FSM-based test derivation methods: From TAROT-1 to TAROT-12

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TAROT 1

TAROT (**Training And Research On Testing**) is a Marie Curie Research Training Network (MCRTN).
It focuses on the protocols, services and systems testing, that is an essential but empirical and neglected domain of validation and Quality of Service (QoS).
Then the TAROT network aims to strengthen and develop the collaboration among major European testing communities.
Moreover TAROT will promote testing in education, research, software engineering and industry.
In order to achieve this objective, the participants will provide training courses, including Ph.D. programs and summer schools.
In addition, workshops will be organized, thanks to which the TAROT network will communicate its results, and maybe find other partners.

...Welcome

Ana Cavalli, coordinator of TAROT

TAROT 2005

TAROT -1 has been held in Paris in 2005

Was an event of big success

Participants agreed to have the annual Summer TAROT School

It is the 12th Summer TAROT School now

At each Summer school a lot of attention has been paid to test derivation based on transition models and this School inherits this tradition

Outline

- *FSM based test derivation: Why FSMs?*
- *Test models for FSMs*
- White box
- Black box: W-methods and its derivatives
- Grey box
- *Deriving tests for complete deterministic FSMs*
- Initialized FSMs: W-method and its derivatives
- Non-initialized FSMs: Checking sequences
- *Partial and nondeterministic FSMs: Reducing the complexity of test derivation*
- Adaptive testing
- Using appropriate projections
- *Extended and Timed FSMs*
- *Conclusions*

Debugging problem

A fragment of C code

```
…
{
unsigned char n1, n2, v;
//initialize n1, n2
v = n1 + n2;
return v;
}
```

Is this code safe?

How to check that $v = n1 + n2$ is not bigger than 255?

Otherwise, the result will be wrong

150 + 150 = 300 (mod256) = 44

Conformance testing

```
int f(int *a, int size_a)
{
int i, m;
i = 0;
m = a[0];
while(i < size_a)
{
if(m < a[i]) m = a[i];
i++;
}
return m;
}
```

The function returns the maximal integer in the array *a* where *size_a* is the dimension of *a*

How to check that the function is correctly implemented?

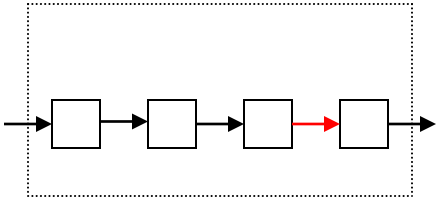
How many arrays should be checked?

Is it enough to check all the arrays of dimension 3?

Hardware testing (shift register)

There is no link →

How to check?



Starts at 0000

It is not enough to apply all input sequences of length 3

An input sequence 1*** of length > 3 has to be used

How to check this fact?

Model based test derivation

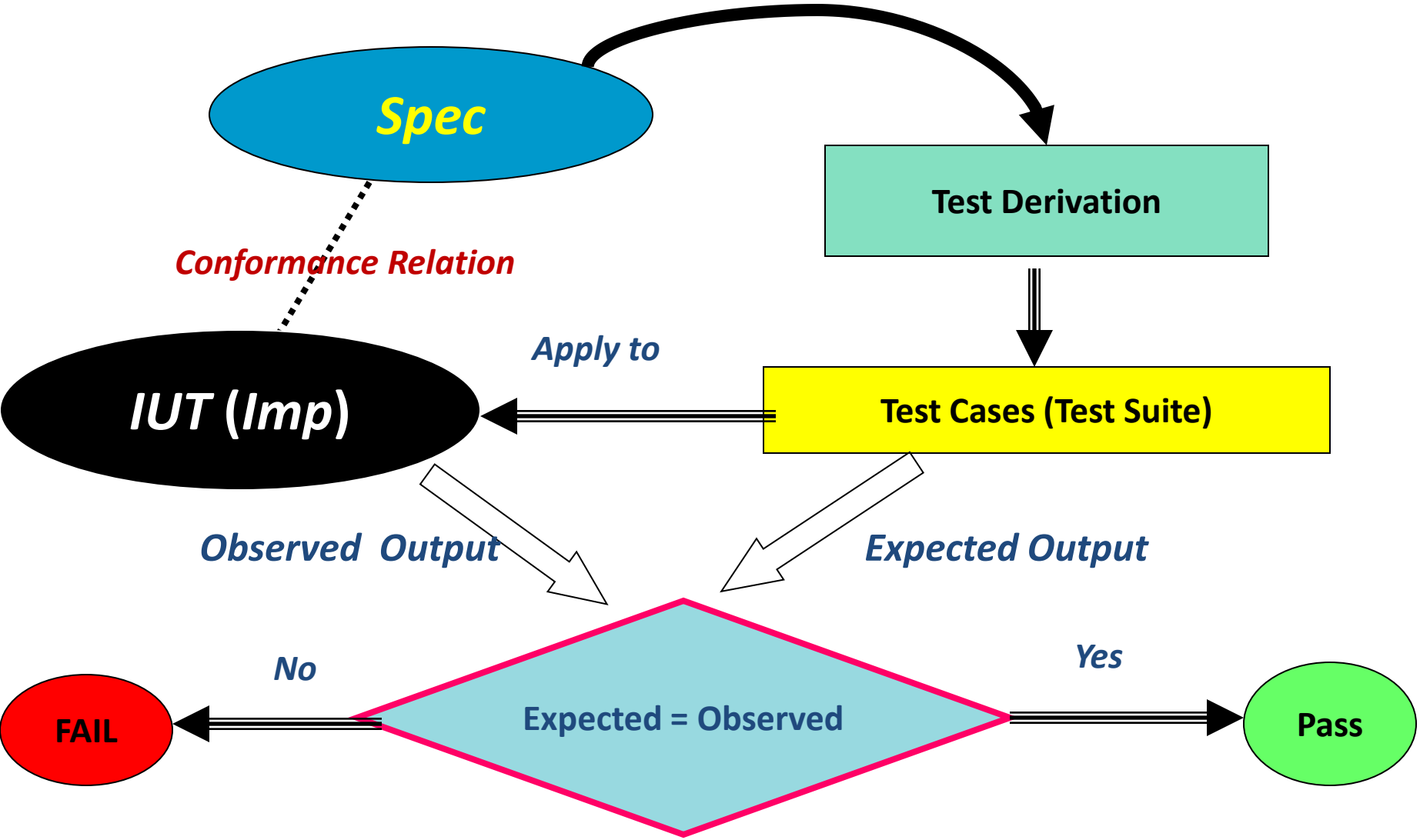
- Solution: to use transition systems as formal models for deriving tests

Question: What can be applied and what can be observed

We assume that

- Inputs can be applied
- Output actions can be observed
- A system moves from state to state under inputs and produces outputs
- States cannot be observed

Conformance Testing



Finite automata and FSMs: why FSMs

I/O automata

Advantages

- Can have infinite number of states, inputs and outputs
- Each transition corresponds to an input or an output or to a non-observable action, i.e., an output can be produced to a sequence of inputs
- A complete test suite is derived from a complete successor tree

