\X formulas

- Future Work

  - Analyzing novel formalisms such as SCEL