Constraint-Based Heuristic On-line Test Generation from Non-deterministic I/O-EFSM

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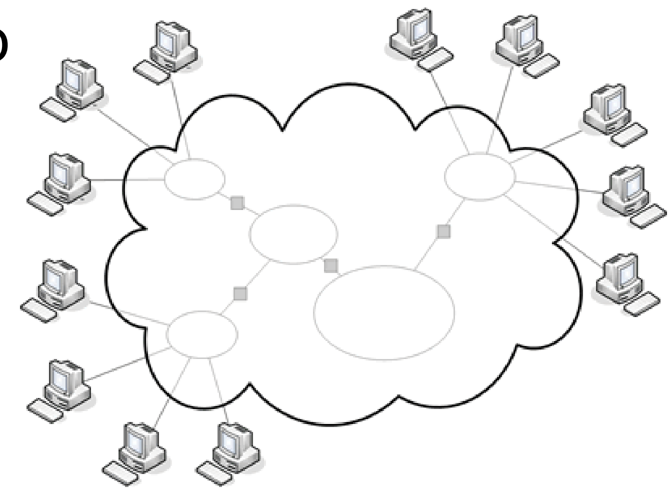
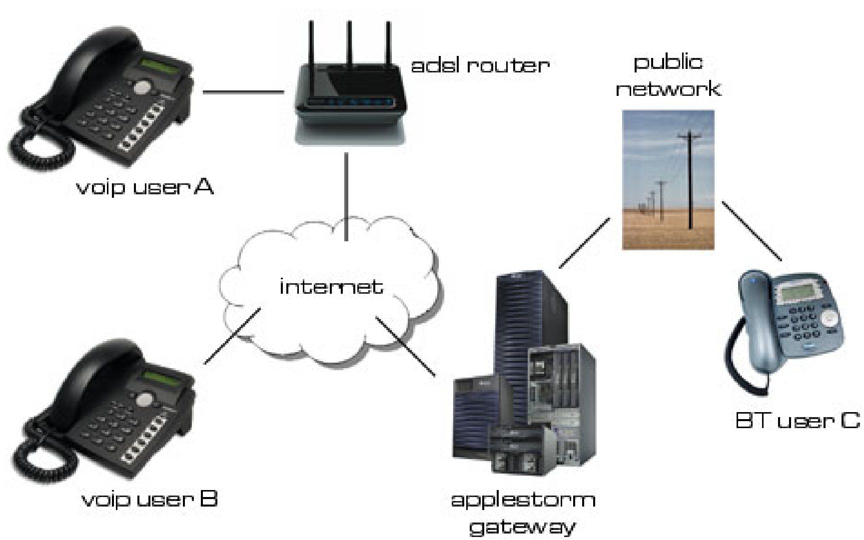
Conformance testing

- A system should communicate to its environment according to a specification/protocol
- Black-box view: test@interface
- Embedded systems, services, communication devices