Disadvantages

- Complete tests are infinite while testing time is finite
- Still there is a problem with distinguishing sequences when *Imps* are explicitly enumerated
- Races between inputs and outputs

FSMs

Disadvantages

- Finite number of states, inputs and outputs
- Each transition corresponds to a pair ‘input/output‘
- No non-observable actions
- A complete test is derived with respect to a given fault model

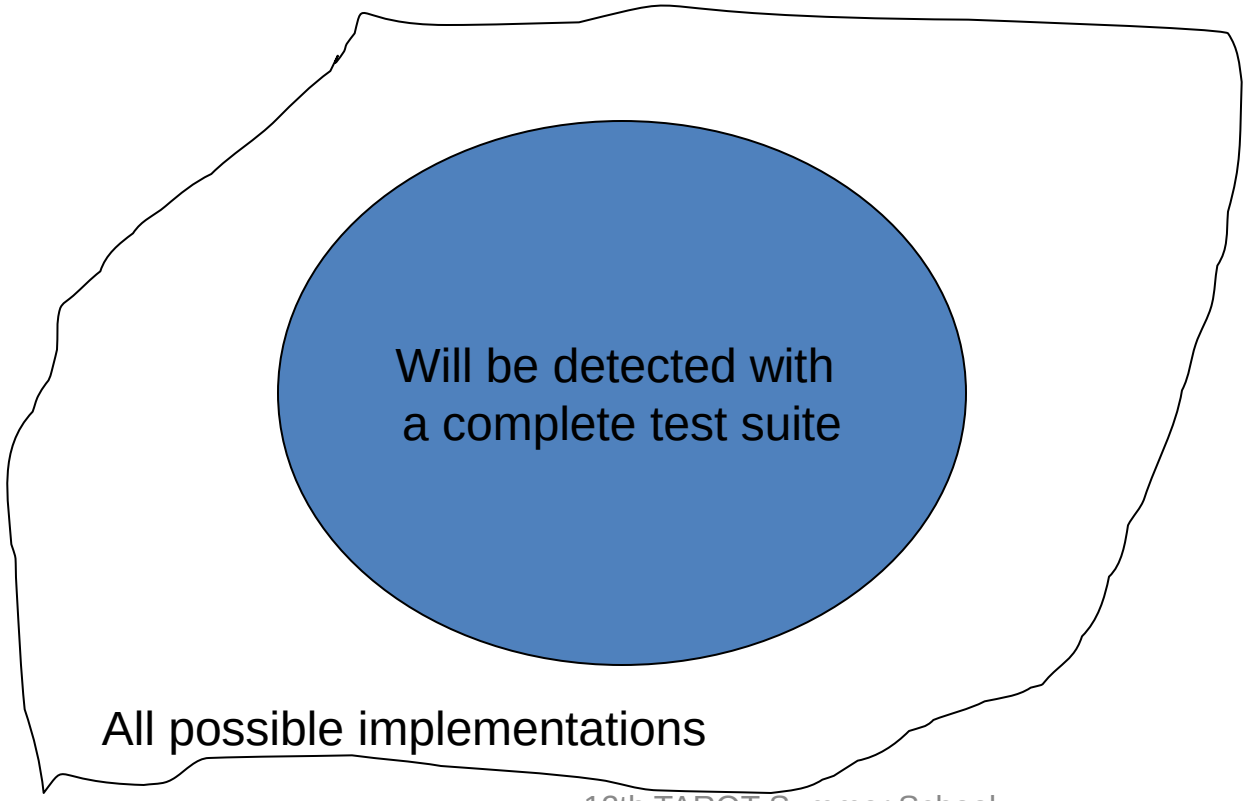
Advantages

- Finite tests with the guaranteed fault coverage
- Good background for deriving distinguishing sequences
- No races between inputs and outputs: next input is applied after receiving the output to the previous input

In both cases, IUT is input enabled

Limiting the number of *Imp* states

! All faulty *Imp*s within  and possibly much more are detected

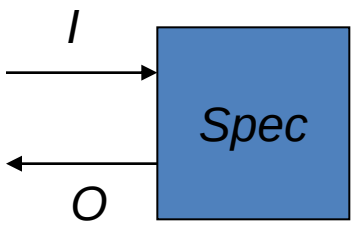


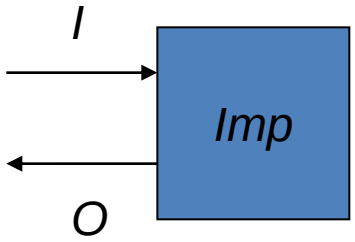
FSM based test derivation

Extract:

- A Formal FSM Specification ***Spec*** (requirements) of the System
- Formally describe a set of faulty implementations

Derive a finite set of finite input sequences (*Test Suite*) such that after applying them to IUT we can guarantee that ***Imp*** conforms to ***Spec***





- **Conforms: has many definitions depending on the Formal Specification**

Fault model in Conformance Testing

$< Spec, \mathcal{R}, FD >$

Formal Specification

Conformance relation

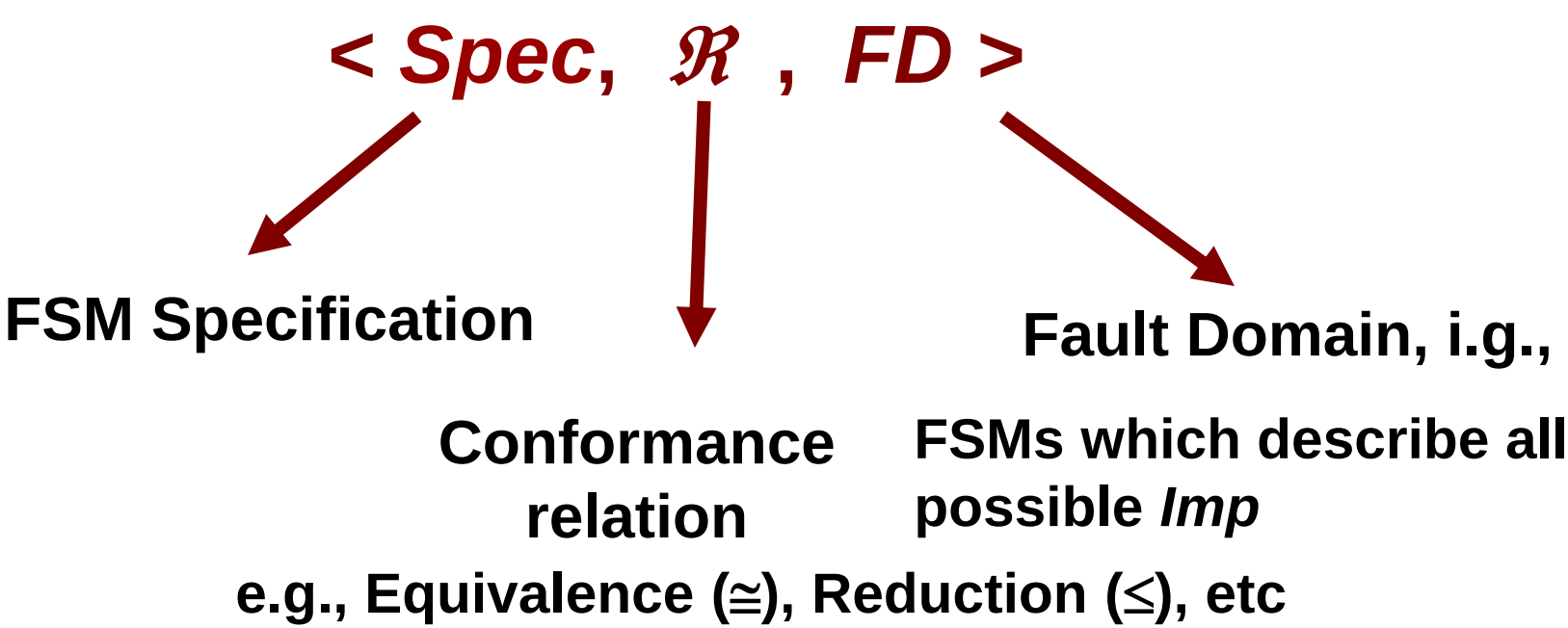
Fault Domain, i,e.

