Verifying distributed systems with unbounded channels

Régis Gascon & Éric Madelaine & Vivien Maisonneuve

INRIA Sophia Antipolis

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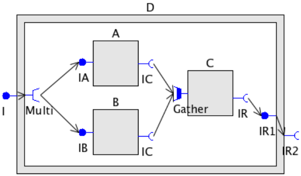
VERCORS in a nutshell

- Platform for specification of distributed applications.
- Based on the semantics features of the ASP calculus and the ProActive library.

  `http://www-sop.inria.fr/oasis/ProActive/`



- Generation of intermediate finite model.
- Various tools can then operate on these models:

  static analysis, model checking, code generation. . .
- The aim is to integrate the platform in a development environment, used by non-specialists.

pNets: Parameterized Networks of Synchronized Automata

- Basically, pNets are made of LTSs synchronized by mean of synchronization vectors.
- Verifying pNets remains to verify systems:
  - manipulating unbounded data,
  - having a parameterized topology,
  - using unbounded communication queues.
- Numerous sources of infinity
  $\Leftrightarrow$ numerous complications for formal verification.
- VerCors uses only finite-sate based model-checkers (through finite abstract interpretation).
- We want to apply infinite state model-checking techniques.

Infinite-state system verification

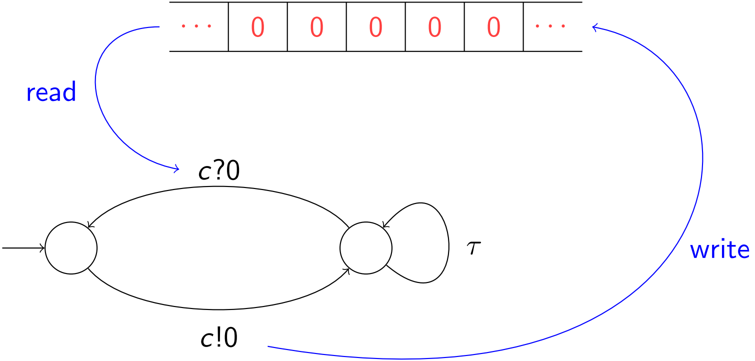
- Well studied theory:
  - counter systems,
  - pushdown systems,
  - parameterized systems,
  - ...
- Few implementations for unbounded queue systems:
  - LASH (Boigelot et al.),
  - TReX (Bouajjani et al.).
- Difficult to find a tool that fits our goals
  - integration to VERCORS
  - possibility of extensions

Outline

1. Introduction
2. Systems with unbounded FIFO queues
3. Reachability and Acceleration
4. Presentation of our prototype
5. Perspectives

Communicating finite state machines

Basically a finite state machine augmented with a set of queues.



Communicating finite state machines

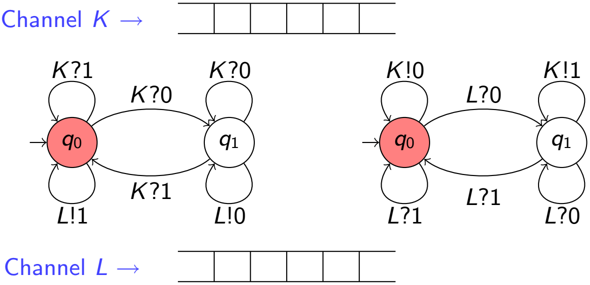
Formally, a communicating finite state machine (CFSM) is a tuple

$$\mathcal{M} = (Q, q_0, C, \Sigma, A, \delta) \quad \text{such that}$$

- $Q =$ is a finite set of states,
- $q_0 \in Q$ is the initial state,
- C is a set of communicating channels/queues,
- Σ is the alphabet of messages,
- A is a finite set of internal actions,
- $\delta \subset Q \times ((C \times \{?, !\} \times \Sigma) \cup A) \times Q$ is the transition relation.

Short Example

- Execution: Sequence respecting the transition relation.



