Sequential and Distributed Test Generation using Boolean Equation Systems

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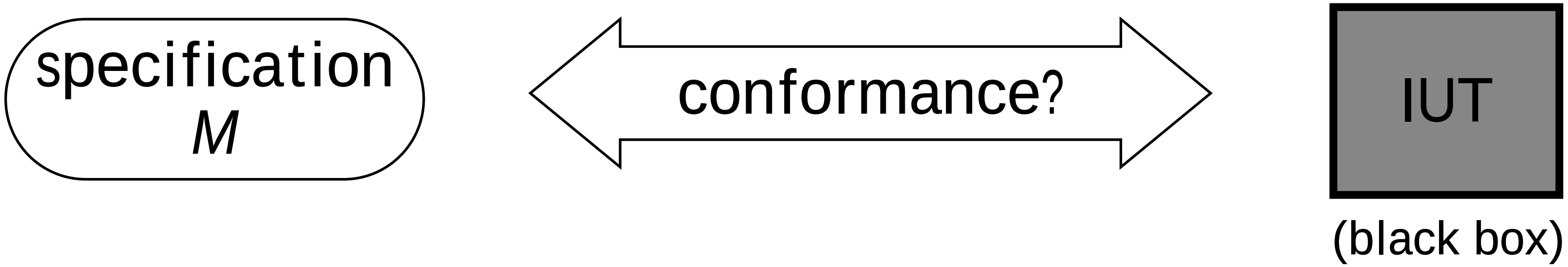
Outline

- Conformance testing
- On-the-fly test generation method used by TGV
- Reformulation using boolean equation systems
- Sequential and distributed resolution algorithms
- Experiments
- Ongoing work

Conformance testing

[Tretmans-97]



- Input/output conformance relation (**ioco**):

  after executing each visible execution trace contained in M, the IUT exhibits only outputs and quiescences that are possible in M

- Inputs of IUT are *controllable* by the environment
- Outputs and quiescences of IUT are only *observable*

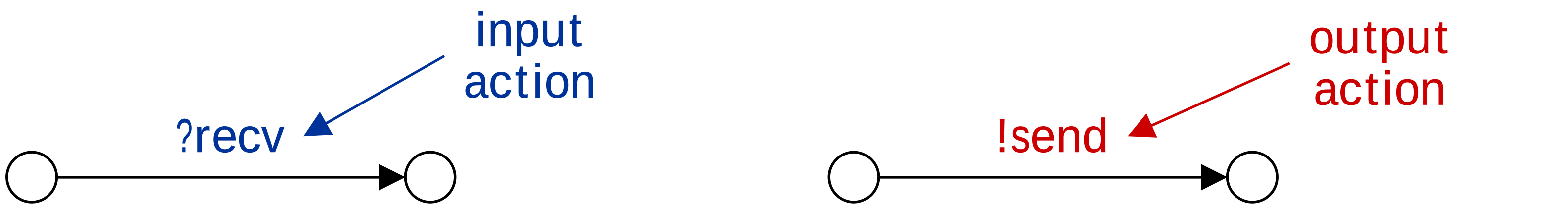
Test generation method underlying TGV

[Fernandez-Jard-Jeron-Viho-96,Jard-Jeron-05]

- Specification M and IUT are represented as IOLTSs (Input/Output Labelled Transition Systems)

$$M = (S, A, T, s_0)$$

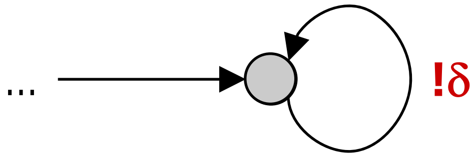
$$A = A_I \cup A_O \cup \{ \tau \}$$



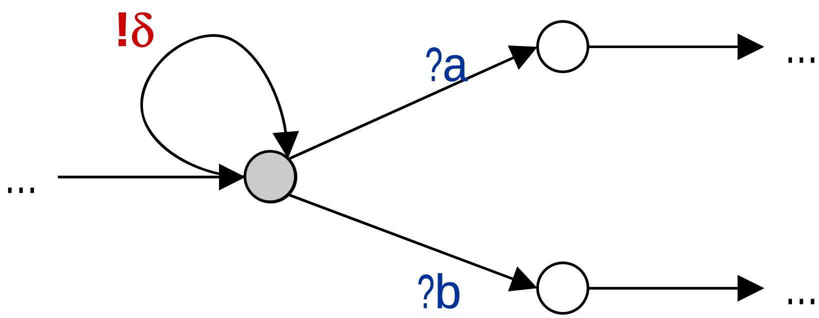
- Assume alphabets of M and IUT are compatible
  - $A_I^M \subseteq A_I^{IUT}$ and $A_O^M \subseteq A_O^{IUT}$
- Assume IUT is (weakly) input complete
  - In every state, all inputs are accepted (possibly after τ*)