All Faulty Implementations (explicitly or implicitly described)

Guaranteed Fault Coverage:

A complete test suite w.r.t. <***Spec***, $\mathcal{R}$, *FD*> has to detect each ***Imp*** $\in$ *FD* such that *Imp* does not conform (i.e., not equivalent, not reduction, etc) to ***Spec***

FSM Model in Conformance Testing



Guaranteed Fault Coverage:

A *complete* test suite w.r.t. <***Spec***, $\mathcal{R}$, *FD*> has to detect each FSM ***Imp*** $\in$ *FD* such that *Imp* does not conform (i.e., not equivalent, not reduction, etc) to ***Spec***

FSMs (Finite State Machines)

Fault models for initialized complete deterministic FSMs

Complete test suites

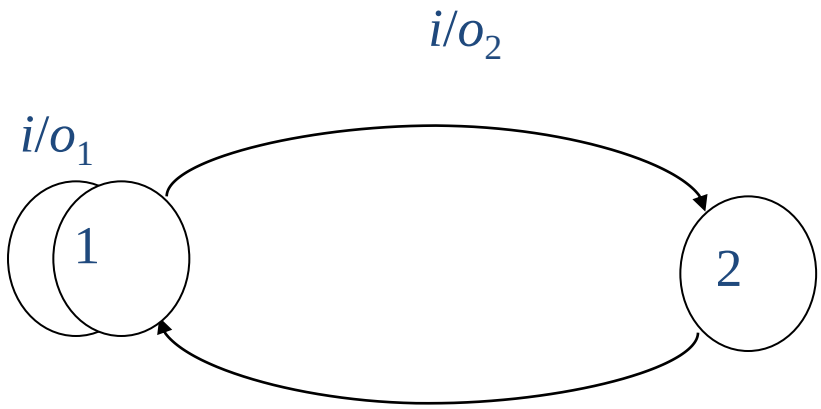
Fault models for non-initialized complete deterministic FSMs

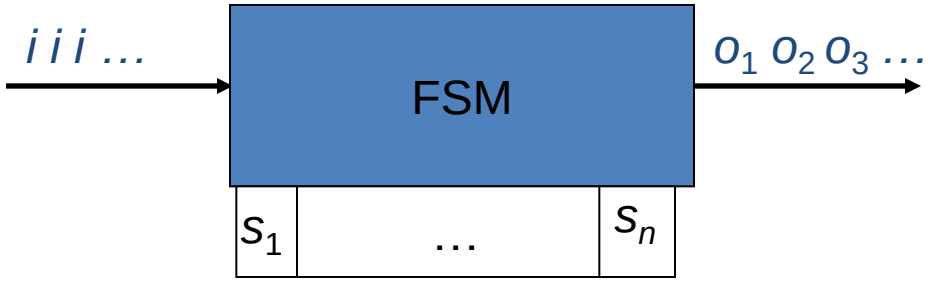
Checking sequences

Finite State Machine (FSM)

$\mathcal{S} = (S, I, O, h_S)$ is an FSM

- S is a finite nonempty set of states with the initial state s_0
- I and O are finite input and output alphabets
- $h_S \subseteq S \times I \times O \times S$ is a behavior relation

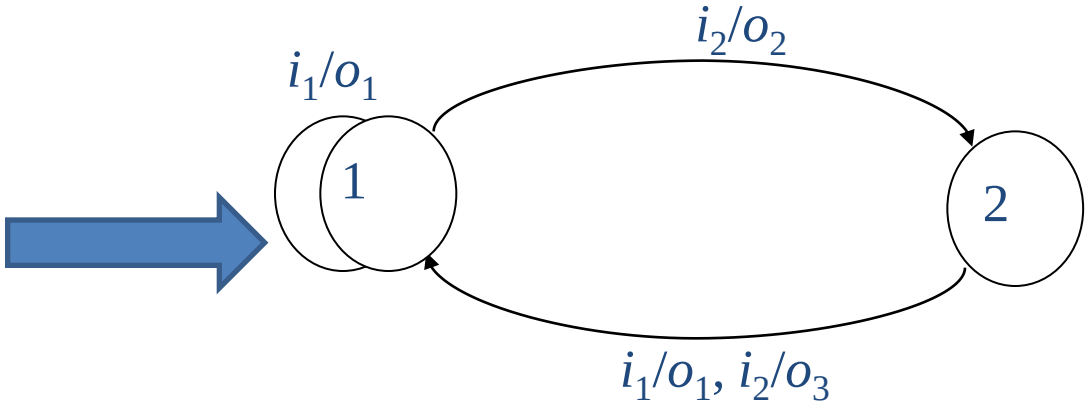




FSM $\mathcal{S} = (S, I, O, h_S)$ can be

- *deterministic* if for each pair $(s, i) \in S \times I$ there exists at most one pair $(o, s') \in O \times S$ such that $(s, i, o, s') \in h_S$
  otherwise, $\mathcal{S}$ is *nondeterministic*
- *complete* if for each pair $(s, i) \in S \times I$ there exists $(o, s') \in O \times S$ such that $(s, i, o, s') \in h_S$
  otherwise, $\mathcal{S}$ is *partial*
- *initialized* if there is the initial state s_1 otherwise,
  otherwise, $\mathcal{S}$ is *non-initialized*