Testing non-deterministic systems

Non-deterministic system may react differently to the same input

- Non-deterministic systems
- Non-deterministic models due to abstraction

On-line testing is needed

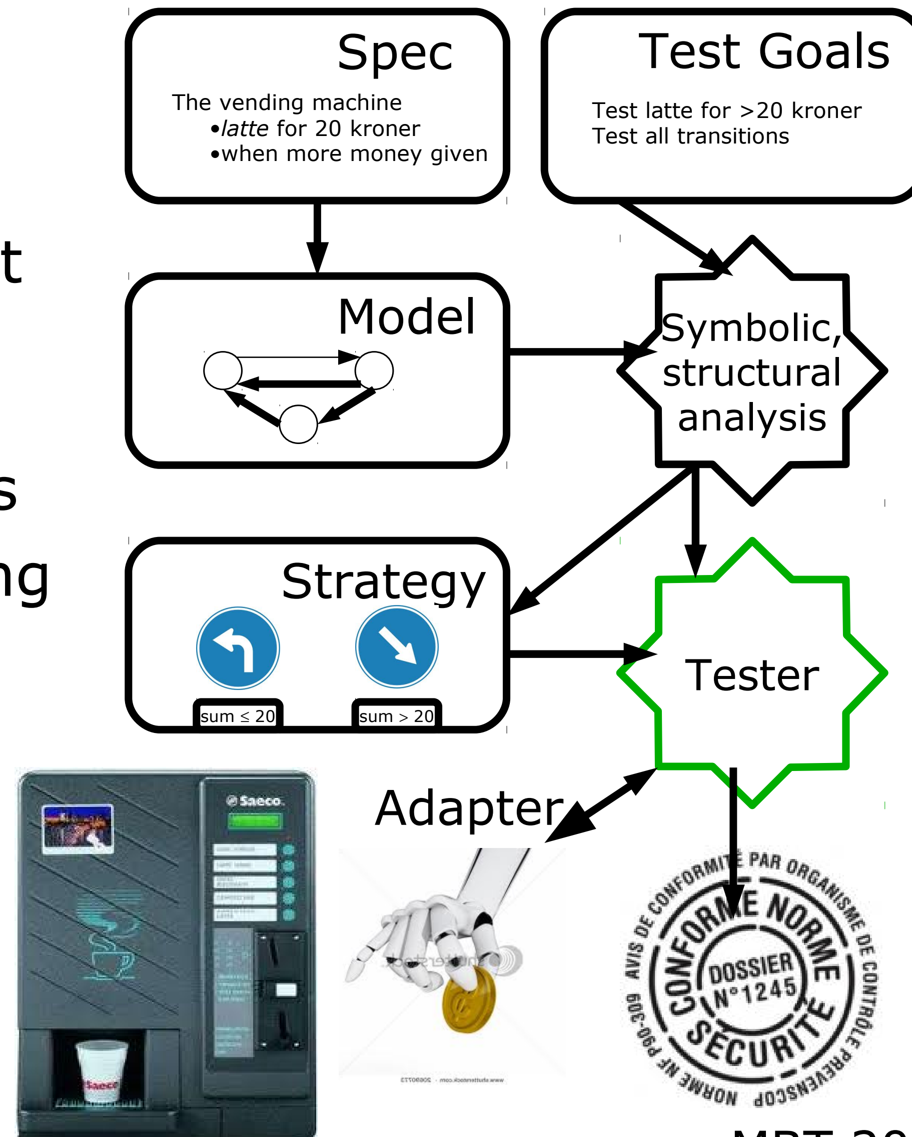
- Test cases cannot be prepared beforehand
- Tester must decide inputs during the test based on observed outputs and active goals
- Extensive test planning is costly and not feasible on-line
  - Industrial requirements: 10-100 ms for each step

Practical non-determinism

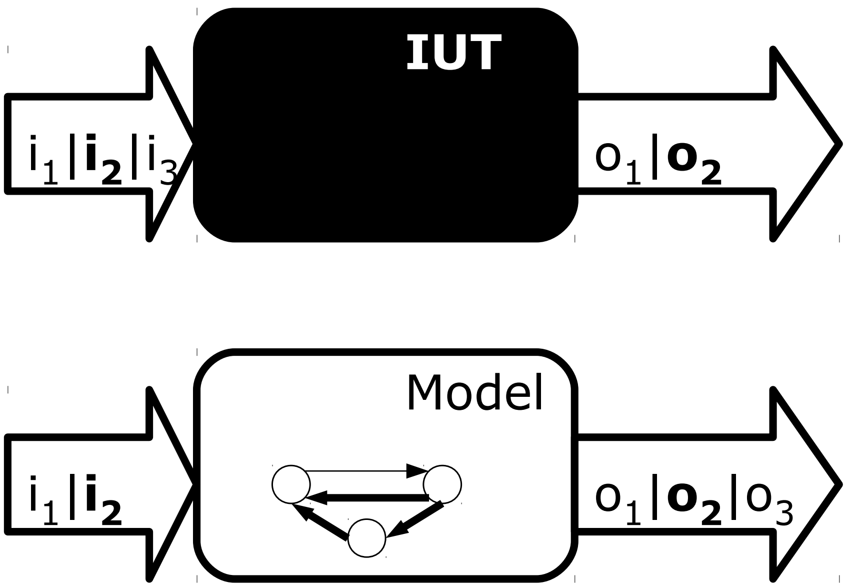
- output-observability – next state can be determined based on the given input and observed output

Talk Outline

- Introduction and background
- Preliminaries
  - Conformance and test coverage
  - Modelling of the system and test goals
  - RPT- Reactive Planning Tester
- χRPT – Heuristic RPT
- Case studies
- Conclusions