Quiescence

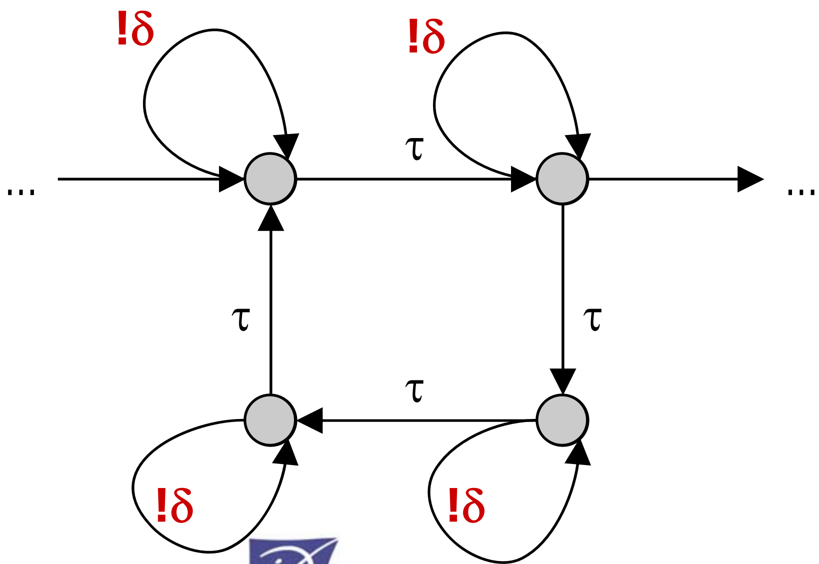
- Deadlock



- Outputlock



- Livelock



Suspension and determinization

- $\Delta(M)$: suspension automaton of *M*
  - Explicitly marks the quiescent states of *M* by self-loops labelled by a special (output) action δ
- Can be done on-the-fly by applying τ-compression (contraction of τ-SCCs) [Mateescu-05]
- $STraces(M) = Traces(\Delta(M))$: suspension traces of *M*
  - Conformance testing = comparison between *STraces*(IUT) and *STraces*(*M*)
- $det(\Delta(M))$: τ-closure & determinization of $\Delta(M)$
  - Keeps only visible actions and suspension traces
  - Must occur *after* suspension (to preserve quiescence)

Test cases

- IOLTS $TC = (S^{TC}, A^{TC}, T^{TC}, s_0^{TC})$
  - Three sets of trap states (verdicts)

    Pass, **Fail**, **Inconc** $\subseteq S^{TC}$
  - $A_O^{TC} \subseteq A_I^M$ (*TC* emits only inputs of *M*)
  - $A_I^{TC} \subseteq A_O^{IUT} \cup \{ \delta \}$ (*TC* foresees outputs and quiescences of IUT)
  - States in **Fail** and **Inconc** only reachable by inputs
  - From each state a verdict must be reachable
  - No choice between two outputs or an input and an output (*controllability*)
  - Input completion in all states where an input is possible
- Test suite: a set of test cases

Test execution

- Parallel composition of a test case and the IUT with synchronization on all visible actions

  $$TC \mid\mid \Delta(\text{IUT})$$

- Verdicts of execution associated to maximal traces (ending with a verdict returned by *TC*)
- *TC* may have loops (⇒ possible infinite execution)
  - Use global timers to limit the test execution
- *TC* *may reject* IUT: there exists a trace in Traces ($TC \mid\mid \Delta(\text{IUT})$) ending with a **Fail** verdict
- Similarly for *may pass* and *may inconc*

Soundness and exhaustiveness

- *TC* sound for M and **ioco**:

  $\forall$ IUT. IUT **ioco** M $\Rightarrow \neg$(*TC may reject* IUT)

- Test suite exhaustive for M and **ioco**:

  $\forall$ IUT. $\neg$(IUT **ioco** M) $\Rightarrow \exists$ TC. *TC may reject* IUT

