New Developments around the μCRL Tool Set

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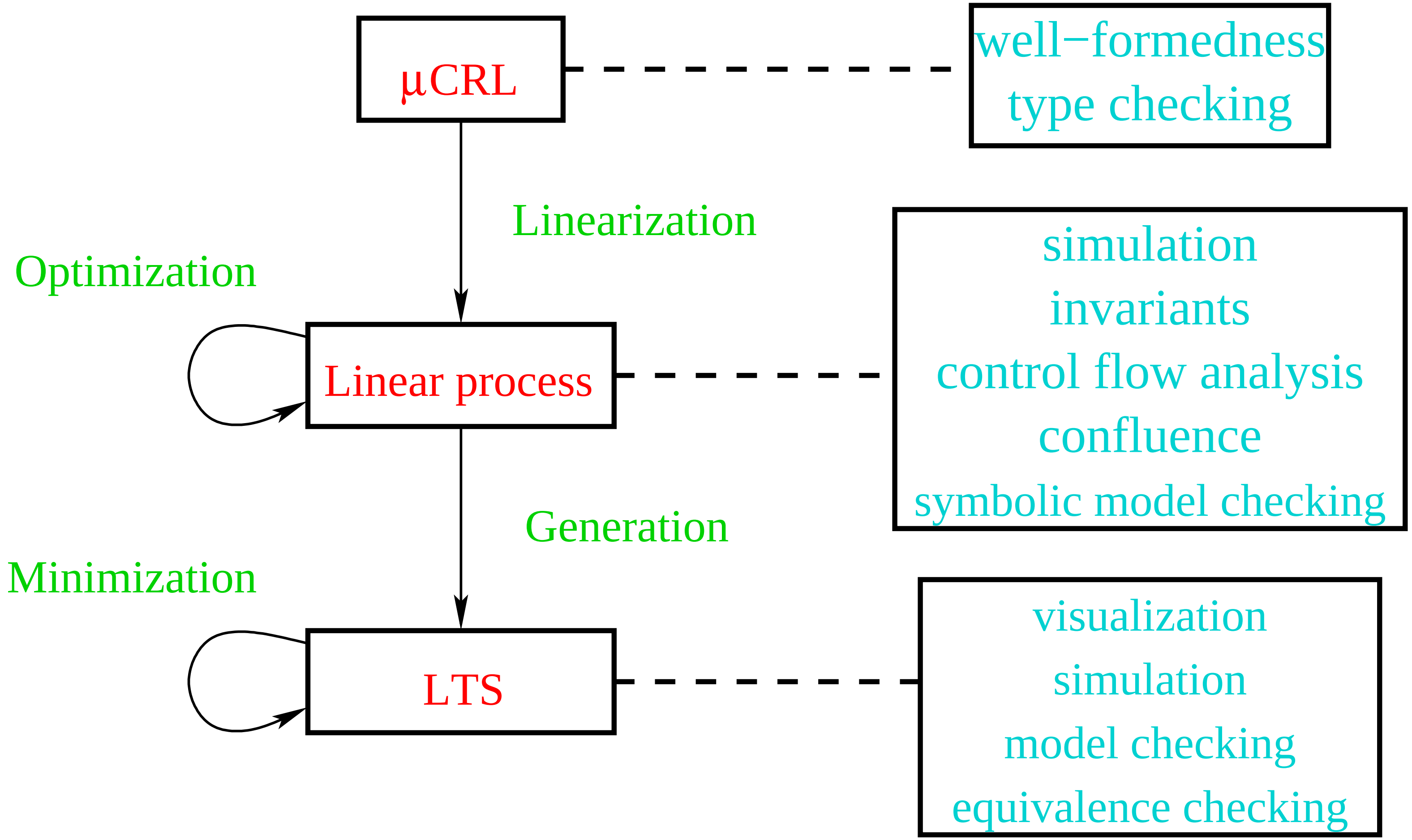
OVERVIEW

- Introduction
- Symbolic verification
  - Linear processes, Static Analysis
  - Confluence
  - Symbolic Model Checking
- Explicit state verification
  - Distributed implementation
  - On-the-fly via Open/Cæsar
  - Visualization
- Some Applications

μCRL Tool Set



μCRL = process algebra + abstract data types

μCRL inherits from abstract data types:

- sorts . . . . Nat, List, Bool
- function symbols . . . . and: Bool $\times$ Bool $\rightarrow$ Bool
- equations . . . . length(cons(x,l)) = succ(length(l))

μCRL inherits from ACP style process algebra :

- atomic actions with synchronization . . . . $read \mid write = comm$
- abstraction, encapsulation, renaming . . . . $\tau, \delta, \cdots$
- process operators . . . . $+, \cdot, \|$
- recursive process equations . . . . $X = a.c.X + b.X$

μCRL $= \cdots +$ integration

μCRL provides connections between data and processes:

atomic actions have data labels: .... $send(frame(x,y))$

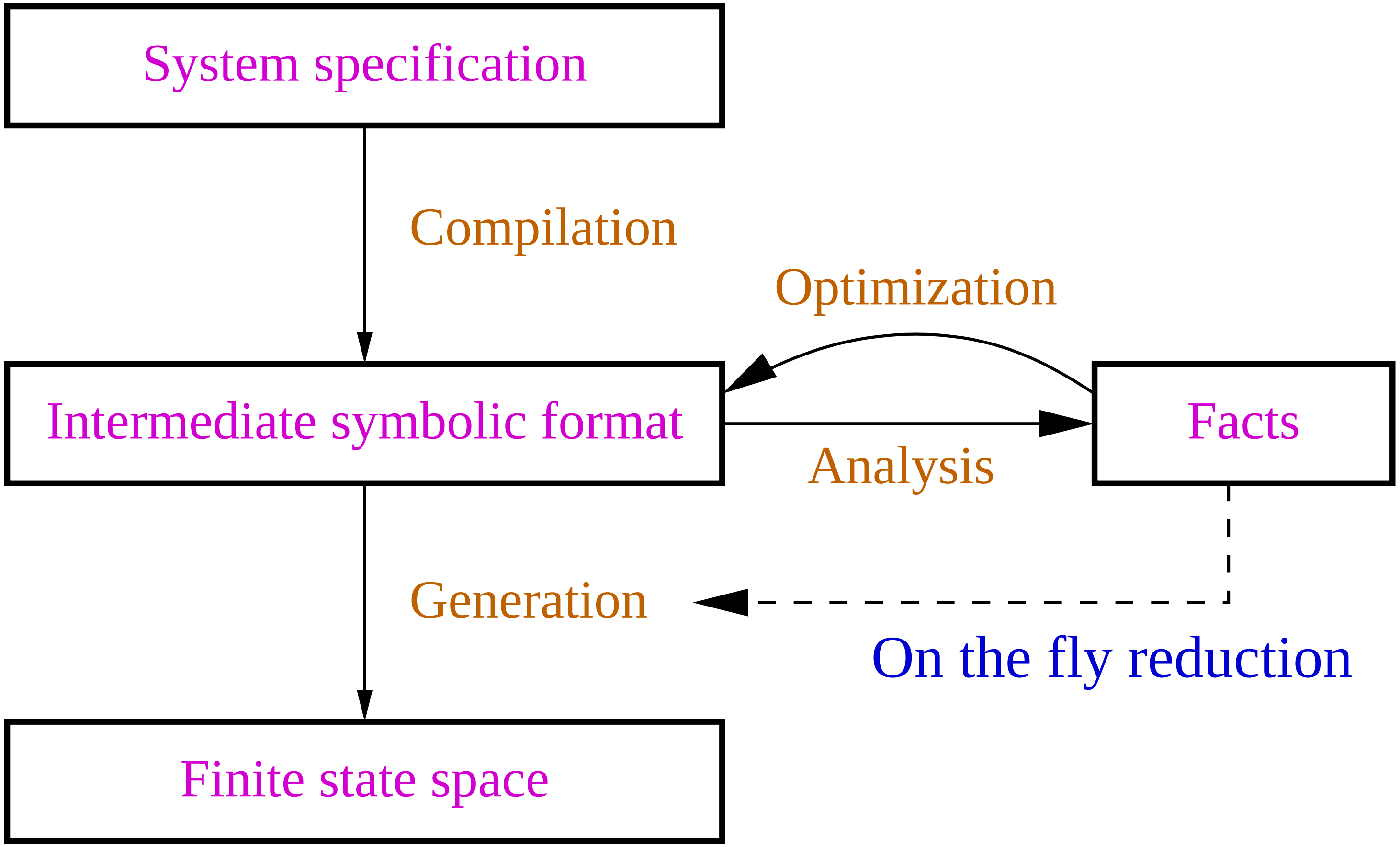
conditions on data: .... $finish \lhd empty(buffer) \rhd continue$

choice over data: .... $\sum_{x:Nat} rd(x).wr(Suc(x))$

parameterized recursion: ....