Conformance



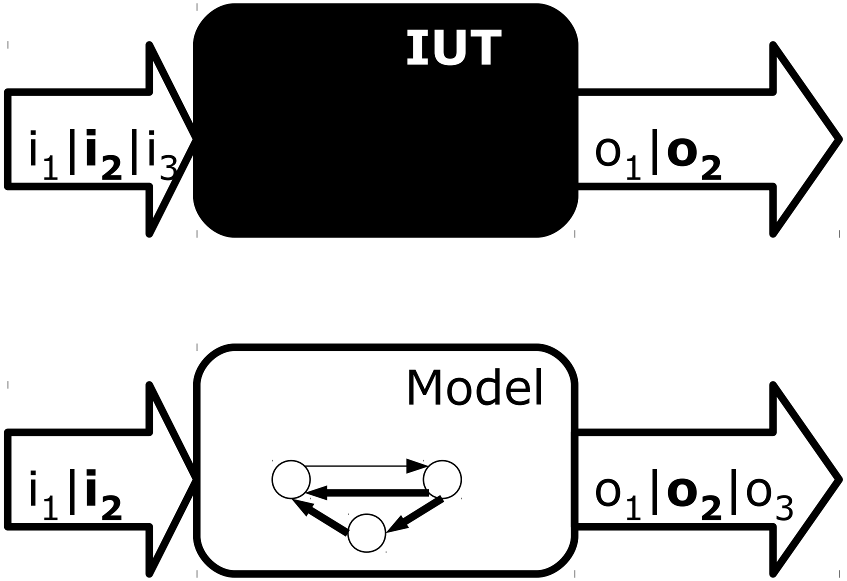
IOCO, alternating simulation:

- Every input of the model is acceptable by the IUT
- The resulting output is possible in the model

Hence:

- Only some aspects may be modelled
  - Some inputs (functionality) is not modelled
- IUT may be more deterministic
  - Spec/standard allows some freedom of implementation

Test coverage



while done?
  generate *input* possible in model
  output ← IUT(*input*)
  if *output* not possible in model
    return(test failed)
endwhile
return(test succeeded)

When to stop testing?

- Conformance
  - all inputs in all states resulting all possible outputs are covered
  - Infeasible/impossible to check all combinations for a general model
- Coverage
  - defined structural elements of the model are covered

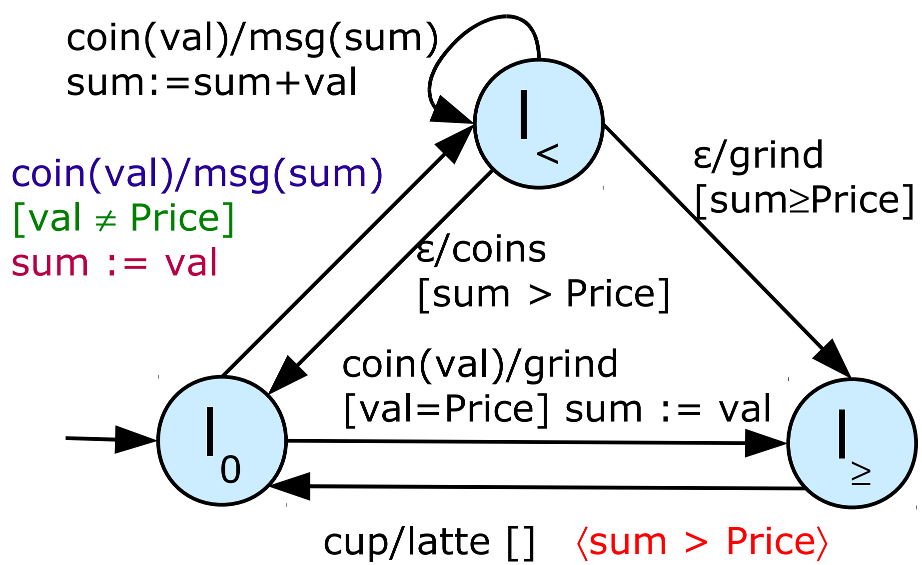
Modelling of IUT and test goals

- IUT is modelled by an **Input/Ooutput Extended Finate State Machines** (I/O-EFSM)
  - State space consists of locations and state variables
  - An edge (transition) has
    - input and output with its data parameters
    - guard
    - update function of the state variables