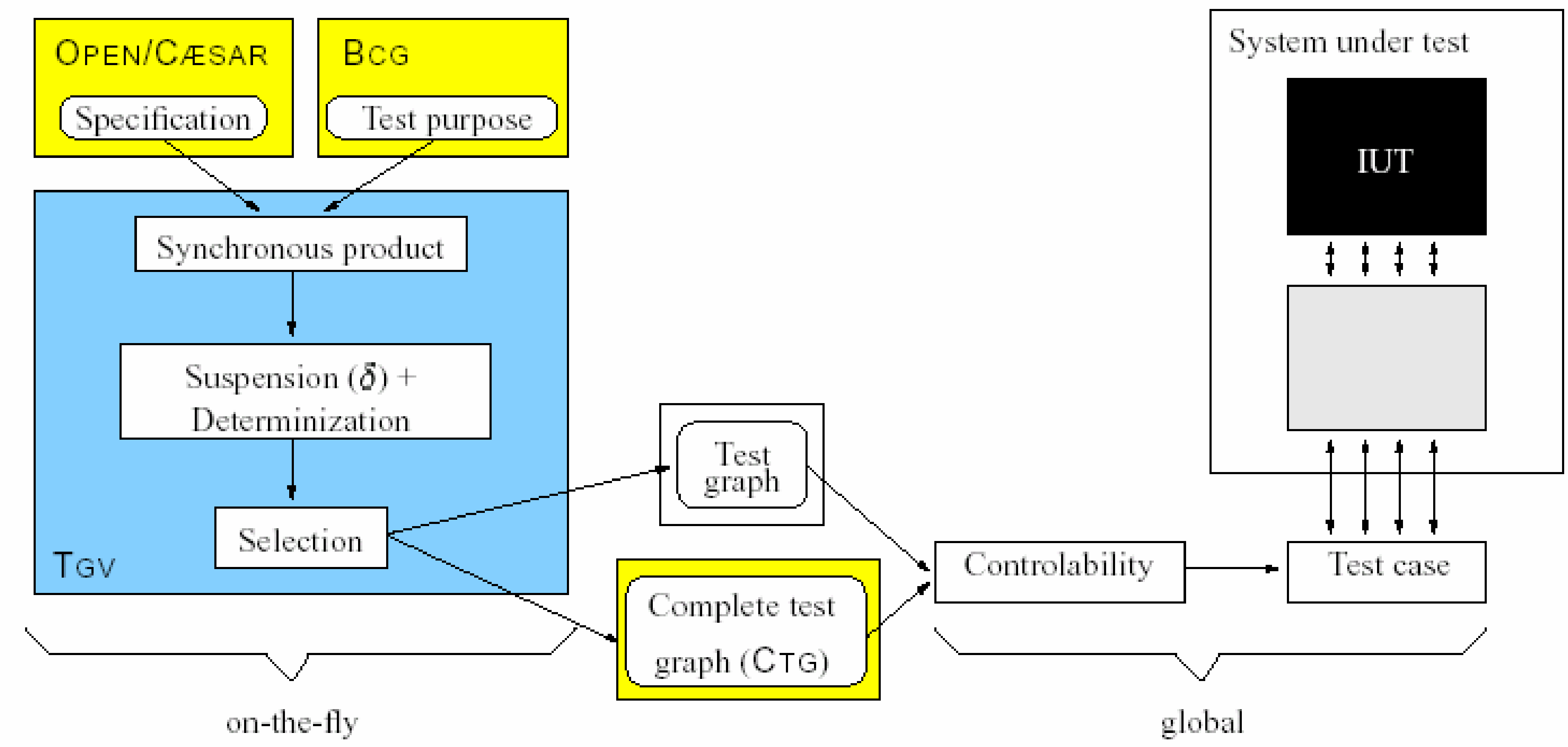
- Complete test suite
  - Sound and exhaustive
  - Test suite does not reject a conformant IUT
  - Every non-conformant IUT is possibly rejected (impossible to ensure with finite test suites)
- In practice: only exhaustiveness of the *test generation method* is required

Test purposes

- Descriptions of the behaviours to be tested
- IOLTS $TP = (S^{TP}, A^{TP}, T^{TP}, s_0^{TP})$
  - Two sets of trap states

    $$Accept^{TP}, Refuse^{TP} \subseteq S^{TP}$$
  - $A^{TP} = A^{M}$ (same alphabet as M)
  - Deterministic
  - Complete (all actions are possible in each state)
  - Trap states have a self-loop for each action
  - "*" action: "any action in A^{TP}" (wildcard)
- $Accept^{TP}$ states: select targeted behaviours
- $Refuse^{TP}$ states: cut the exploration of M