- $\langle q_0, q_0, \varepsilon, \varepsilon \rangle$

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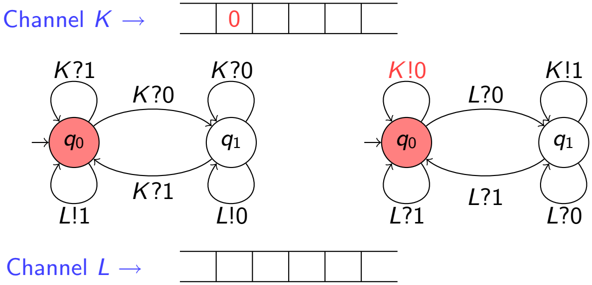

- $\langle q_0, q_0, \varepsilon, \varepsilon \rangle \xrightarrow{K!0} \langle q_0, q_0, 0, \varepsilon \rangle$

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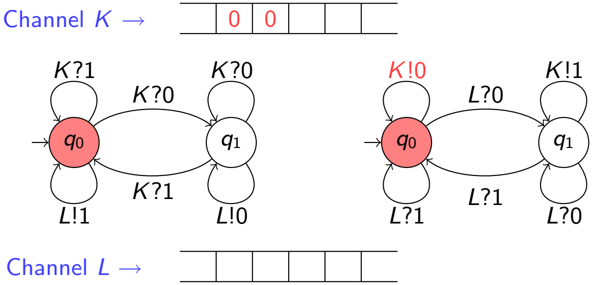

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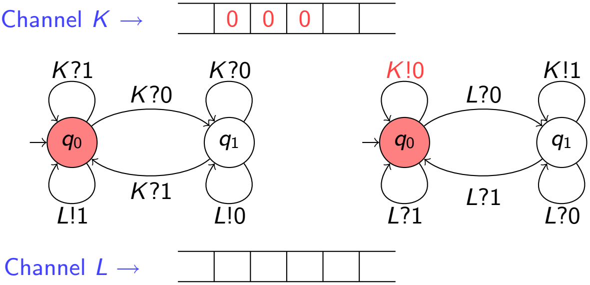

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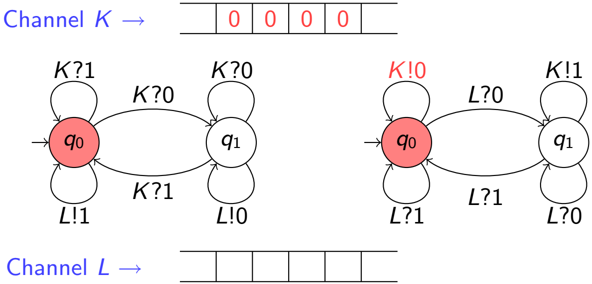

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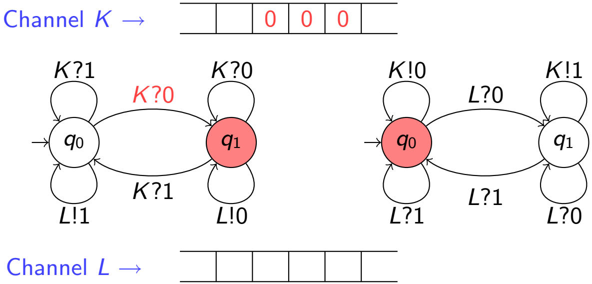

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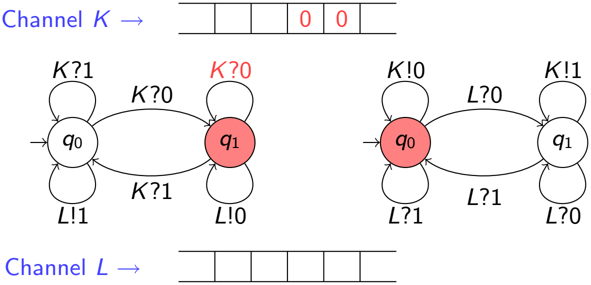

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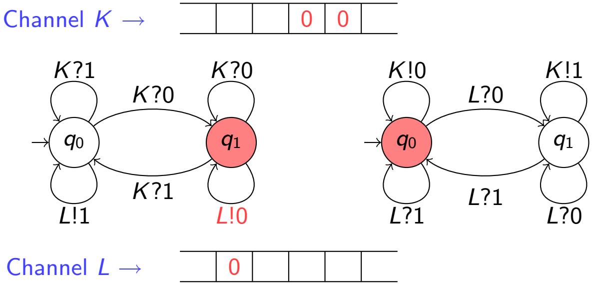