This one is non-initialized, complete and deterministic



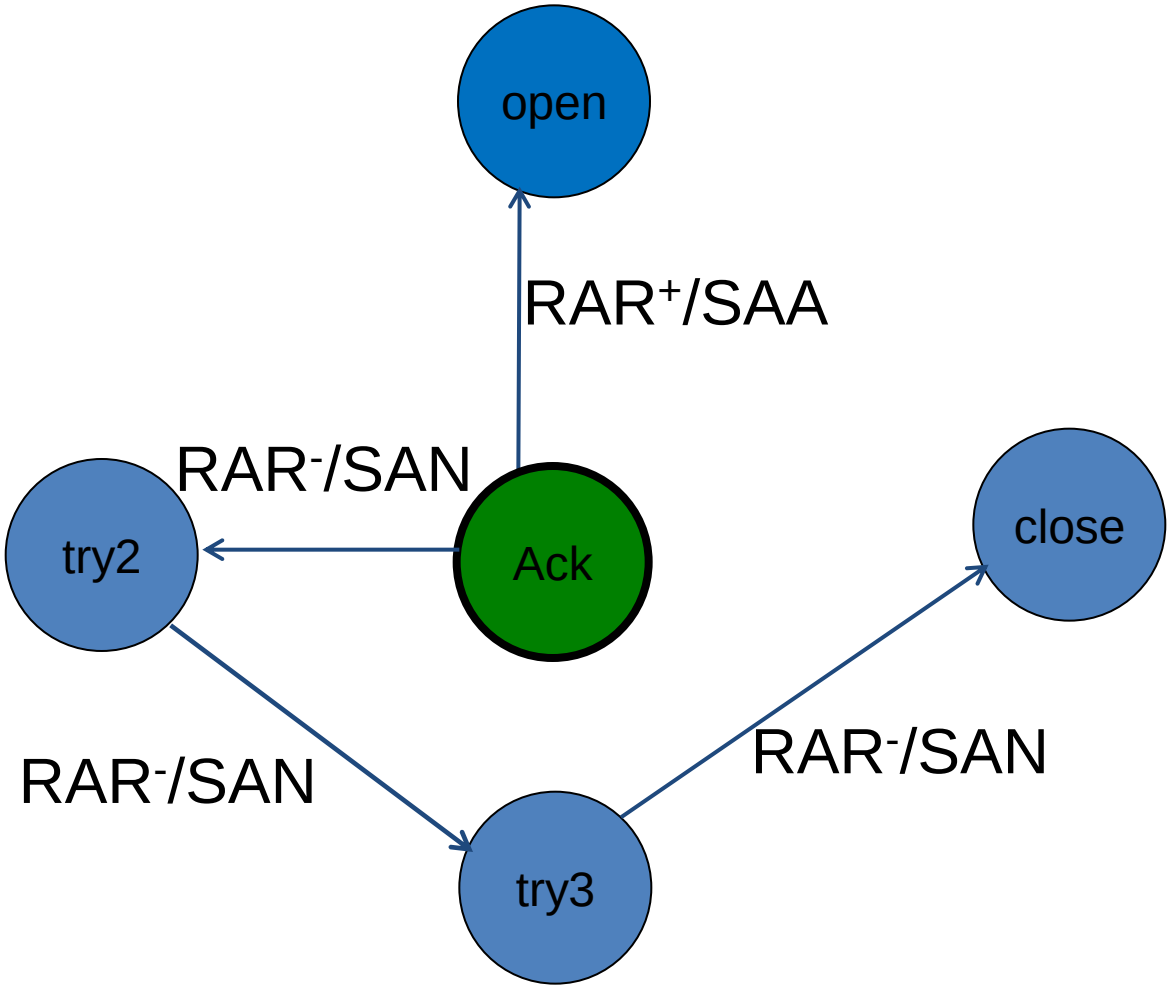
One of FSMs for PAP (Password Authentification Protocol)

RAR^{+} - «good» login

RAR^{-} - «bad» login

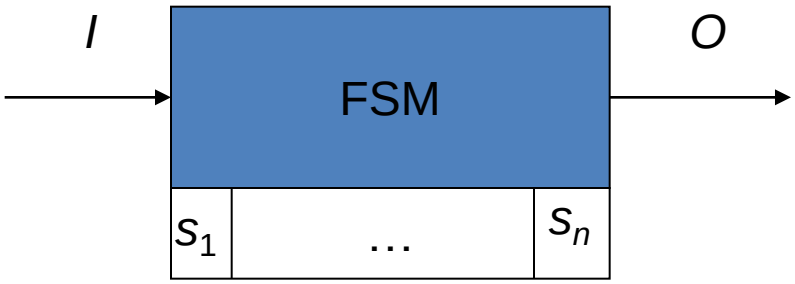
SAA - Ack

SAN – Nack



Complete deterministic FSMs

Deterministic complete FSM is a 5-tuple $(S, I, O, \delta_S, \lambda_S)$



S is a finite set of states with the initial state s_1
I is a finite non-empty set of inputs
O is a finite non-empty set of outputs

transition function $\delta_S(s, i)$
output function $\lambda_S(s, i)$

(s, i, o, s') is a transition from state s under input i to state s' with the output o if $\delta_S(s, i) = s'$ and $\lambda_S(s, i) = o$

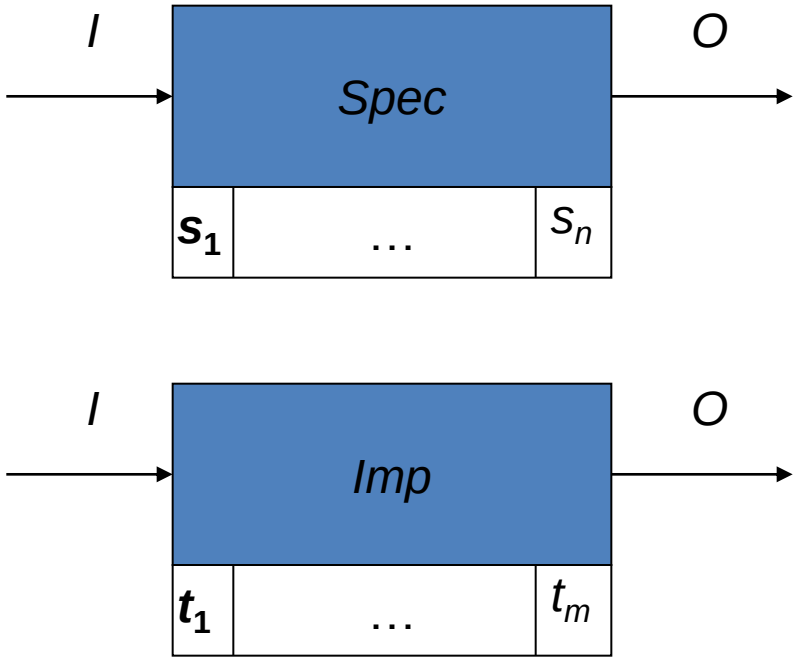
! At each state for each input sequence there is a single output sequence

Equivalence relation between initialized complete deterministic FSMs

FSMs *Imp* and *Spec* are *equivalent* if their output responses to each input sequence coincide