- **Background theory**
  - linear arithmetics
  - other theories possible

- Test goals modelled by ***traps***

  A trap is a ⟨predicate⟩ associated to an edge



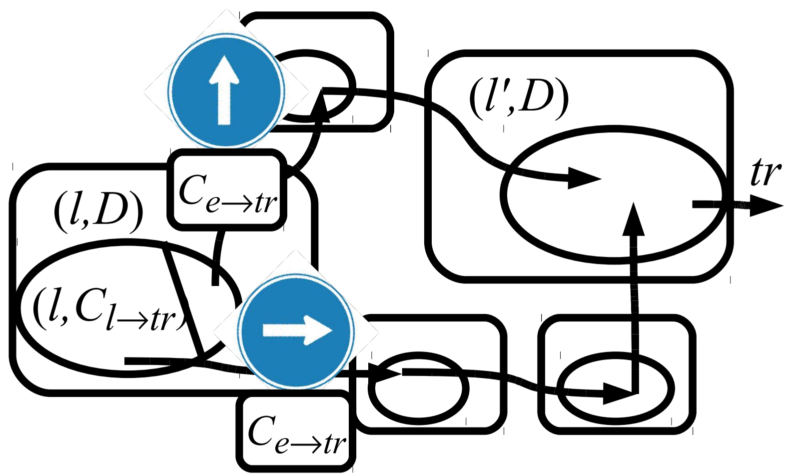
The power of traps

- A trap is a ⟨predicate⟩ associated to an edge
- Several goals can be expressed by traps
  - transition coverage:
    every edge has a trap *true*
  - transition sequence
    trap with reference to other traps
  - Advanced goals using auxiliary variables
    consequent transitions, repeated pass, …
- Properties not expressible by traps
  - Liveness properties
    but it is not possible to test for liveness anyway
  - Assertions/invariants – it never happens/always holds
    The model specifies only allowed behaviours
  - No LTL, CTL, but still quite powerful
    Many significant subsets can be modelled by aux variables

RPT – Reactive Planning Tester

- Offline symbolic test strategy generation
  - Based on backwards symbolic reachability analysis
  - Relates input and reachability of a trap
  - Predicates $\mathrm{Strategy}_{l \to trap}(I,S)$
    - l – location
    - I – input with its parameters
    - S – state (valuation of the state variables
- Online test data generation
  - next trap to be covered is selected
  - the strategy predicates are used to find an input

    by model generation using SMT solver
  - input is sent to the SUT and output observed