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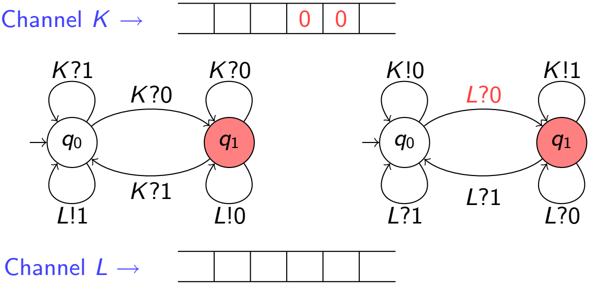

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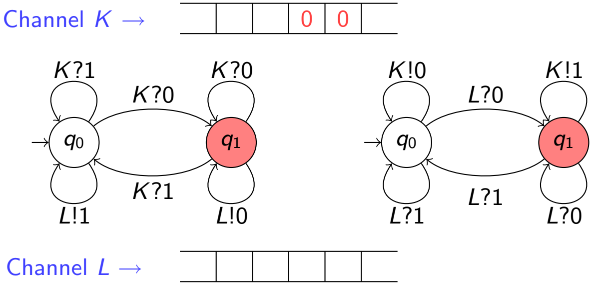

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Operational Semantics

- We consider unbounded FIFO queues.
- Consider a set of CFSM sharing a set of queues $\{K, L\}$.
- Configuration: $\langle q_1, q_2, w_K, w_L \rangle$ (for a pair of CFSM)

  Global state + Queue contents
- Operations:
  - Send (non-blocking).

    if $\langle q_1, K!a, q_1' \rangle \in \delta_1$ then

    $$\langle q_1, q_2, w_K, w_L \rangle \xrightarrow{K!a} \langle q_1', q_2, w_K \cdot a, w_L \rangle$$
  - Receive (blocking).
  - Internal Action.

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    if $\langle q_1, \tau, q_1' \rangle \in \delta_1$ with $\tau \in A$ then

$$\langle q_1, q_2, w_K, w_L \rangle \xrightarrow{\tau} \langle q_1', q_2, w_K, w_L \rangle$$

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Reachability Problem

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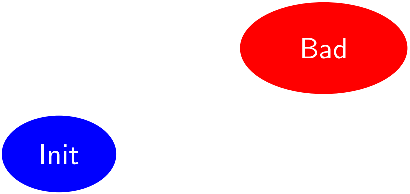

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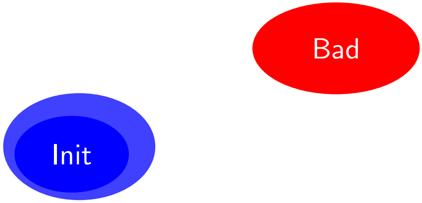

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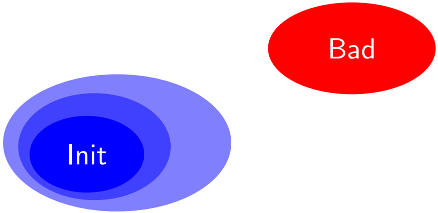

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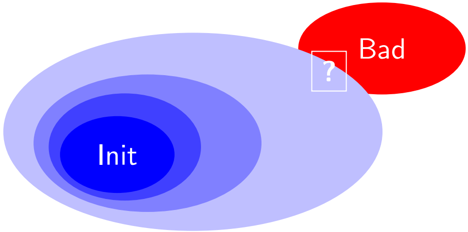

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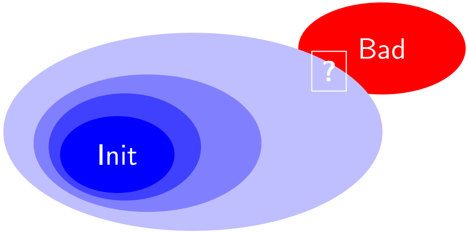

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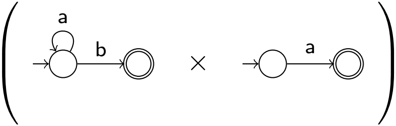
- $\mathrm{Post}^*(X) = \bigcup_{i \geq 0} \mathrm{Post}^i(X)$. UNDECIDABLE (semi-algorithm)

Representing Sets of Configurations

- We need to represent possibly infinite sets of configurations.
- We associate to each tuple of states of the CFSM a set of finite state automata (FUDFA) over Σ.