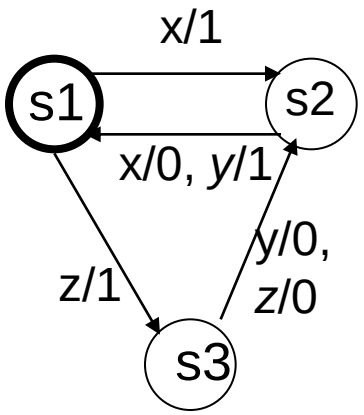
Caution: Number of input sequences is infinite, while we can apply only finite number of input sequences when testing the conformance

Equivalent FSMs have the same set of traces



Reduced FSM

A complete deterministic FSM is *reduced* if every two different states are not equivalent



FSM is reduced
Separating sequences:
$\gamma(s1, s2) = x$
$\gamma(s2, s3) = y$
$\gamma(s1, s3) = z$

For each deterministic complete FSM there exists a reduced FSM with the same Input/Output behavior, i.e., a reduced FSM with the same set of traces

Conclusion: we can consider only reduced specification FSMs

Test derivation for initialized FSMs

Fault model - <***Spec***, ≅ , *FD*>

Spec is a complete deterministic reduced FSM

FD – fault domain that contains complete deterministic FSMs, possibly with more states

⇓

- *Output* faults
- *Transfer* faults
- Implementation has *more* states and transitions

! Reliable reset is assumed

Fault model

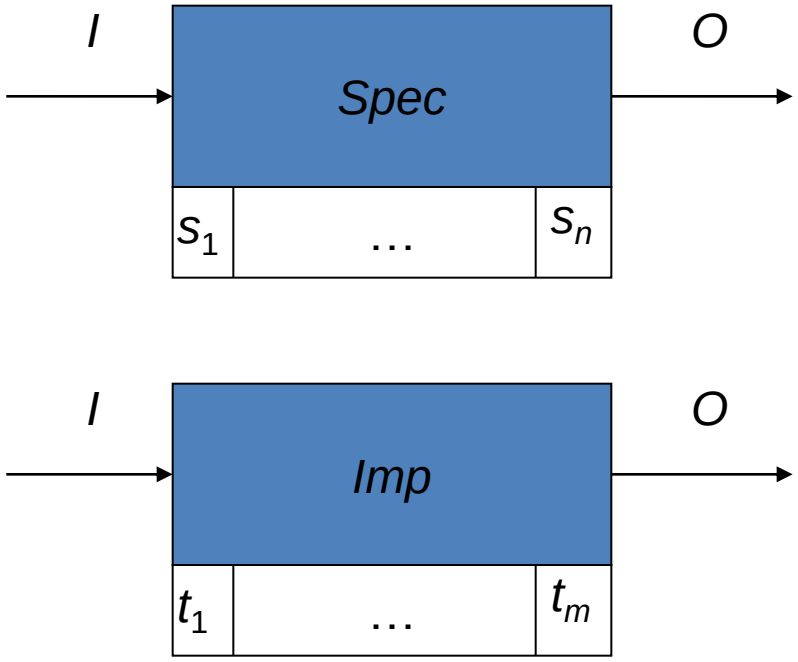
< Spec, ≅ , FD >

Spec – the initialized specification FSM with *n* states

! Usually *Spec* is a complete deterministic reduced FSM

***FD* is the fault domain that contains each FSM that describes each possible IUT that is complete and deterministic**

Equivalent FSMs have the same set of traces



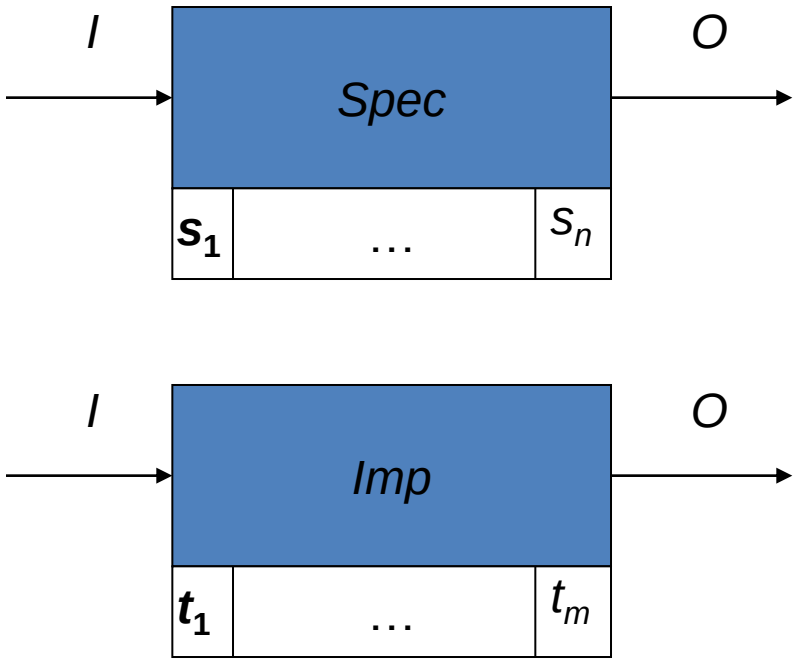
Test Suite

A *test case* is a finite input sequence of the specification FSM *Spec.* A *test suite* is a finite set of test cases

We assume that each implementation FSM *Imp* has a reliable reset *r* that takes the *Imp* from each state to the initial state

Each test case in the test suite is headed by *r*, i.e. is applied to *Imp* at the initial state

Specification and implementation FSMs



Complete test suite

Fault domain *FD* - the set of FSMs that describe all possible faults when implementing the specification:

$$FD = \{Imp_1, \ldots, Imp_n, \ldots\}$$

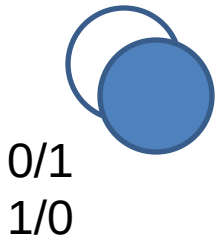
A test suite *TS* is *complete* w.r.t. *FD* if *TS* detects each FSM $Imp \in FD$ that is not equivalent to Spec

! If the fault domain contains each FSM over alphabets *I* and *O* and *Spec* is complete and deterministic then there is no complete test suite w.r.t. such fault domain