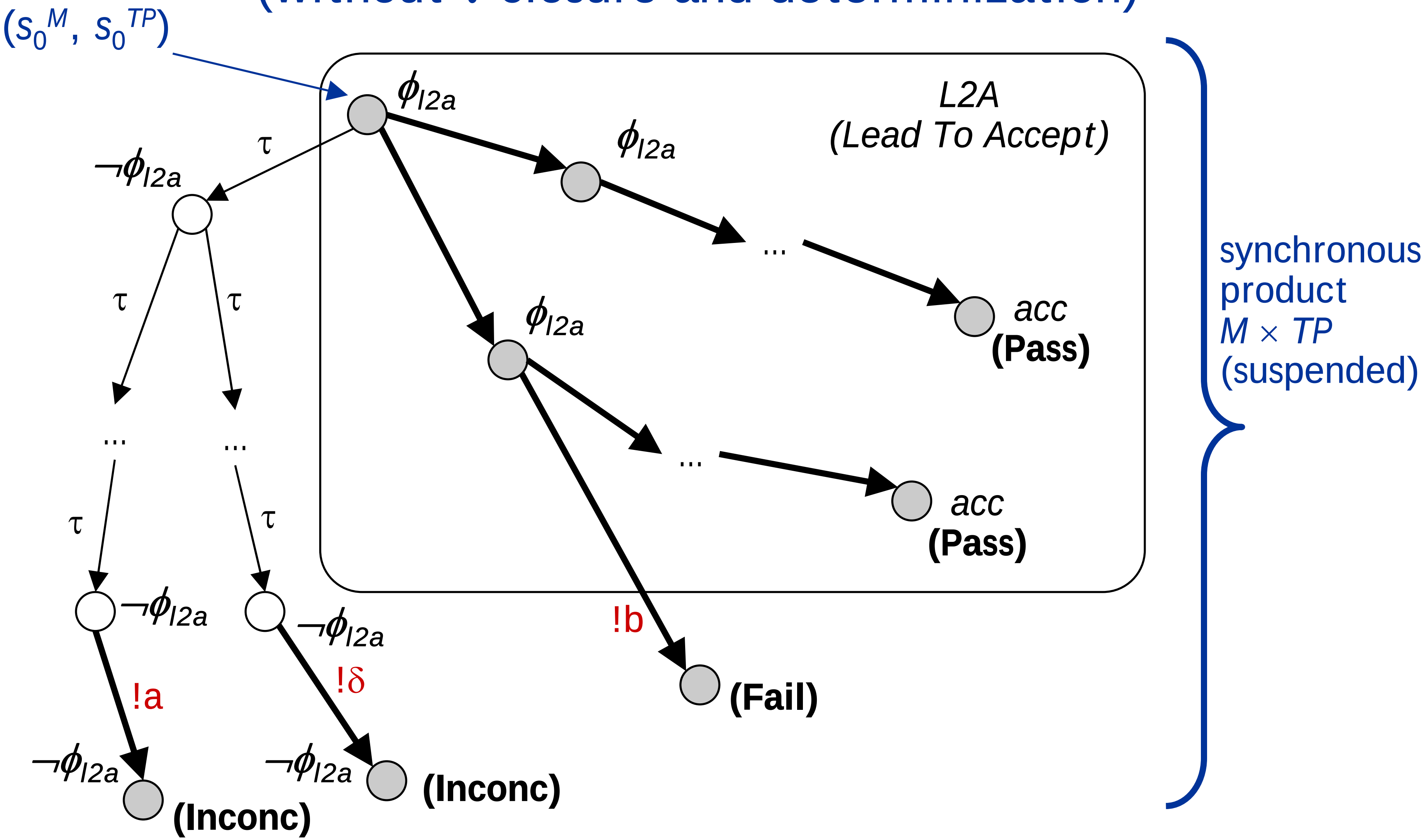
Functioning of TGV



- Based upon DFS algorithms (unsuitable for distribution)

Test selection

(without τ-closure and determinization)



Characterization in modal μ-calculus

- $\phi_{l2a} = \mu X \,.\, acc \vee \langle - \rangle X$
  - States from which a **Pass** verdict (*acc* state) is reachable
- $\phi_{inc} = \nu Y \,.\, \langle\, !\delta \vee !a \,\rangle\, \text{true} \wedge [\, \tau \,]\, Y$
  - States from which an **Inconc** verdict is τ^*-reachable
  - ϕ_{inc} = true
- $\phi_{ctg} = \phi_{l2a} \wedge \nu Z \,.\, [\, \text{true} \,]\, ((\phi_{l2a} \Rightarrow Z) \wedge (\neg\phi_{l2a} \Rightarrow \phi_{inc}))$
  - States of the "raw" CTG (containing τ-transitions)
  - νZ-subformula = true
  - $\phi_{ctg} = \phi_{l2a}$
- CTG contains a test case iff $s_0 \models \phi_{ctg}$

Translation to BES resolution with diagnostic

$$s \models \phi_{ctg} = X_s \wedge Z_s$$

disjunctive block

$$\{ X_s =_\mu acc_s \vee \bigvee_{s \to s'} X_{s'} \}$$

conjunctive blocks

$$\{ Y_s =_\nu \bigvee_{s \to !a\, s'} \text{true} \wedge \bigwedge_{s \to \tau\, s'} Y_{s'} \}$$

$$\{ Z_s =_\nu \bigwedge_{s \to s'} ((X_{s'} \Rightarrow Z_{s'}) \wedge (\neg X_{s'} \Rightarrow Y_{s'})) \}$$

