Distributed State Space Generation and Minimization

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Overview

1. The μCRL project
2. Verification Approach
3. Distributed State Space Generation
4. Distributed State Space Minimization
5. Implications for GRID

μCRL

μCRL = abstract datatypes + process algebra

- ADT: constructors + maps + equations
- Process algebra: ACP style

Most intriguing construct: Σ - potentially infinite choice.

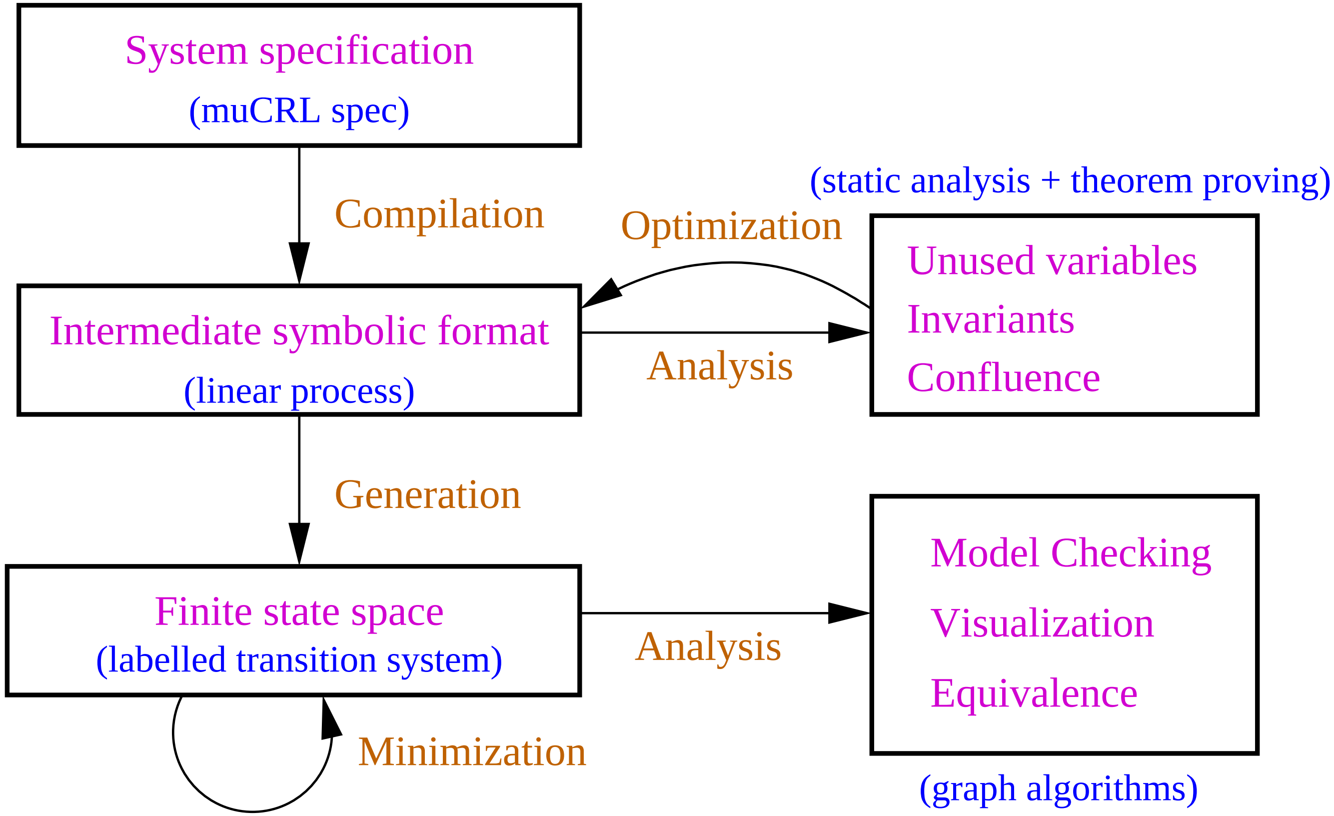
Example from Security Protocols:

$$Alice \,||\, Intruder(K)$$

$$\Big(\sum_m recv(m) \triangleleft protocol(m)\Big) \,||\, \Big(\sum_m send(m) \triangleleft synthesize(m, K)\Big)$$

Techniques: Term rewriting + enumeration (= narrowing?)
(enumerate m such that $protocol(m) \wedge synthesize(m, K)$)

Verification in the μCRL toolset



Fight State Space Explosion!