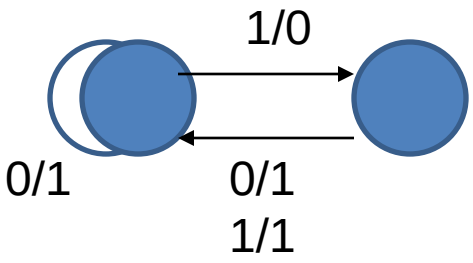
Example

Inverter

FSM Spec with a single state



FSM Imp with two states



Complete tests

- Complete test when *Imp* has a single state

{01} or {10}

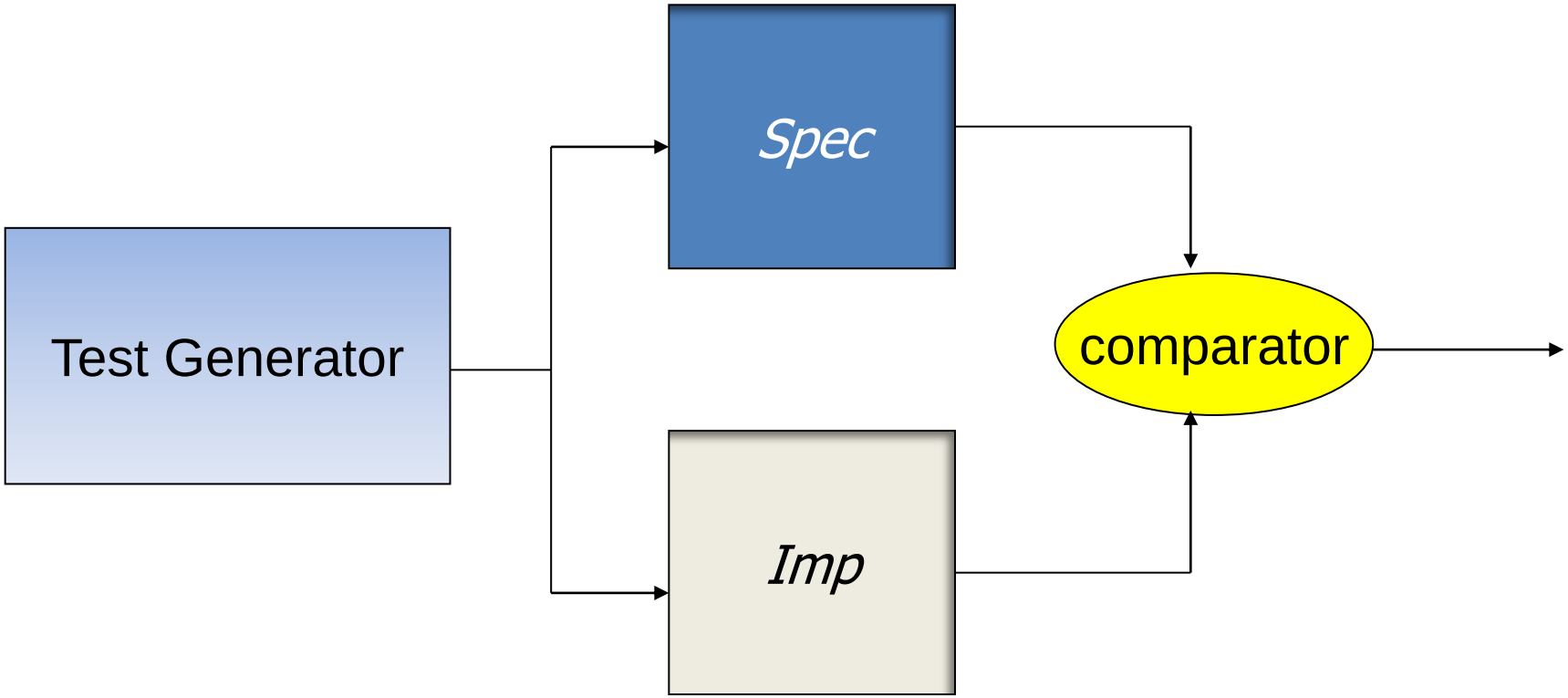
- Complete test when *Imp* has at most two states

{01, 10, 00, 11}

! Nothing can be deleted

Conclusion: a complete test significantly depends on the number of states of Imp

Test architecture



Conformance relation – the *equivalence*

Deriving FSM based tests

Test assumptions

• We can ‘build’ a complete deterministic FSM that simulates a faulty implementation

• There can be faults of three types:

-Transition faults

- Output faults

- New faulty transitions can be added

• When testing we can only apply input sequences and observe output sequences

! Sometimes states also can be observed but we do not discuss such testing

FSM based test models

- White box (explicit enumeration)
- Black box (the IUT structure is unknown: possibly the upper bound on the number of the IUT states is available)
- Grey box (the IUT structure is partly available)

Explicit enumeration (white box testing)

Explicit enumeration can be used when the number of mutants of *Spec* is not big

Faults are explicitly enumerated

Advantage: Easy to implement

Disadvantage: Cannot be applied when the number of faults (the number of mutants) is huge

Check whether *Spec* and *Imp* are equivalent

$Spec \cap Imp$

If $Spec \cap Imp$ is not complete then derive a distinguishing sequence (a *test case* that kills a faulty *implementation Imp*)

Methods for deriving distinguishing sequences for two deterministic FSMs are well elaborated

Distinguishing sequences for two FSMs

If *Spec* ∩ *Imp* is not complete

then derive an input sequence α to reach a state with an undefined input *i*

The sequence α is a *distinguishing* sequence

If *Spec* has *n* states while *Imp* has *m* states then

the length of α is at most $m + n - 1$ (despite the fact that the product *Spec* ∩ *Imp* can have up to *mn* states)

! Other methods for deriving a distinguishing sequence can be used

Black box testing

- An implementation FSM under test is not known

- Tests are derived based on the specification FSM

Question: What can be guaranteed in this case?

Reply: If nothing is known about the FD then a complete test suite cannot be derived (Moore, 1956, Gill, 1964)

The set FD should be finite and the weakest assumption is that the upper bound on the number of states of an implementation FSM is known

Most popular test derivation methods for black box testing

- Transition tour (guaranteed killing output faults)

Transition tour is a set of input sequences that traverse each transition of the specification FSM

- W-method and its derivatives (guaranteed killing output and transfer faults)