$$X(prev:Nat) = \sum_{next:Nat} read(next).send(prev).X(next)$$

Outline of our Verification Process



Optimizations

Various optimizations are implemented

- Compiler techniques (control + data flow analysis)
  - replace unchanged variables by constants
  - remove variables that are not used
  - reset variables when temporarily not used
- Automated theorem prover based
  - invariant generation/checking
  - reachability analysis
  - Partial-order-like reduction based on
    * Confluence detection (static)
    * Confluence-based state space reduction (on-the-fly)

Linear process format

$$
\begin{aligned}
X(d:D) \quad = \quad & \sum_{e_1:E} \underline{c_1(d,e_1)} \Rightarrow \underline{a_1(d,e_1)}.X(\underline{g_1(d,e_1)}) \\
+ \quad & \cdots \\
+ \quad & \sum_{e_n:E} c_n(d,e_n) \Rightarrow a_n(d,e_n).X(g_n(d,e_n))
\end{aligned}
$$

- d is a vector of state variables
- e_i is the vector of local variables for summand i
- c_i is the enabling condition for summand i
- a_i is the (visible/invisible) actions for summand i
- g_i is the next-state function for summand i

$X(d) \xrightarrow{a} X(d')$ iff for some i,

$$\exists e_i.\ c_i(d,e_i) \wedge d' = g_i(d,e_i) \wedge a = a_i(d,e_i)$$

Example: linearization of lossy channel

$$K(a:Nat) = \sum_d in(a,d) \cdot \big(\tau \cdot loss + \tau \cdot out(a,d)\big) \cdot K(a)$$

$K(17)$ is linearized by introducing a program counter:

Example: linearization of lossy channel

$$K(a:Nat) = {}_0\sum_d in(a,d) \cdot_1 \big(\tau \cdot_2 loss + \tau \cdot_3 out(a,d)\big) \cdot_0 K(a)$$

$K(17)$ is linearized by introducing a program counter:

$$\begin{array}{llcll}
\textbf{proc} & K(a,x,pc) & = & \sum_d & pc=0 \Rightarrow in(a,d)\cdot K(a,d,1) \\
 & & + & & pc=1 \Rightarrow \tau \cdot K(a,x,2) \\
 & & + & & pc=1 \Rightarrow \tau \cdot K(a,x,3) \\
 & & + & & pc=2 \Rightarrow loss \cdot K(a,x,0) \\
 & & + & & pc=3 \Rightarrow out(a,x)\cdot K(a,x,0) \\
\textbf{init} & K(17,\perp,0) & & &
\end{array}$$

Parallel composition and hiding are defined directly on linear processes.
In practice, no problematic blow-up occurs.

Example: linearization of lossy channel

$$K(a : Nat) =_0 \sum_d in(a,d) \cdot_1 \big(\tau \cdot_2 loss + \tau \cdot_3 out(a,d)\big) \cdot_0 K(a)$$

The linear process can be optimized in various places:

$$\begin{array}{llcll}
\textbf{proc} & K(a,x,pc) & = & \sum_d & pc = 0 \Rightarrow in(a,d) \cdot K(a,d,1) \\
& & + & & pc = 1 \Rightarrow \tau \cdot K(a,x,2) \\
& & + & & pc = 1 \Rightarrow \tau \cdot K(a,x,3) \\
& & + & & pc = 2 \Rightarrow loss \cdot K(a,x,0) \\
& & + & & pc = 3 \Rightarrow out(a,x) \cdot K(a,x,0) \\
\textbf{init} & K(17,\perp,0) & & &
\end{array}$$

Example: linearization of lossy channel

$$K(a : Nat) =_0 \sum_d in(a,d) \cdot_1 \big(\tau \cdot_2 loss + \tau \cdot_3 out(a,d)\big) \cdot_0 K(a)$$