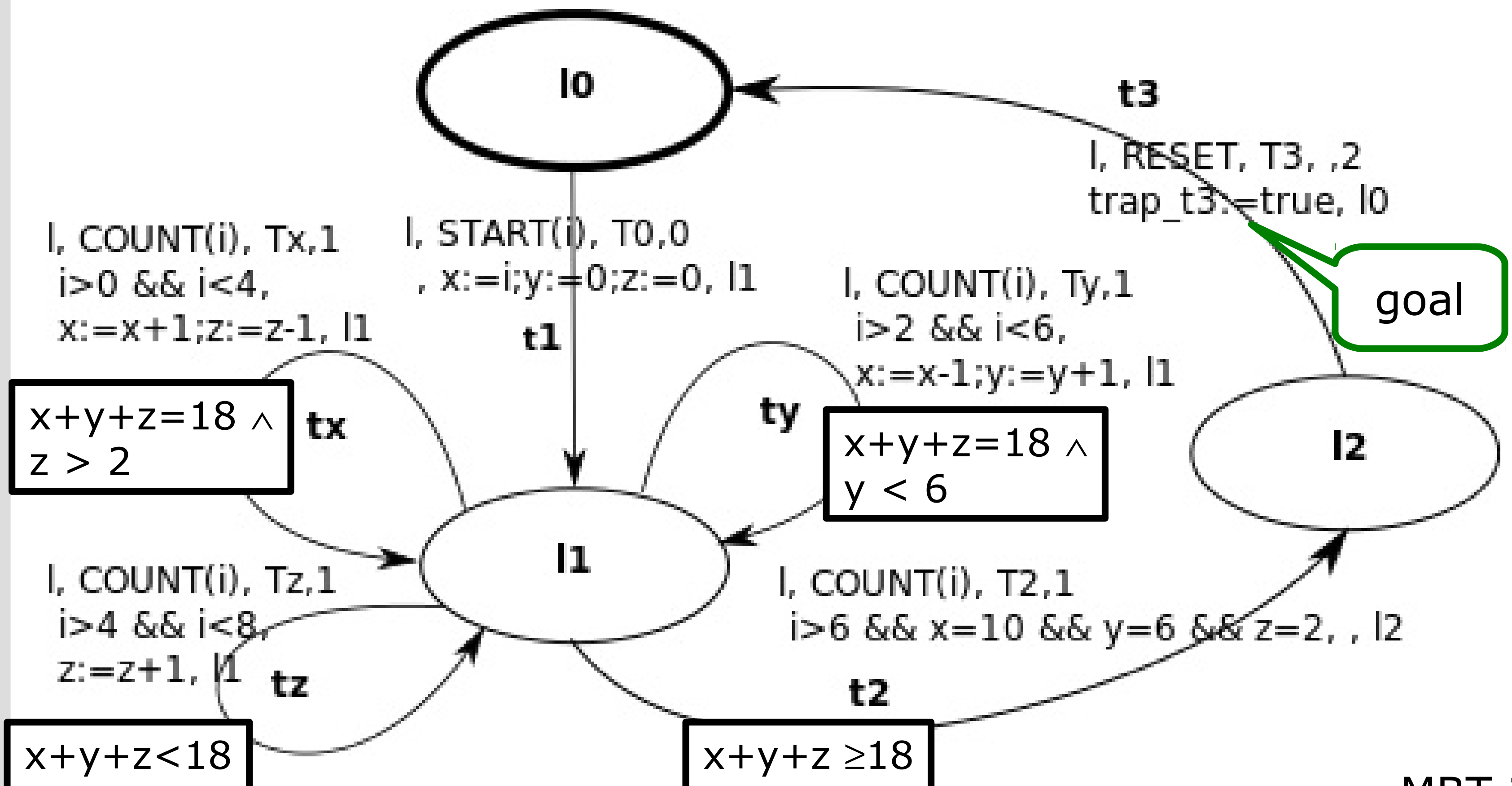


Testing process

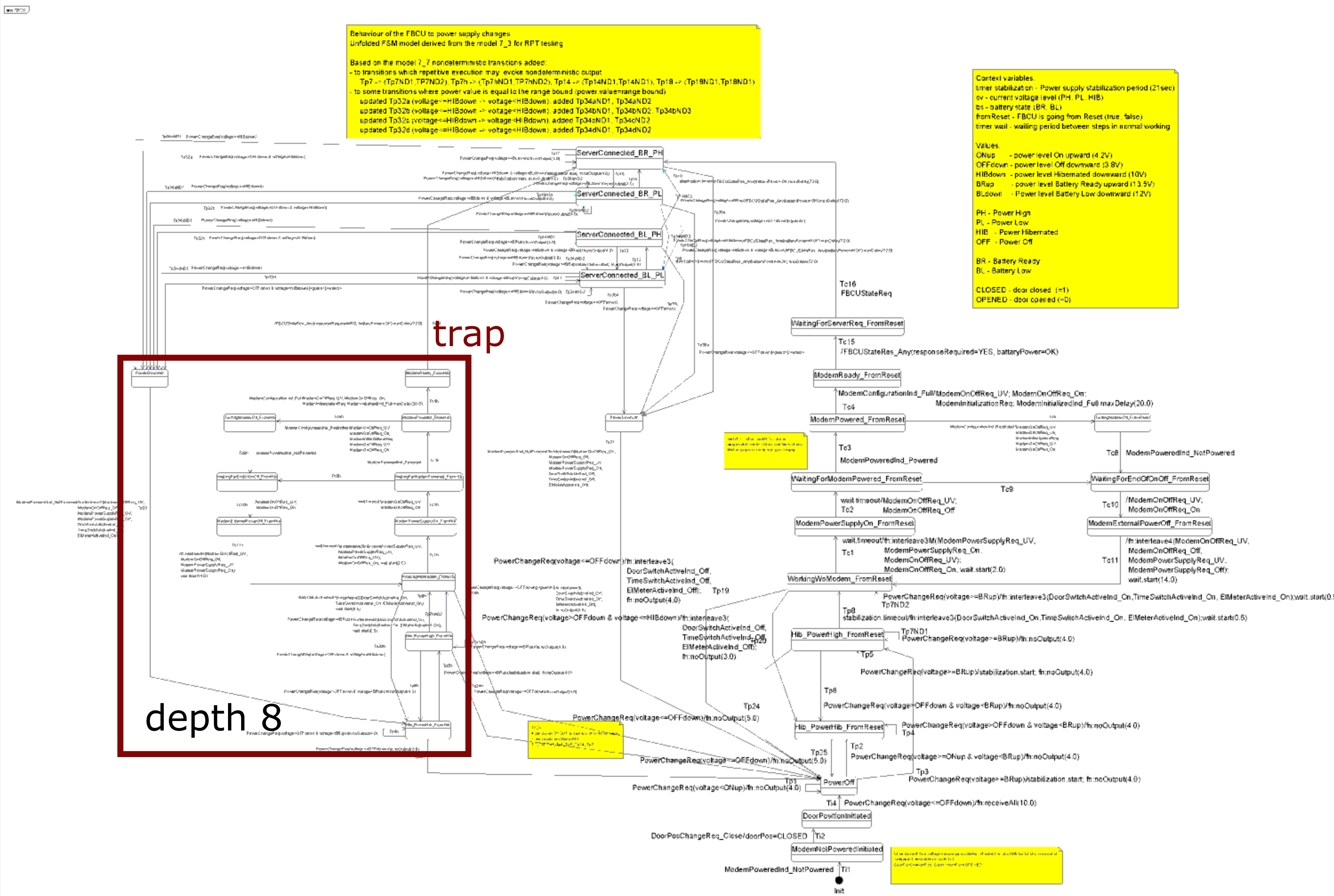
- Data generation based on the test strategy
  - should be done on-line for non-deterministic model
  - constraint solving / satisfying model generation used
- Several goals at the same time
  - Minimize the length of the overall testing process
  - Reset to the initial state may be expensive
    - Eg reboot of the SUT
  - The purpose is to cover as many test goals (traps) in one run as possible