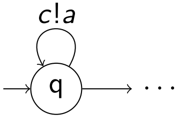
$$Roy\&Chakraborty, CIAA'06$$

- The set of configurations corresponds to the (regular) language associated to each state.
- Ex: $\langle q_1, q_2 \rangle +$ 

  represents the set of configurations $\langle q_1, q_2, a^* b, a \rangle$.

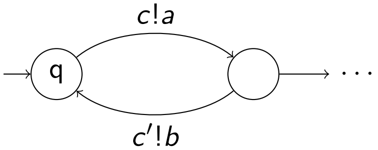
Improving convergence

- FUDFA allows the direct computation of configuration sets after iterating some cycles:



$\rightsquigarrow \quad \langle q, a^* \rangle$

- Pb: Cycles can induce non-regular sets of queue contents:



$\rightsquigarrow \quad \langle q, a^n, b^n \rangle$

- Need for characterization of accelerable loops.

Algorithm with accelerations

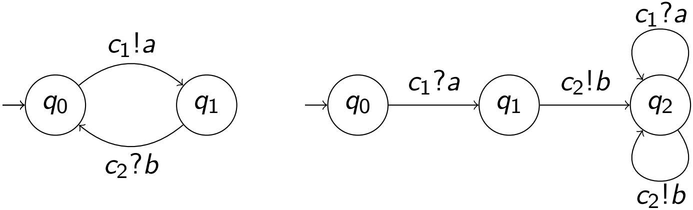
- $F[s]$ is the FUDFA associated to global state s.
- We apply a depth-first exploration method.

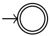
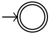
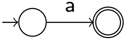
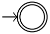
While $S \neq \emptyset$ **do**
  Choose and remove some $s \in S$

  Acceleration:
  For all cycle θ from s
    If θ can be accelerated **then**
      Compute the effect of θ^* on $F[s]$

  OneStep successors:
  For all possible transition $s \xrightarrow{\mathrm{op}} s'$
    Compute the effect of op on $F[s]$
    Add new reached configurations to $F[s']$.

Complete example



$\langle q_0, q_0 \rangle$	 × 	$\langle q_0, q_1 \rangle$	 × 
$\langle q_0, q_2 \rangle$	 a ×  b	$\langle q_1, q_0 \rangle$	 a × 
$\langle q_1, q_1 \rangle$	 × 	$\langle q_1, q_2 \rangle$	 a ×  b

Important issues for the implementation

1. Data structure,
2. Selection of cycles for acceleration,
   - global cycles or local cycles,
   - heuristics.
3. Exploration strategy,
4. Using the result of the computation.

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Implementation

- Algorithm implemented in JAVA.
- Input: A set of CFSMs sharing a set of channels: text format or graphical editor (eclipse plugin).
- Computes successively the set of reachable states step by step + acceleration (at each iteration).
- A FUDFA is associated to each global state and the main loop of the algorithm can be executed.
- The algorithm follows strictly the method described.

Exploring the statespace

We have concentrated on useful functionalities (exploration, utilisation of the result).

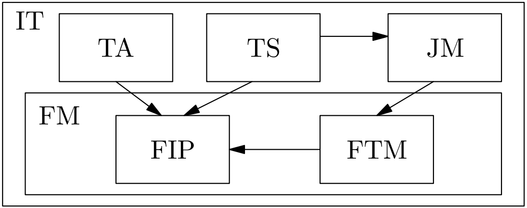
- If the computation converges $\leadsto$ OK
- Otherwise, the user can specify:
  - a set of final configurations,
  - a timeout (number of iterations),
  - a bound on the size of representations ($\neq$ bounding the size of the queues).

Performance scale

- On the other hand, there is no fine tunning of the implementation for the moment:
  - data structure quite big (naive implementation of DFAs),
  - possible improvements in data manipulation.
- In this context, we have checked the implementation w.r.t. the utilisation of the computation.
  $\rightsquigarrow$ no evaluation in terms of computation performance.
- Objective: giving a readable diagnosis of the analysis.