Linear Process Equations

- First, a μCRL specification is linearized.
  (this step eliminates $||$ and $\cdot$ at the expense of adding data)
- A linear process has the form:

$$
\begin{array}{rcl}
P(\vec{x}) & = & \sum_{\vec{y}} . a_1(\vec{x},\vec{y}) \cdot P(g_1(\vec{x},\vec{y})) \triangleleft b_1(\vec{x},\vec{y}) \\
 & + & \cdots \\
 & + & \sum_{\vec{y}} . a_n(\vec{x},\vec{y}) \cdot P(g_n(\vec{x},\vec{y})) \triangleleft b_n(\vec{x},\vec{y})
\end{array}
$$

- Here $\vec{x}$ is the state vector, containing state variables of all components + program counters. a_i are actions, b_i Boolean guards, g_i next states, and $\vec{y}$ are local choice parameters.
- Advantage: simple structure + relatively succinct
- Symbolic state space reductions are LPE transformations.

Symbolic Optimizations

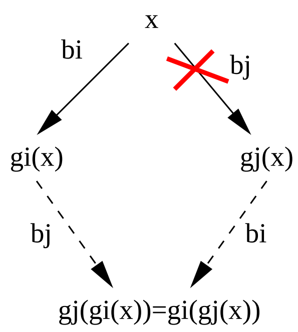
- Constant propagation, Resetting dead variables
- Dead code elimination, tau-confluence reduction

I is an invariant for all summands:

$$\bigwedge_i \forall \vec{x}, \vec{y} : I(\vec{x}) \wedge b_i(\vec{x}, \vec{y}) \Rightarrow I(g_i(\vec{x}, \vec{y}))$$

Summand i commutes with j (for confluence reduction):

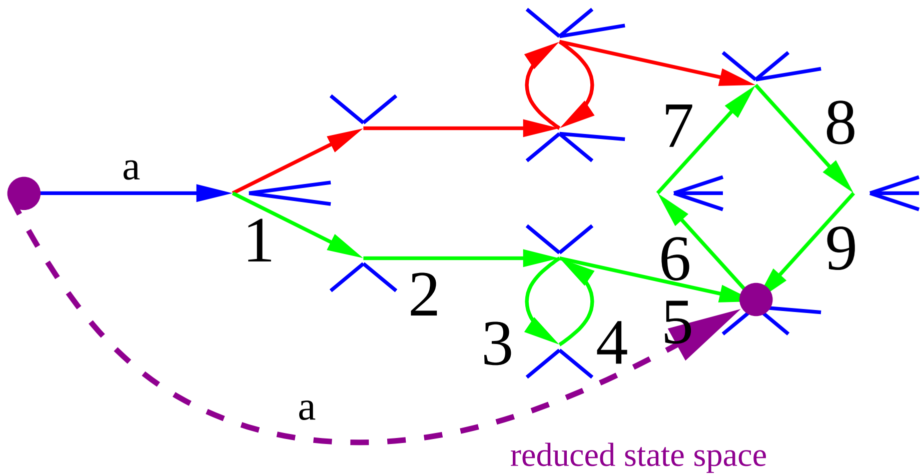
$$\forall \vec{x} : b_i(\vec{x}) \wedge b_j(\vec{x}) \Rightarrow b_j(g_i(\vec{x})) \wedge b_j(g_i(\vec{x})) \wedge g_j(g_i(\vec{x})) = g_i(g_j(\vec{x}))$$



- Invariant generation / checking
- Confluence detection by theorem proving
- Confluence reduction on the fly (avoid loops!)
- $\Rightarrow$ Parallellization of theorem prover ??