Simple loop example

- Simple artificial example where the right sequence of inputs should be given to reach the goal

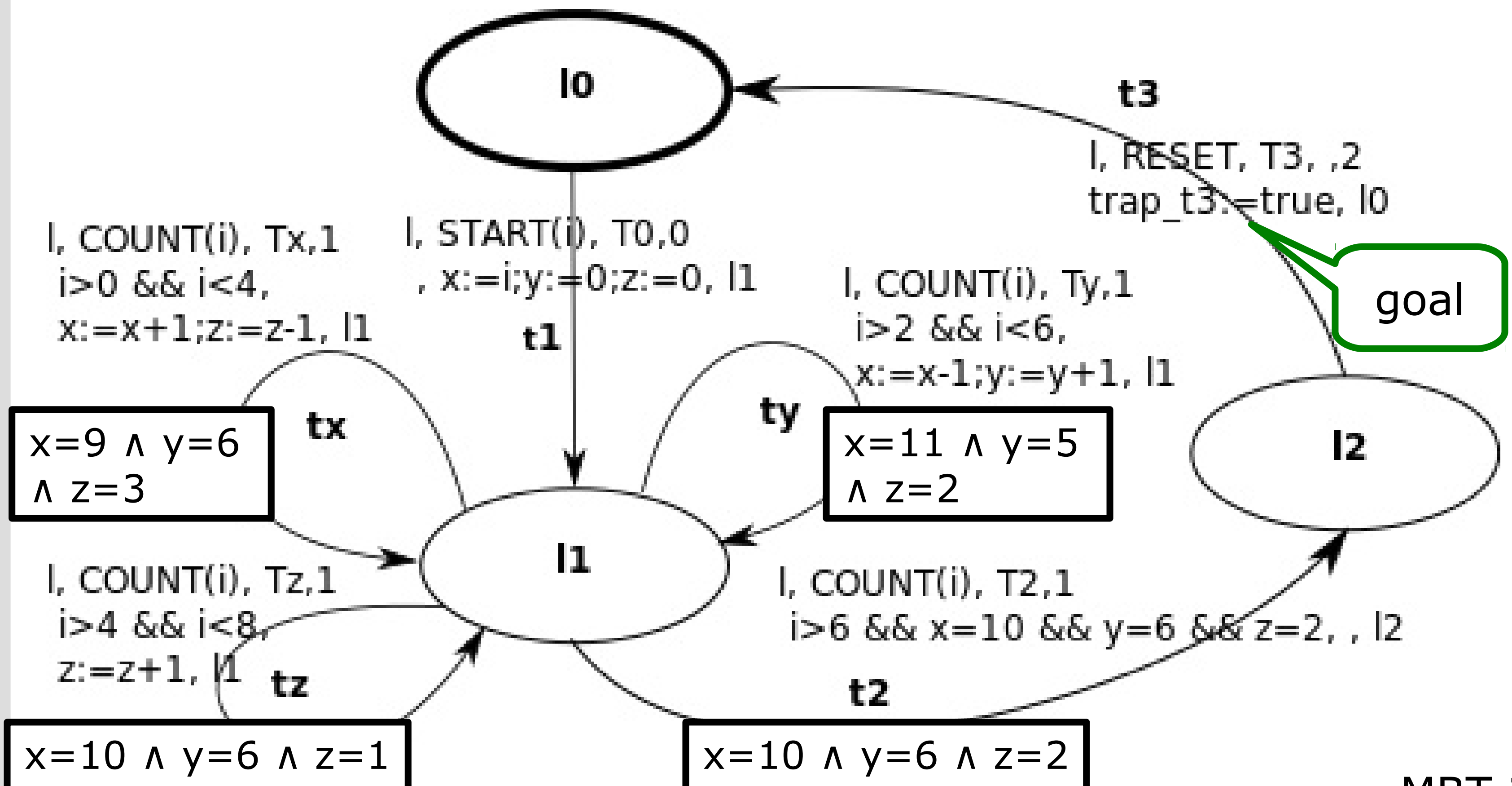


Bounded analysis



Bounded analysis of the simple loop example

- Constraints generated with bound (traversal depth) 2



χRPT- Heuristic Reactive Planning Tester

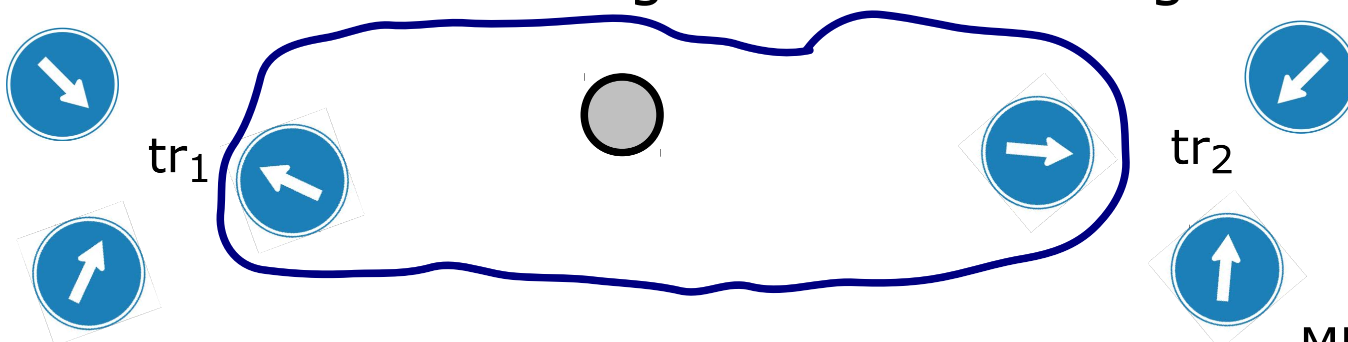
- Complementary to bounded strategy generation
  - Guides the testing process until a state is reached where a RPT strategy is applicable
- Uses an objective function to find an action that guides IUT towards some test goal
- Aims several goals (traps) at the same time to minimize the overall test time
- Based on the ideas of
  - forward, explicit state analysis
  - local search
  - tabu search

On-line test generation

```
while exist uncovered traps
    if RPT strategy exists in the current state for any uncovered trap
        RPT on-line testing
    else
        candidates ← Generate_Action_Candidates
        action ← Choose_Most_Promising_Action(candidates, tabu_list)
        output ← Interact_with_IUT(action)
        if the output of does not conform to the model
            stop(test_failed)
        simulate input/output on model and determine the next_state
        add next_state to the tabu_list
end while
stop(test_passed)
```

Search neighbourhood (candidates)

- Partitioning of the traps
  - **uncovered**
  - covered
  - unreachable
- Tabu lists
  - avoid the state that is explored already
- Closest locations with strategy constraints
  - a set of closest locations with strategy constraints for every pair of location and trap found off-line
  - these locations are the goals of heuristic guidance



Selecting tester action

- possible actions are simulated on the model and the result is evaluated using an objective function
- objective consists of
  - graph based distance between the simulated location and the location with a RPT strategy
  - violation degree of the RPT strategy constraint in the simulated state