Example: Integrated toolkit

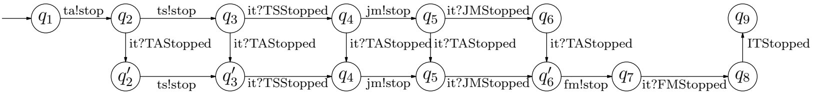
- Hierarchical components example.
- Arrows represent dependencies.



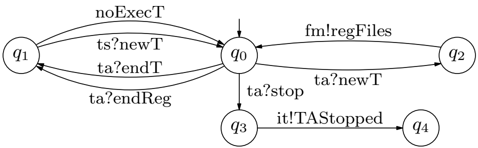
- Each box has an associated CFSM and queue.

Example: Integrated toolkit

IT (stop procedure)



TA



What does happen when the system is stopped?

Experimental scenario

When trying to compute the configuration where IT is stopped, computation does not converge.

- 15 iterations $\rightsquigarrow$ 2460 DFAs and 19096 states
- $+$ Size Limit $\rightsquigarrow$ 78 DFAs and 275 states
- Result: $ta = (\mathrm{NewT}^* \cdot \mathrm{EndReg}^* \cdot \mathrm{EndT}^*)^*$
- Then one can check that a configuration where *ta* is not empty can be reached.

So TA can leave requests unsatisfied.

Summary

- Modeling of unbounded communication queues (FIFO).
- Reachability algorithm based on:
  - Automata representation of queues,
  - Acceleration operations for selected cycles.
- Implementation of this algorithm into a prototype.
- First experiments for practical usability

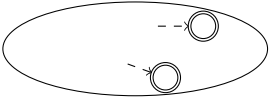
Future Work

- Improvements of exploration techniques.
- Comparisons with existing tools (LASH, TReX,...).
- Extension of the representation:
  - representation of non-regular sets of queues,
  - addition of data (ex: queues + counters)
- Combination with other techniques (parameterized sytems)

QUESTIONS ???

Basic Operations

- Add a letter (!a):



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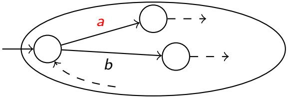

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- Generalisation to sequences: just iterate!

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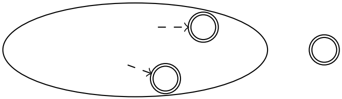

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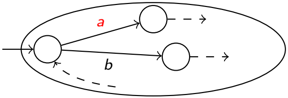

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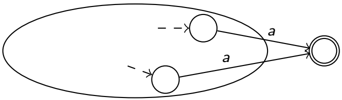

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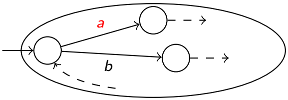

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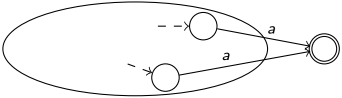

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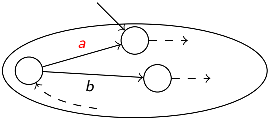

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Cycle selection and acceleration

- All the material needed can be adapted from Boigelot's thesis.
  - exact characterisation of accelerable cycles,
  - computation of the acceleration.
- For every sequence of operations σ,
  - $\sharp_!(\sigma)$ is the number of send operations,
  - $\sharp_?(\sigma)$ is the number of receive operations.
- A sequence involving only one queue is counting iff
  - $|\Sigma| = 1$ and $\sharp_!(\theta) > \sharp_?(\theta)$,
  - $|\Sigma| > 1$ and $\sharp_!(\theta) > 0$.
- Given a system with queues $\{c_1, \ldots, c_n\}$ and a cycle θ, $\theta_{|i}$ is the sub-sequence of transitions manipulating c_i.

Fundamental Results for acceleration

- For systems with only one queue, the result is the following.

Theorem (Single-queue systems)

For every set of configurations X and cycle θ, the set $\mathrm{Post}_\theta^*(X)$ is FUDFA representable.

- The result for systems with several queues is more restrictive.

Theorem (Multi-queue systems)

For every set of configurations X and cycle θ, the set $\mathrm{Post}_\theta^*(X)$ is FUDFA representable iff there do not exist i and j s.t $\theta_{|i}$ and $\theta_{|j}$ are counting.