Sequential local resolution

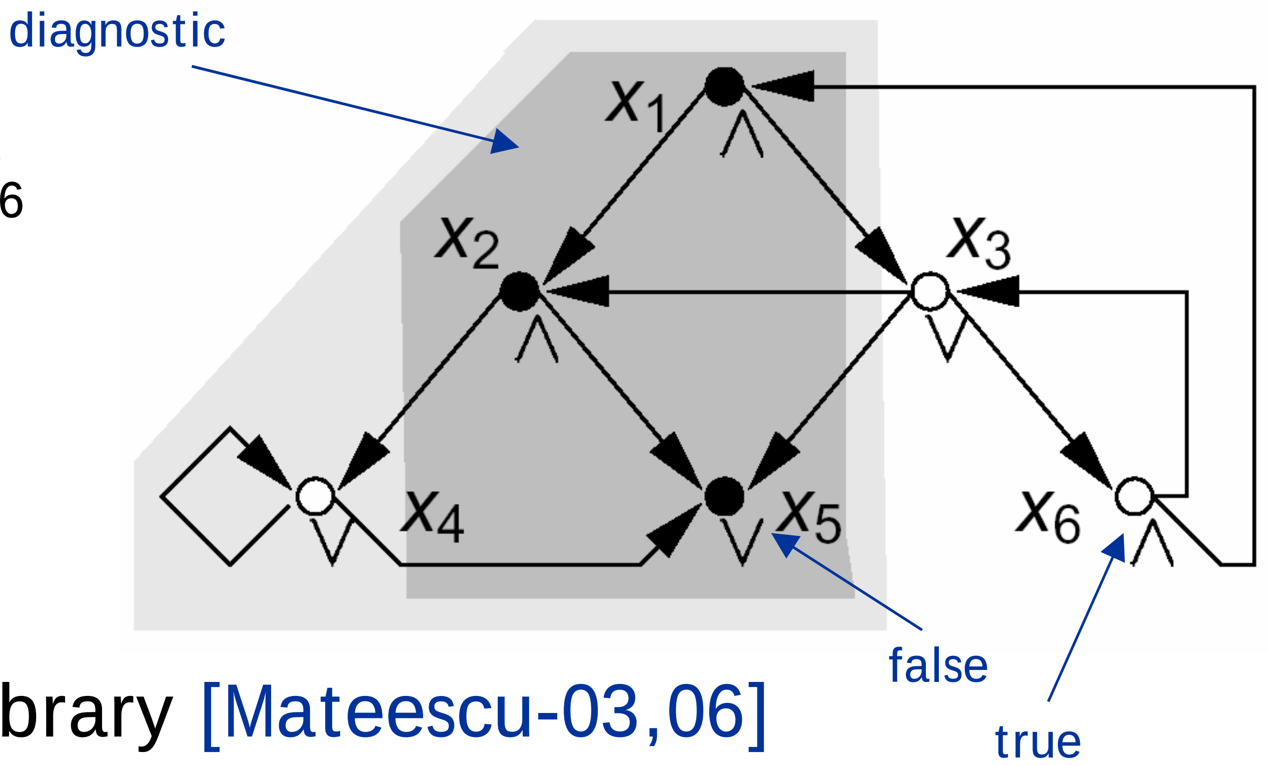
(alternation-free BESs)

BES

$$\begin{cases} x_1 =_\nu x_2 \wedge x_3 \\ x_2 =_\nu x_4 \wedge x_5 \\ x_3 =_\nu x_2 \vee x_5 \vee x_6 \\ x_4 =_\nu x_4 \vee x_5 \\ x_5 =_\nu \text{false} \\ x_6 =_\nu x_1 \wedge x_3 \end{cases}$$

boolean graph

[Andersen-94]



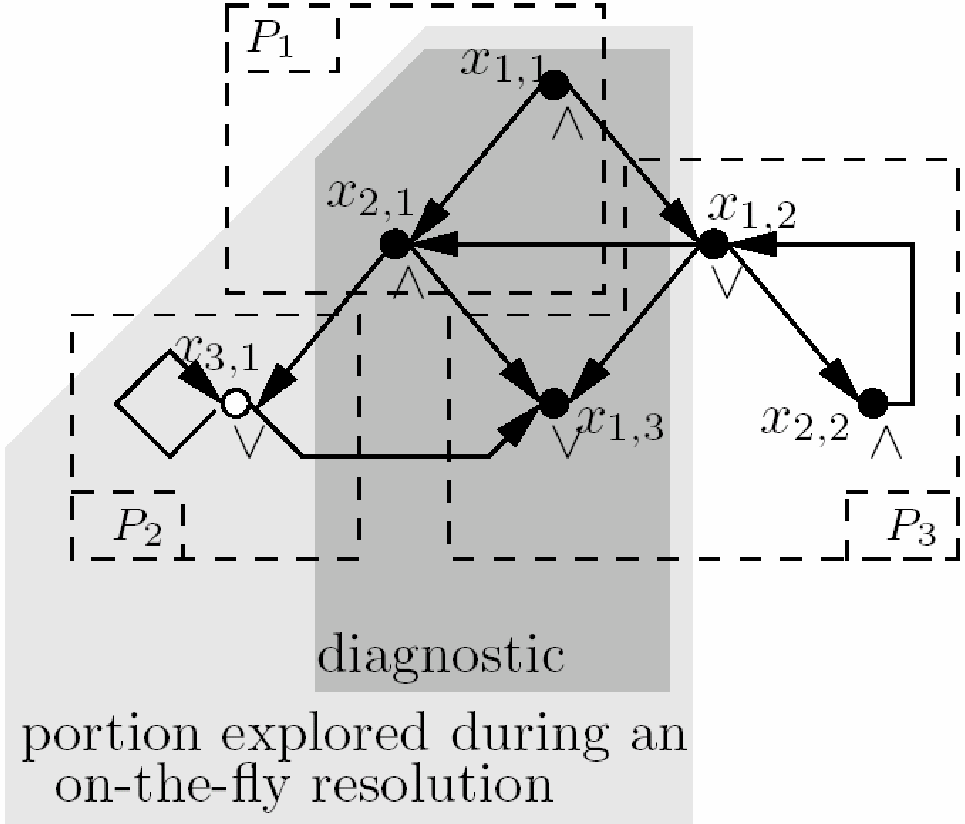
- Caesar_Solve library [Mateescu-03,06]
  - 5 resolution algorithms + diagnostic generation