$$f = dist^2 + viol^2$$

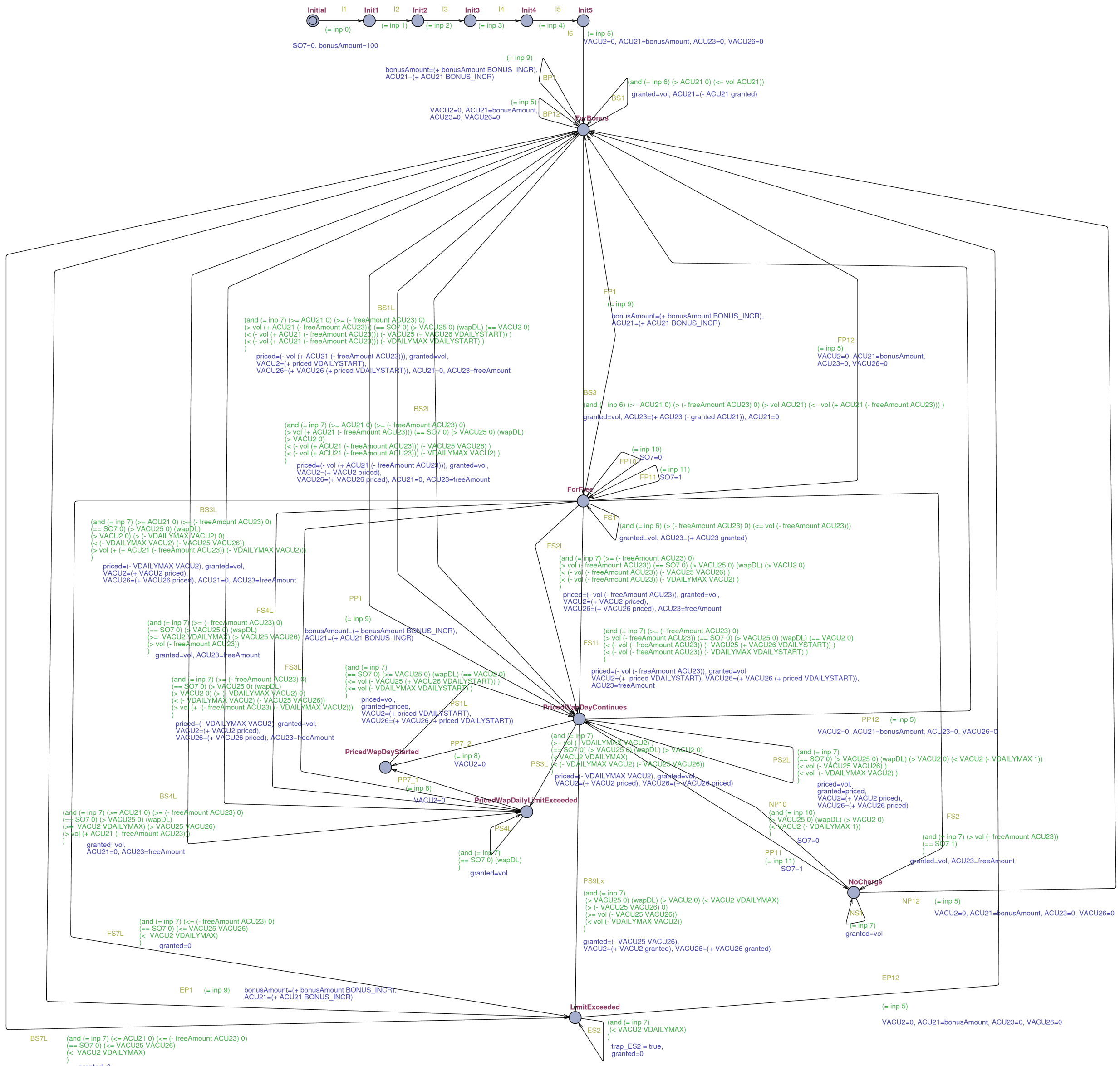
- Selection of the candidate actions narrowed in 3 phases
  - most promising actions optimized for the best input parameters and the best selected for the next step

Violation degree

- Measures how much the current state (valuation) violates some constraint
  - 0 if the constraint is satisfiable in the current state
  - >0 if not satisfiable

A, B – logical formulae, a, b – arithmetic expression	
$\nu(a \geq b) = abs(min(0, \nu(a) - \nu(b)))$	$\nu(a = b) = abs(\nu(s)\text{-}\nu(b))$
$\nu(a > b) = abs(min(0, -1 + \nu(a) - \nu(b)))$	$\nu(a \neq b) = abs(\nu(s)\text{-}\nu(b))$
$\nu(a < b) = abs(max(0, 1 + \nu(a) - \nu(b)))$	$\nu(A \vee B) = min(\nu(A), \nu(B))$
$\nu(a \leq b) = abs(max(0, \nu(a) - \nu(b)))$	$\nu(A \wedge B) = \nu(A) + \nu(B)$

Telecom Billing Case-Study



Telecom Billing Case-Study

- Model: 13 locations, 47 transitions
- 7 variables of range [0 .. 32000]
- Path length to trap from initial state: 189
- Size of ASCII representation of the strategy: 34MB
- Time for test generation (symbolic analysis + input) [1 GHz Opteron]

Strategy generation path length (time (s))	189 (4644)			
Bounded strategy depth (time (s))	100 (2120)	50 (1086)	10 (95)	2 (16)
Heuristic test data path length (time (s))	230 (6,7)	255 (17,4)	275 (17,0)	1051 (153,4)
Avg test data gen (ms)	51	84	63	146

Complexity issues

- Constraints limited to decidable theories
  - linear arithmetic (+ others supported by solvers)
- Theoretical limits
  - SAT problem is NP-complete
  - decision procedure of Presburger arithmetic is double-exponential
- Practical aspects
  - number of constraints is in O(traps*transitions)
  - Z3 does a good job in satisfiability checking and simplification in strategy generation
  - Comet used for constraint solving and violation degree calculation in χRPT
- Balancing complexity of the strategy and on-line data generation
  - feasibility can be achieved by tuning the balance

Main results

- Model-based conformance testing framework for non-deterministic I/O-EFSM models
- Computationally expensive strategy generation and neighbourhood analysis done off-line
- Efficient on-line test planning
  - selection of input for each step in 10-100 ms range
  - usable in the industrial setting