The optimized linear process will be:

$$
\begin{array}{llcll}
\textbf{proc} & K(x, pc) & = & \sum_d & pc = 0 \Rightarrow in(17, d) \cdot K(d, 1) \\
 & & + & & pc = 1 \Rightarrow \tau \cdot K(\perp, 2) \\
 & & + & & pc = 1 \Rightarrow \tau \cdot K(x, 3) \\
 & & + & & pc = 2 \Rightarrow loss \cdot K(\perp, 0) \\
 & & + & & pc = 3 \Rightarrow out(17, x) \cdot K(\perp, 0) \\
\textbf{init} & K(\perp, 0) & & &
\end{array}
$$

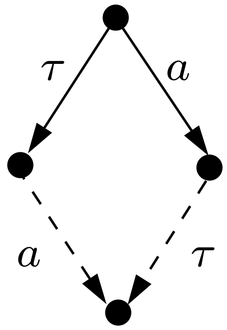
Correctness of static analysis tools

- most optimization tools yield state mappings on LPOs
- state mappings on LPOs yield functional bisimulations on LTSs
- invariants can be used to verify state mappings
- state mappings preserve invariants (in two directions)
- the Focus and Cones method provides matching criteria to prove that two linear processes are branching bisimilar
- LPO meta-theory has been completely verified in PVS
- `mcrl2pvs`: individual specifications can be translated to PVS automatically, and verified by interactive theorem proving

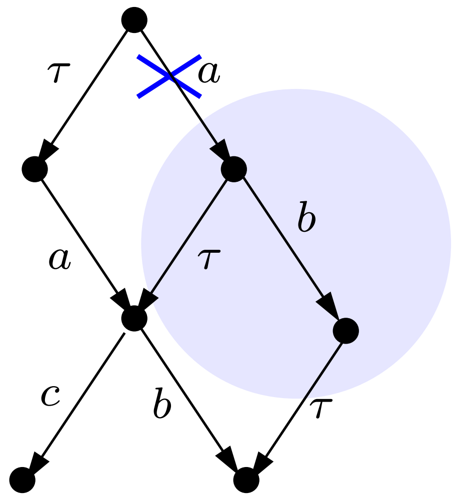
State Space Reduction by Confluence

An LTS can be reduced, by exploiting confluence properties.

strong commutation:



state space reduction:



We will study subsets $\xrightarrow{\textcircled{\tau}} \subseteq \xrightarrow{\tau}$.

Confluence Notions

$\xrightarrow{\tau} \subseteq \xrightarrow{\tau}$ is step/reduce confluent in an LTS iff:

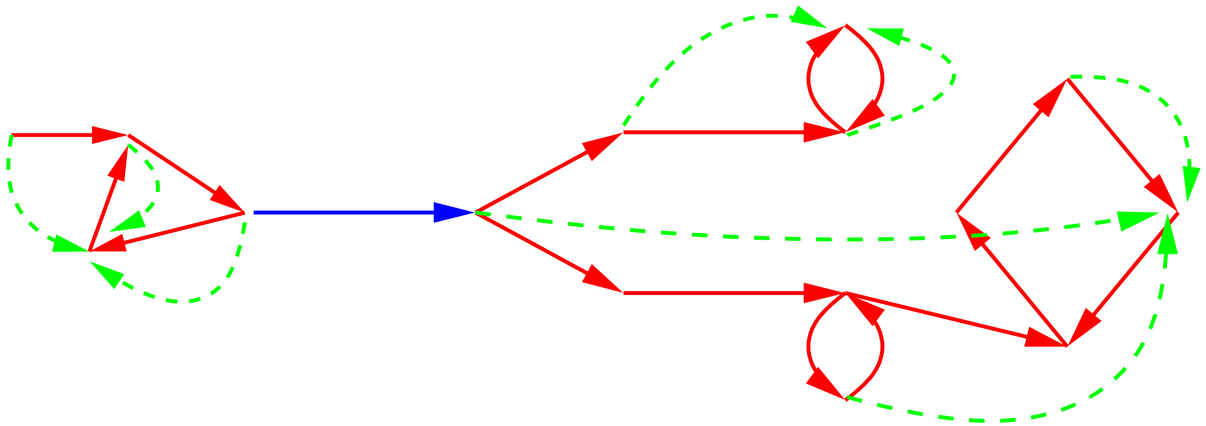
$$\begin{tikzcd} \cdot \arrow[r, "\tau"] \arrow[d, "a"'] \arrow[dr, phantom, "SC"] & \cdot \arrow[d, Rightarrow, dashed, "a"] \\ \cdot \arrow[r, dashed, "\tau"'] & \cdot \end{tikzcd}$$