Distributed local resolution

$$\text{block 1} \begin{cases} x_{1,1} \stackrel{\nu}{=} x_{2,1} \wedge x_{1,2} \\ x_{2,1} \stackrel{\nu}{=} x_{3,1} \wedge x_{1,3} \\ x_{3,1} \stackrel{\nu}{=} x_{3,1} \vee x_{1,3} \end{cases}$$

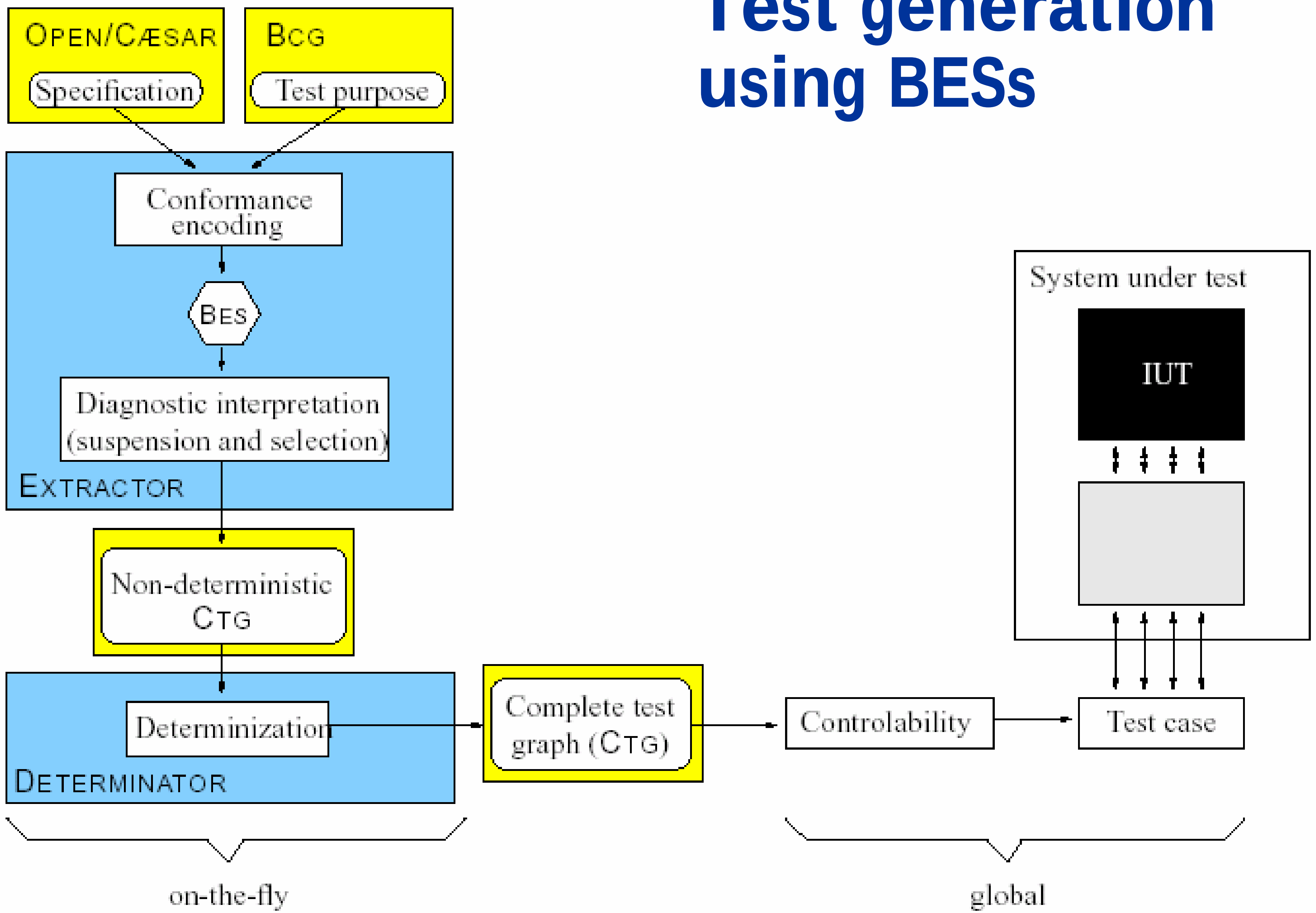
$$\text{block 2} \begin{cases} x_{1,2} \stackrel{\mu}{=} x_{2,1} \vee x_{1,3} \vee x_{2,2} \\ x_{2,2} \stackrel{\mu}{=} x_{1,2} \end{cases}$$