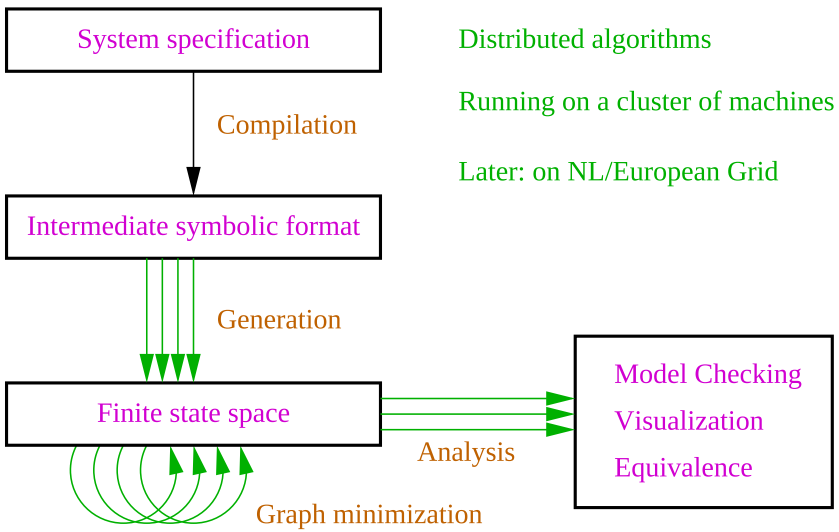
On-the-fly τ-Confluence Reduction

- After detecting some confluent τ summands, we want on the fly:
  - Give priority to confluent τ-steps
  - Compress sequences of confluent τ-steps
- A concrete transition $s \rightarrow_a t$ is transformed to $s \rightarrow_a rep(t)$, where $rep(t)$ is found by Tarjan's SCC algorithm.
- Below: blue are visible steps, while green (visited) and red (not visited) are confluent tau-steps



Explicit state space generation

- When symbolic reduction is exhausted, we start brute force
- Generating state space is time consuming (narrowing!)
- Hence: explicit generation + storage of full state space.
- Various analyses can be performed without regeneration
- Use distributed generation to scale in memory + time.



Distributed State Space Generation

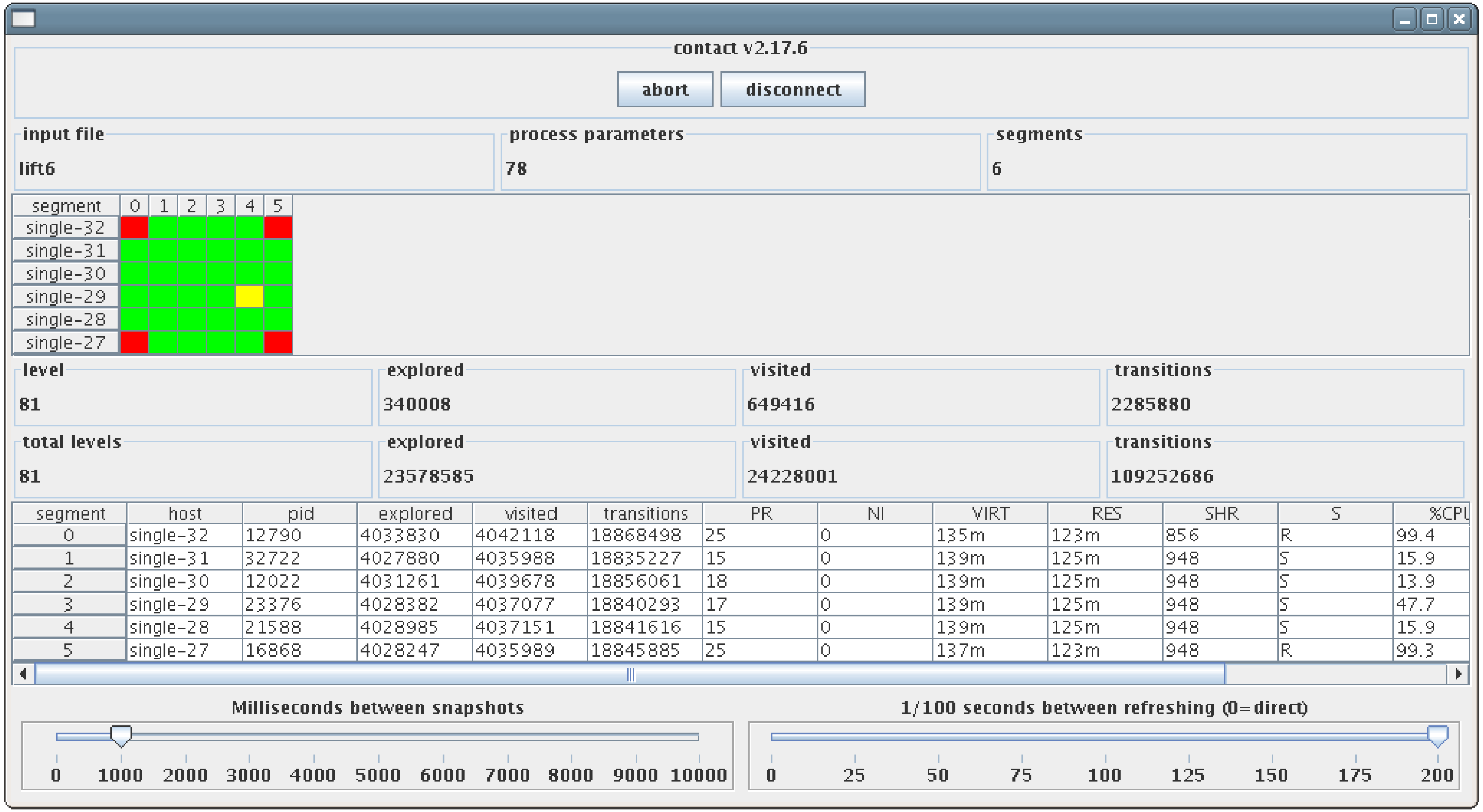
Extra Functionality:

- on-the-fly verification of simple safety properties (deadlock, occurrences of bad actions)
- debug traces for diagnostics
- on-the-fly confluence reduction
- search in time slices to find shortest schedules (i.e.: barrier synchronization on special "tick" actions)

Conclusion:

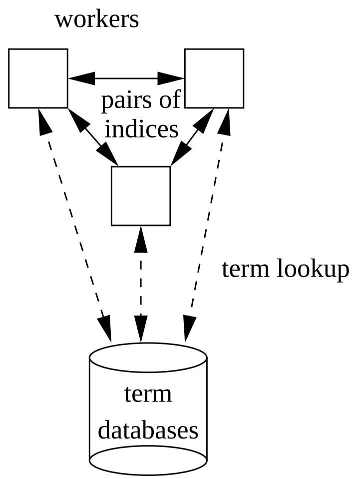
- Scales up in time + memory ($> 10^8$ transitions, 32 nodes)

Distributed State Space Generation



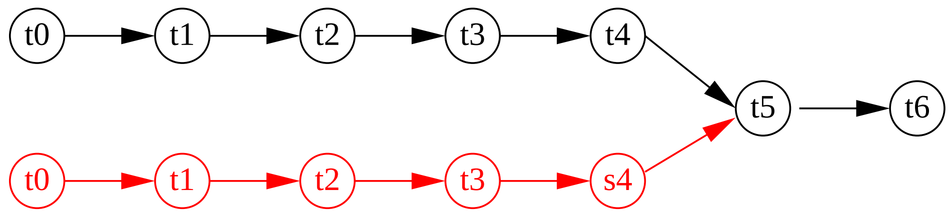
Distributed Generation with On-the-fly τ-Confluence Reduction

- Strict breadth first exploration of the state space.
  (only reason: shortest traces as counter example)
- As usual: states are allocated by a static hash function to nodes in a network, who send each other batches of successor states.
- Actually, we send indices of states to avoid serialization overhead.

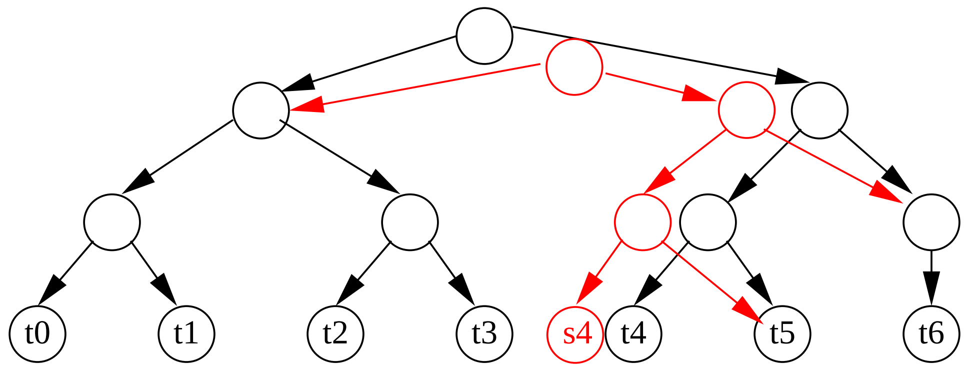


Single node Memory Footprint

- We use the ATerm Library (CWI, SEN 1) to represent the state space as one maximally shared forest.
- Nice trick (JF Groote): arrange state vector as tree instead of list:
- List arrangement: avg. $\frac{1}{2}n$ list nodes duplicated $t4 \mapsto s4$