$$\begin{tikzcd} \cdot \arrow[r, "\tau"] \arrow[d, "a"'] \arrow[dr, phantom, "RC"] & \cdot \arrow[d, Rightarrow, dashed, "a"] \\ \cdot \arrow[r, dashed, two heads, "\tau"'] & \cdot \end{tikzcd}$$

Note: $SC \Rightarrow RC$

Reduction based on Confluence Information

A representation map replaces each state by its representative, which must be unique in the final strongly connected components.



$\longrightarrow$ is a visible step, $\longrightarrow$ are $\xrightarrow{\tau}$ steps.

Representation maps can be computed on-the-fly by an adaptation of Tarjan's algorithm.

Theorem: if $\xrightarrow{\tau}$ is RC and ϕ is a representation map, then $L \mathrel{\underline{\leftrightarrow}}_b L_\phi$.

Confluence detection on LPO

- Mark all τ-summands that commute with all other summands.
- Invariants can be used to prove commutation.
- $\xrightarrow{\textcircled{\tau}}$:= the transitions generated from marked τ-summands.
- Then $\xrightarrow{\textcircled{\tau}}$ is an SC, and hence RC, subset of $\xrightarrow{\tau}$, so it can be used for on-the-fly reduction.
- Confluence marking is preserved by state mappings
- All meta-theory on confluence has been verified in PVS.

Confluence Formula Generation

$$\sum_{e_a} c_a(d,e_a) \Rightarrow a(d,e_a).X(g_a(d,e_a))$$
$$\sum_{e_\tau} c_\tau(d,e_\tau) \Rightarrow \tau.X(g_\tau(d,e_\tau))$$

The commutation formula for this (a,τ)-pair is:

$$\begin{aligned}
\forall d, e_a, e_\tau.\ c_a(d,e_a) \wedge c_\tau(d,e_\tau) \longrightarrow \\
& c_\tau(g_a(d,e_a),e_\tau) \\
\wedge \quad & c_a(g_\tau(d,e_\tau),e_\tau) \\
\wedge \quad & a(d,e_a) = a(g_\tau(d,e_\tau),e_a) \\
\wedge \quad & g_a(g_\tau(d,e_\tau),e_a) = g_\tau(g_a(d,e_a),e_\tau)
\end{aligned}$$