$$\text{block 3} \begin{cases} x_{1,3} \stackrel{\nu}{=} \mathsf{false} \end{cases}$$

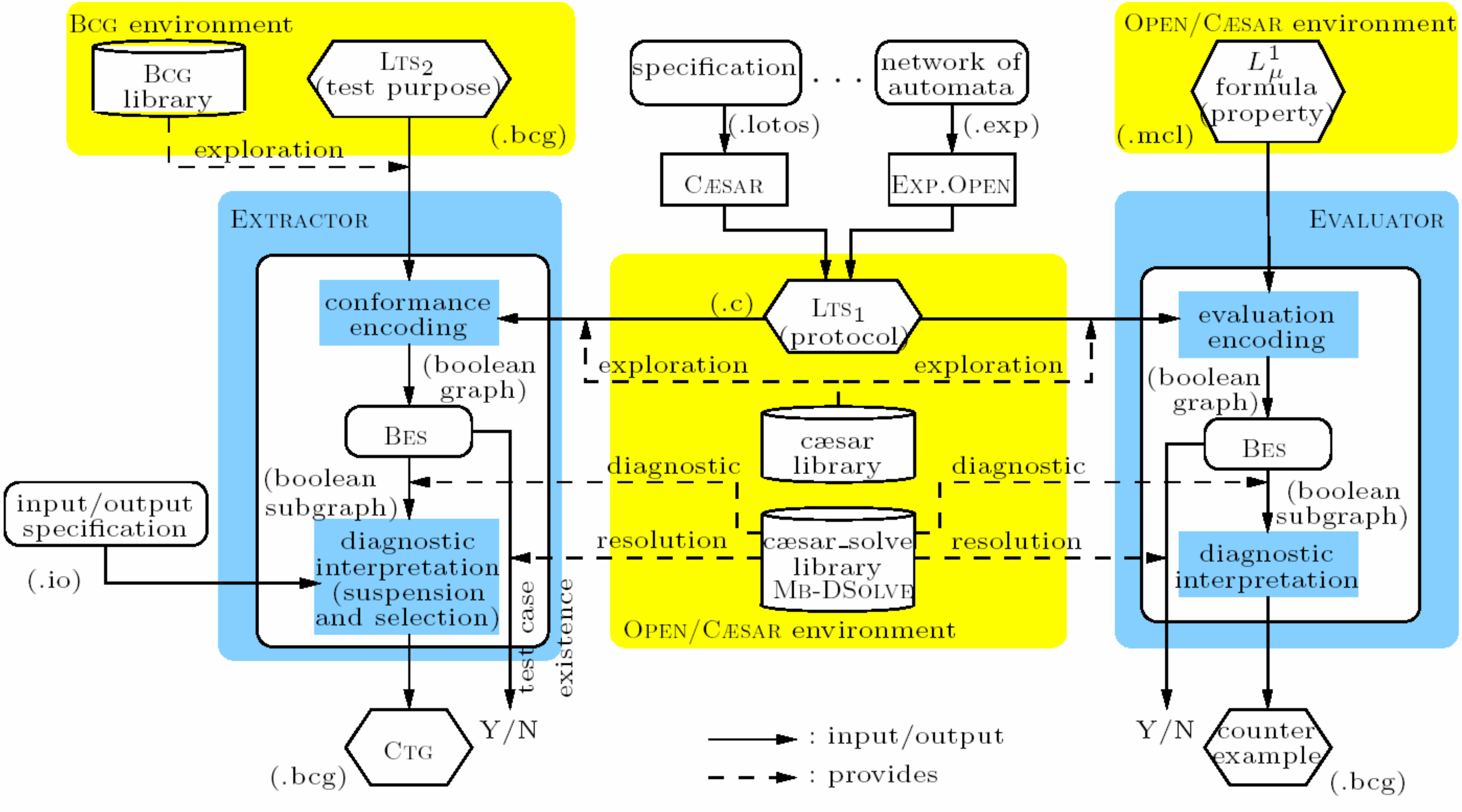


- MB-DSolve algorithm [Joubert-Mateescu-06]
  - Two distributed BFS traversals of the boolean graph (forward expansion and backward stabilization)
  - Partial distributed termination detection (stabilization of a portion of a block)