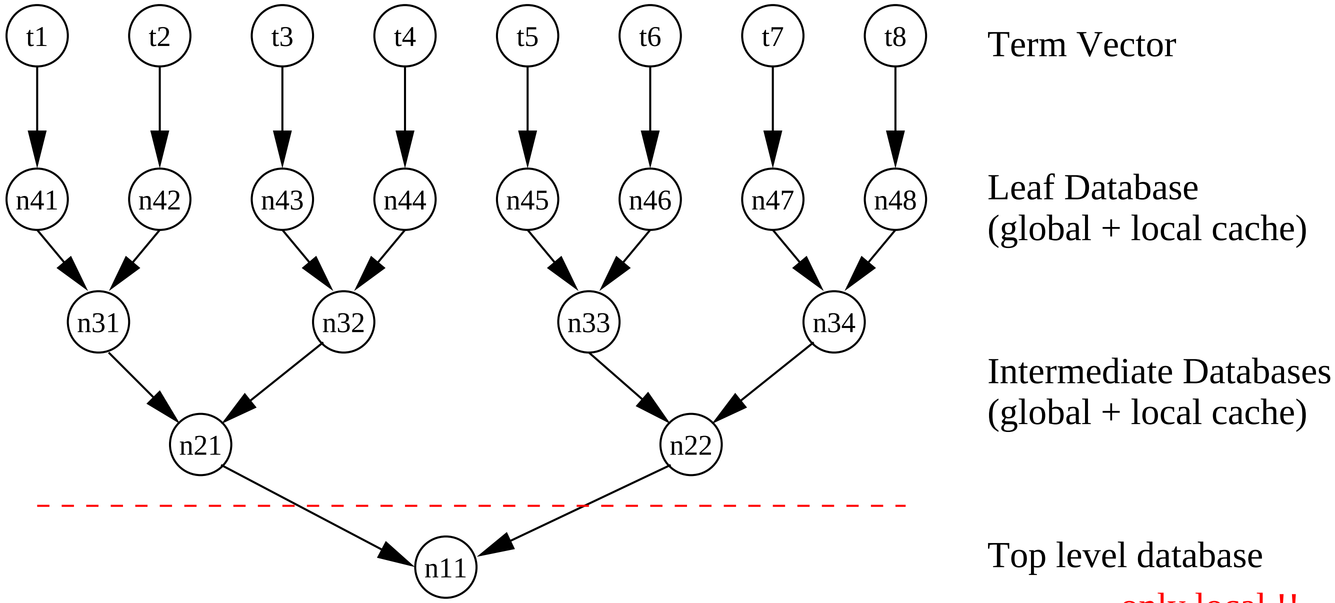
- Tree arrangement: $\log n$ list nodes duplicated.



Distributing shared terms?

- The nodes send each other batches of new states to be explored.
- Problem: ATerms are pointers, which are only locally meaningful.
- Bad solution: serialization/deserialization for communication.
- Our solution:
  - Assign indices to states, only communicate indices
  - Store term indices in a shared global database
  - Exploit another tree-folding trick to avoid bottlenecks
- Goal: a global unique bijection: States $\leftrightarrow \{0, \ldots, n\}$
  (but avoid a database of size n)
- Idea: Use the Cartesian structure of the state vector

Shared global term databases



- With perfect balancing: database n_{kj} at level k has $\sqrt[k]{|S|}$ states
- Balancing can be improved by pairing/projecting the state vector
- Several ad hoc tricks reduce communication overhead.
- Most communication overhead only at the beginning!

State Space Minimization

- We have the following instances:
  - Strong bisimulation reduction (Blom,Orzan)
  - Branching bisimulation reduction (Blom, Orzan)
  - τ-cycle elimination (Orzan, van de Pol)
- Algorithms:
  - Partition refinement, based on "observable signatures".
  - The nodes synchronize in "rounds"
- Conclusion:
  - it works in practice, memory usage is OK
  - decent speedup for large enough examples
  - result after minimization often fits in one machine

Implications for GRID

- intensive inter-node communication
- synchronized levels for BFS (can be relaxed), and for partition refinement (essential?)
- shared data base
- need for persistent data storage

Implications for Interfaces

- data enumeration is important (for open systems)
- extensions for confluence/partial-order reduction needed
- several symbolic optimizations are language specific.