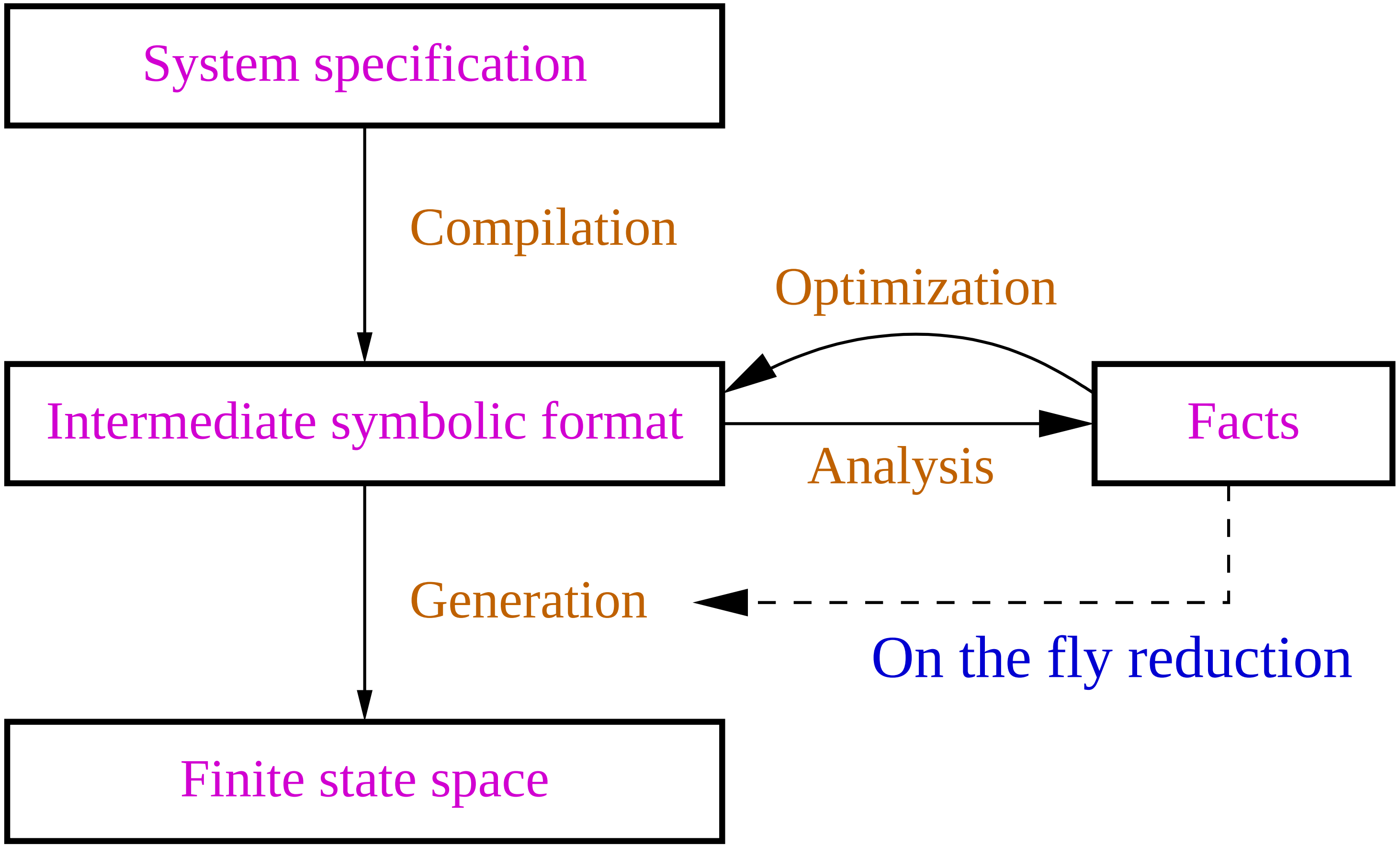
Special-purpose theorem prover

- The μCRL toolset comes with a special-purpose automated theorem prover.
- It handles q.f.f. Boolean formulas over an abstract data type.
- It is based on EQ-BDDs, an extension of BDDs with equations and function symbols (Groote, vdP).
- Other applications are:
  - inductive invariant checking
  - removal of "dead" summands
  - enhance static analysis tools
  - Future: check user provided state mappings

Very Recent Developments

- Symbolic Model Checking on LPO [Groote, Willemse]
  - handles regular μ-calculus with data and quantifiers
  - applies directly to LPOs (possibly infinite state spaces)
  - transformed to Boolean equation systems with data parameters [Groote, Mateescu]
  - solved by equational binary decision diagrams
- Abstract interpretation of LPO [Valero, JvdP]
  - based on abstraction of data domains.
  - results in a Modal LPO, containing may/must transitions.
  - yields under/over approximations, using 3-valued logic.
- Symmetry Reduction [van Langevelde]