Test generation using BESs

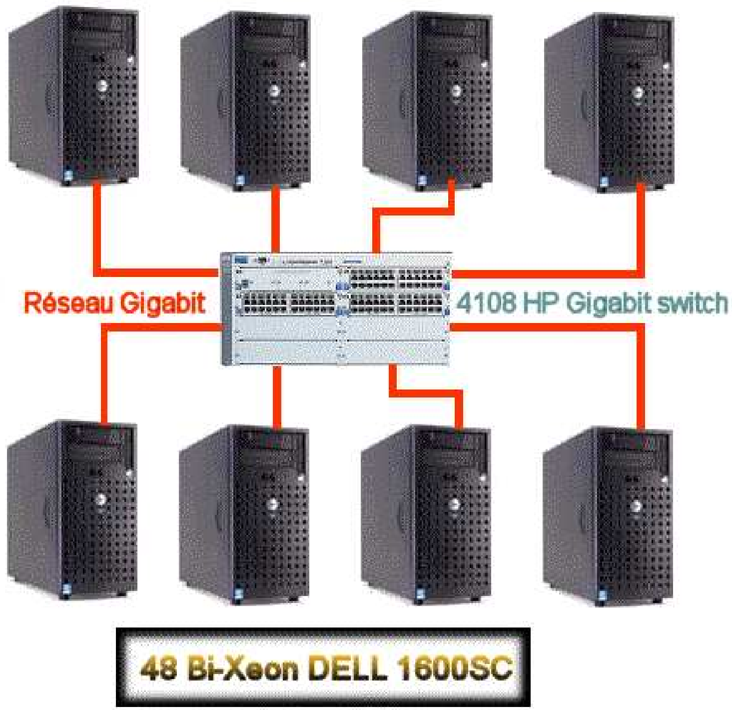


Tools architecture



Experiments

- IDPOT cluster
  - 48 bi-Xeon
  - 2.4 GHz, 1.5 Gb



- VLTS benchmark suite
  - http://www.inrialpes.fr/vasy/cadp/resources/benchmark_bcg.html

Sequential Extractor vs. TGV

(generic TP – accepting state after 10 visible actions, VLTS)

Example	TGV				(sequential) Extractor					
	time	MB	states	trans.	time	%	MB	%	states	trans.
vasy_164_1619	15'8s	242	100 319	231 266	3'47s	75	210	13	438 861	2 982 696
vasy_166_651	20'23s	242	170 657	586 602	1'41s	92	113	53	444 542	1 504 985
cwi_371_641	6'5s	1600	125 894	597 445	5'20s	12	310	81	1 912 260	3 163 177
vasy_386_1171	9s	11	3 319	3 892	7s	22	10	9	5 561	6 324
vasy_1112_5290	23s	33	10 827	20 888	13s	44	28	15	15 008	41 225
b256	597'4s	2322	264 194	854 786	139'22s	77	2772	-2	12 139 232	39 020 231

TGV:

- 1.82 times slower than Extractor + Determinator
- Produces CTGs between 30% and 50% smaller

"raw" CTGs
(contain τ-transitions)

Distributed Extractor + Determinator

(generic TP, 7 nodes, VLTS)

Example	(distributed) Extractor		Determinator			
	time	MB	time	MB	states (final)	transitions (final)
vasy_164_1619	4'39s	470	4'40s	55	103 658	975 594
vasy_166_651	2'59s	335	2'27s	50	173 259	801 675
cwi_371_641	12'4s	880	25'8s	185	127 218	777 278
vasy_386_1171	16s	104	15s	6	2 452	3 894
vasy_1112_5290	27s	228	17s	7	8 369	41 225
b256	180'	6127	19'	459	527 875	1 709 058

final CTGs
(without τ-transitions)
strongly equivalent to
those produced by TGV

Sequential Extractor vs. TGV
(memory)

Example	M states	M trans.	Extractor + Determinator
cwi_214_684	214	684	8 s., 19 MB, no test case
cwi_566_3984	566	3 984	1195 s., 145 MB, (32 states, 49 trans.)

- TGV fails by memory shortage (> 3Gb)

Conclusion and future work

- Summary
  - Conformance test generation encoded as BES resolution with diagnostic (Extractor)
  - MB-DSolve: distributed local resolution of multiple block BESs
  - Generic implementation using OPEN/CAESAR
  - Performance comparable with TGV
- Ongoing and future work
  - Further experiments and benchmarks
  - Handling of heterogeneous architectures (grids)
  - Other applications (discrete controller synthesis)