Outline of our Verification Process



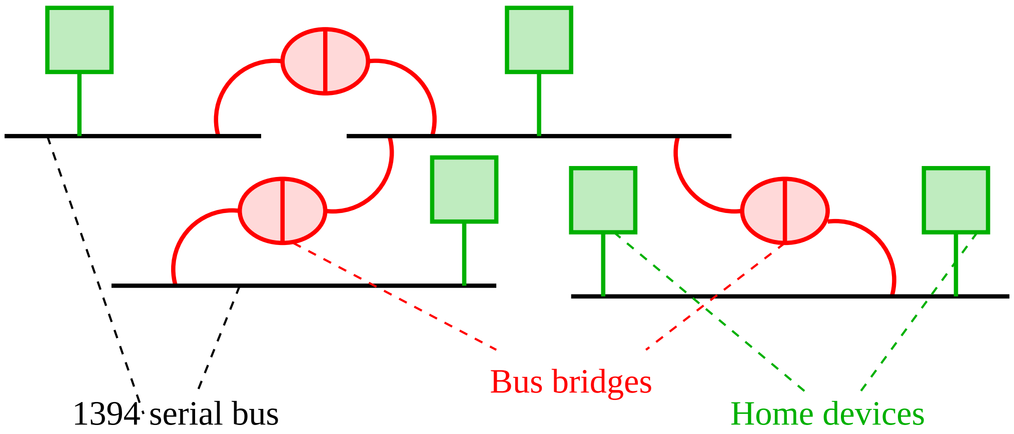
State Space Generation and Analysis

(this is only possible for finite state spaces)

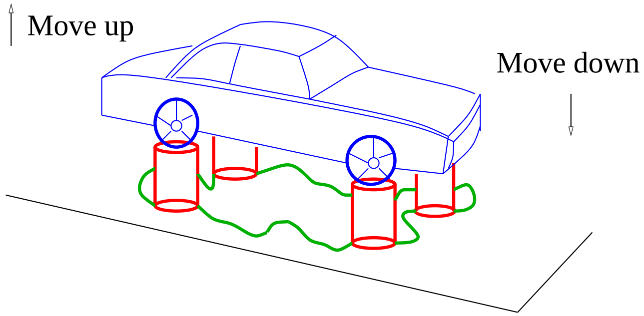
- Explicit LTS Generation from a linear process
  (narrowing-like technique to solve $\sum$ over infinite domains)
- Distributed implementations [Blom, Orzan]
  - state space generation (in files S_i, T_{ij})
  - strong bisimulation minimization
  - branching bisimulation minimization
- Open/Cæsar interface is implemented.
  - on-the-fly analysis of μCRL specs by CADP toolset
  - model checking, equivalence checking, visualization ...
- Visualization of state space of $> 10^6$ nodes [Groote, van Ham]

Protocols and Distributed Algorithms

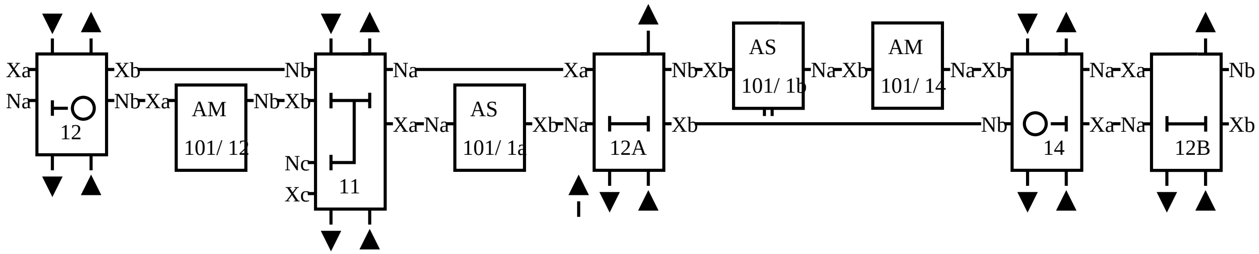
- Sliding Window Protocol
- Leader Election Protocol [Dolev,Klaw,Rodeh]
- Cache Coherence Protocol for Java Distributed Memory Model
- Failure recovery algorithms for Telecom [Arts, Benac Earle]
- IEEE 1394.1 Firewire Busbridges Standardization



Embedded Systems



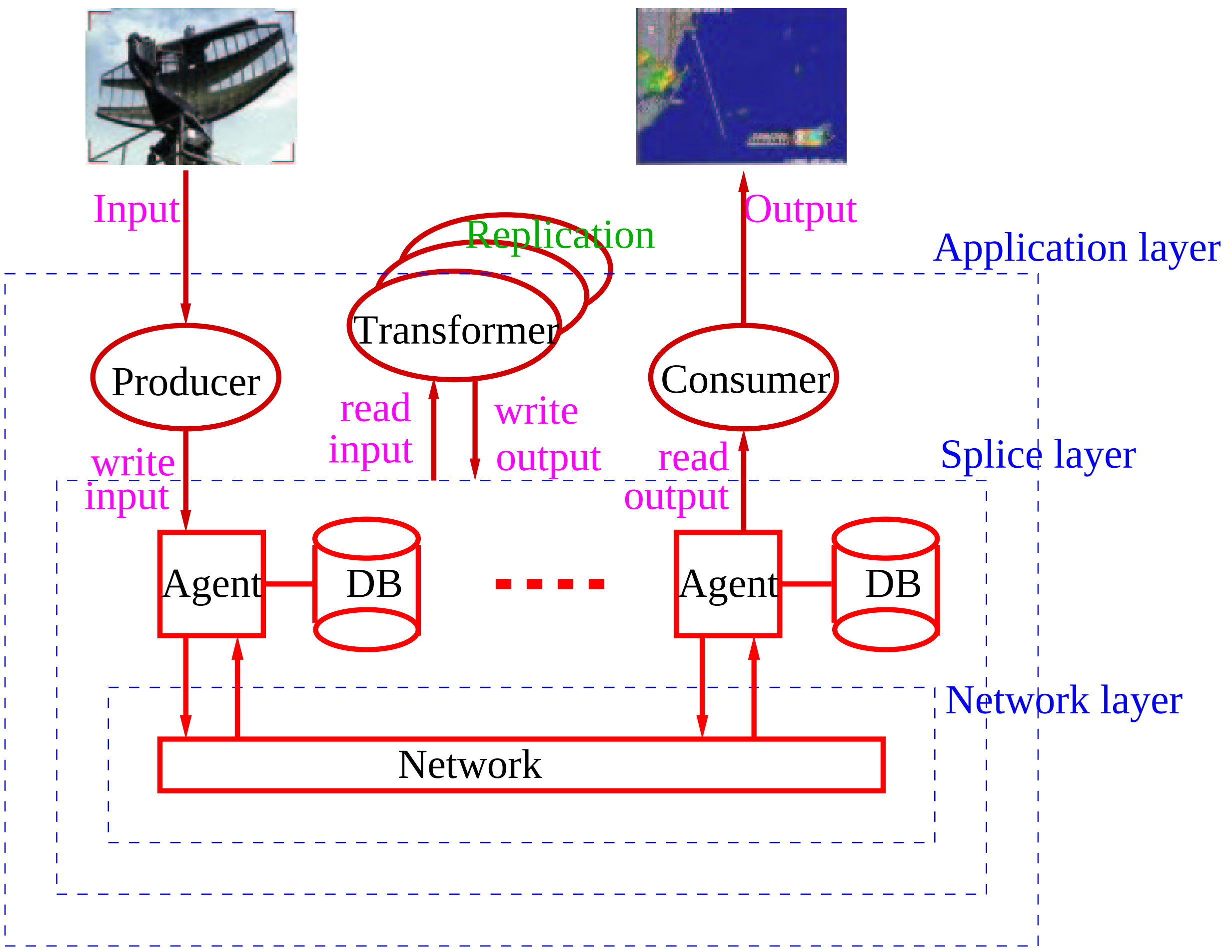
- Truck lift controllers built by Add-controls
- In-flight Data-acquisition Unit for Lynx helicopter [RNLN, NLR]
- Avionics Control Systems [Moscow State Univ., RedLab Ltd.]
- Safety of railroad tracks (Euris specifications)



Shared Dataspace Architectures

- JavaSpaces^{tm} Distributed Applications [Sun Microsystems]
  - read/write/take on a global shared object space
  - transactions, notification events, resource leasing
  - dining philosophers, termination detection, parallel summation
- Splice Coordination Architecture [Thales]
  - Real-time distributed databases with replicated data
  - Publish/subscribe mechanism for loosely coupled components
  - Verification question: transparent replication of software components

Replication in Splice



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  - Static Analysis yields state mappings
  - Confluence for state space reduction
  - Symbolic Model Checking
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Conclusion

- LPO format contributes to modularity of the tool set
- Methodological integration of symbolic, on-the-fly and explicit state analysis
- Combination of interactive (PVS) and automated theorem proving (EQ-BDDs), symbolic and explicit state model checking.
- Meta-theory is completely verified in PVS
- In principle, an individual verification in the tool set could be mapped onto PVS, for a "second opinion"