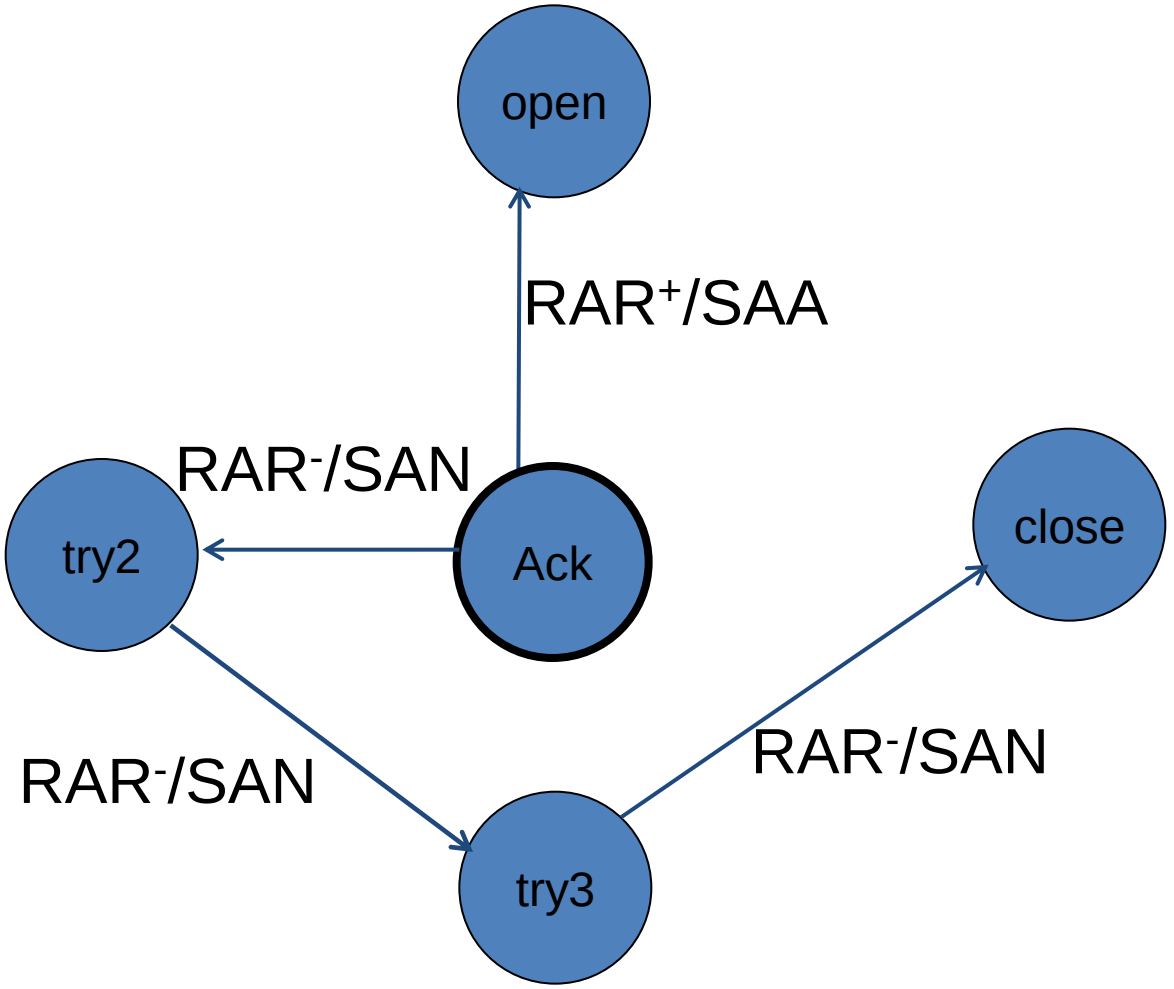
One of FSMs for PAP

RAR^{+} - «good» login

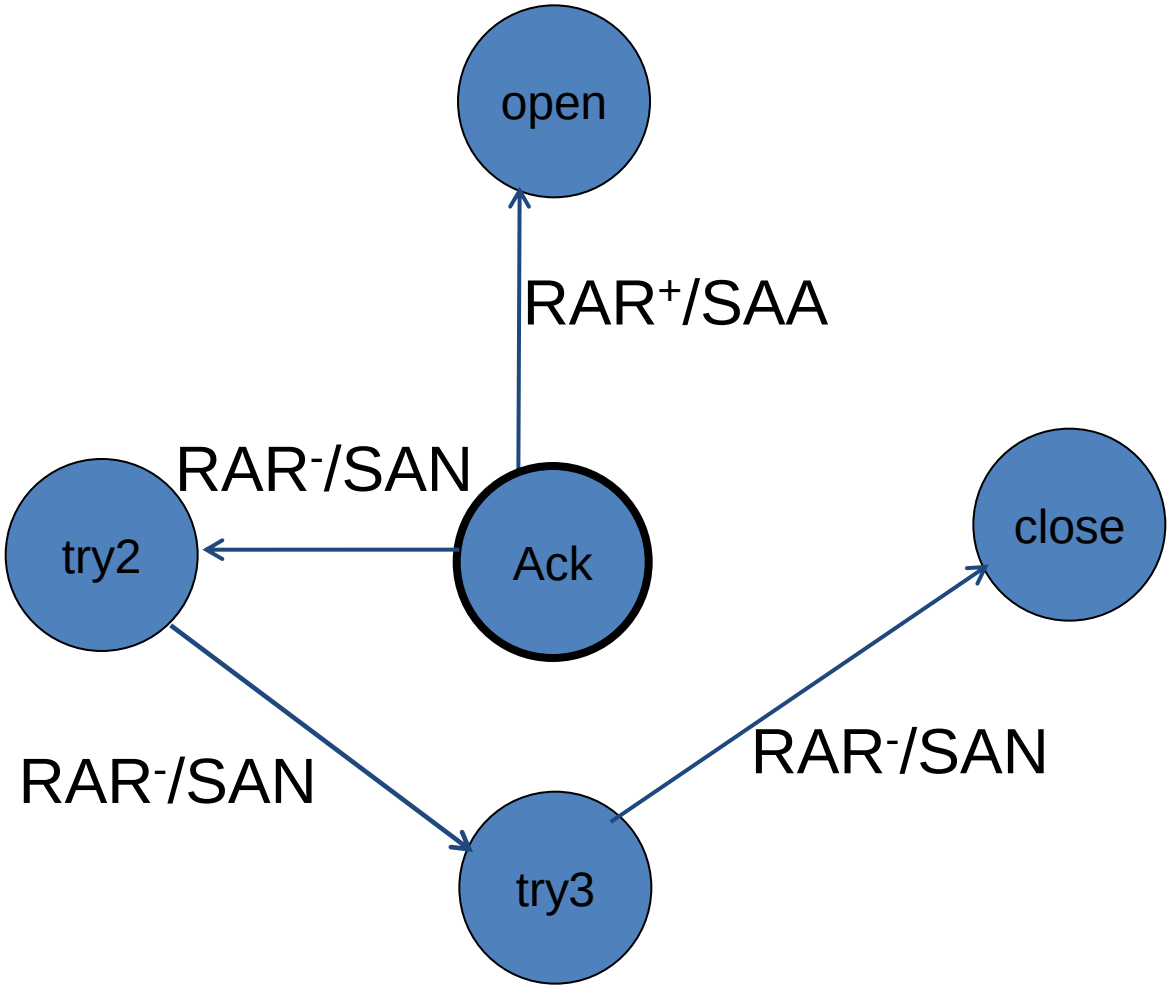
RAR^{-} - «bad» login

SAA - Ack

SAN – Nack



Transition tour for the PAP model



Test suite:

RAR+

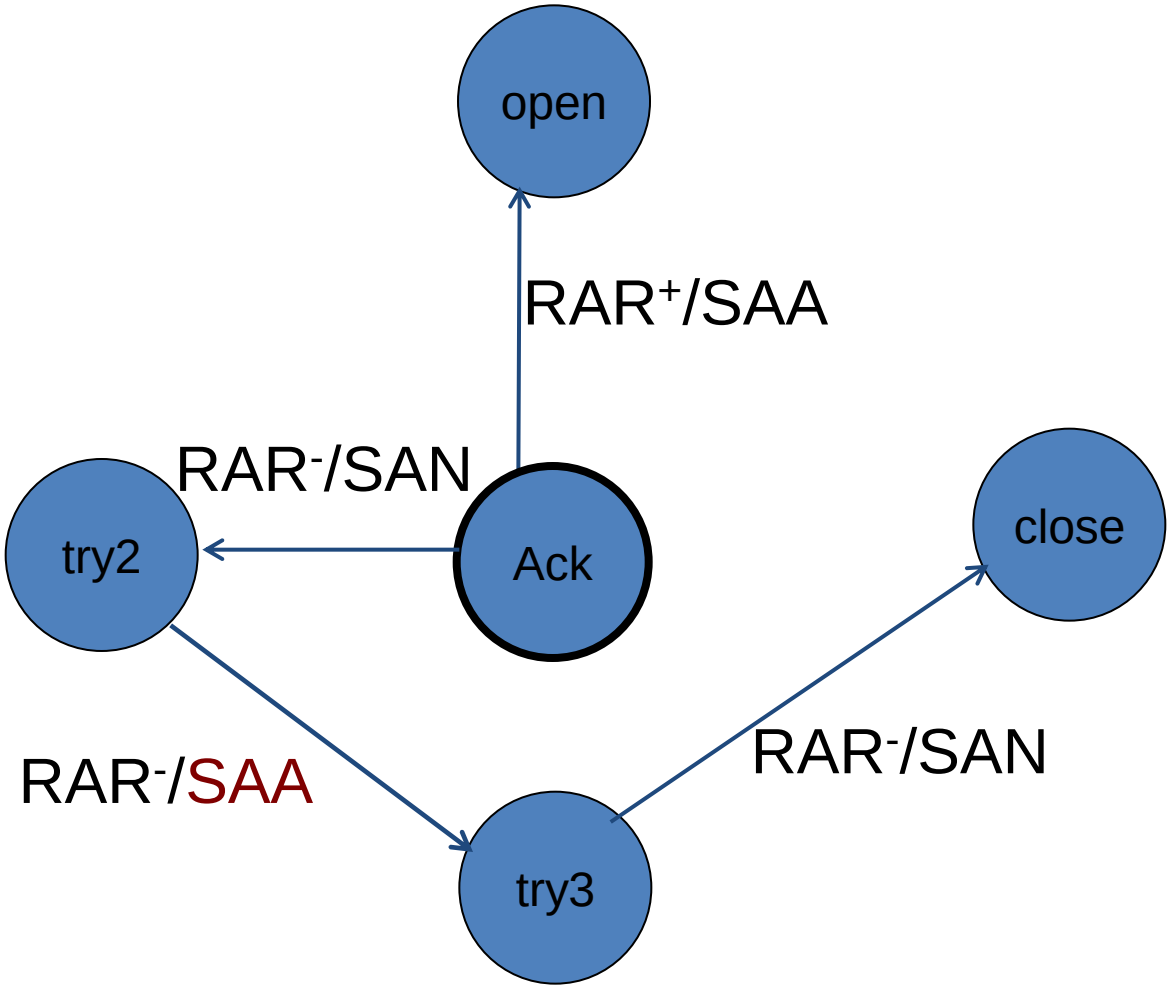
RAR-RAR-RAR-

Expected output reactions:

SAA

SAN SAN SAN

Detecting an output fault



Test suite:

RAR+

RAR-RAR-RAR-

Expected:

SAA

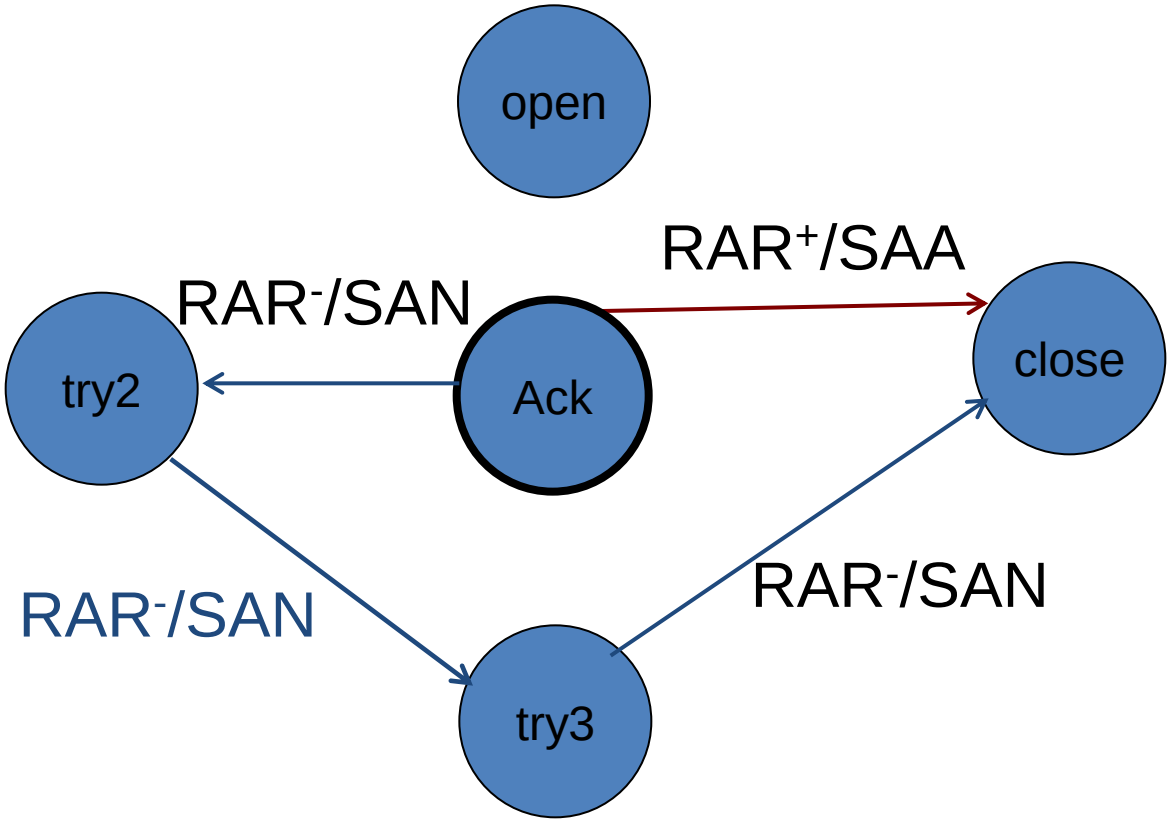
SAN SAN SAN

Observed:

SAA

SAN SAA SAN

Trying to detect a transfer fault



Test suite:

RAR+

RAR-RAR-RAR-

Expected:

SAA

SAN SAN SAN

Observed:

SAA

SAN SAN SAN

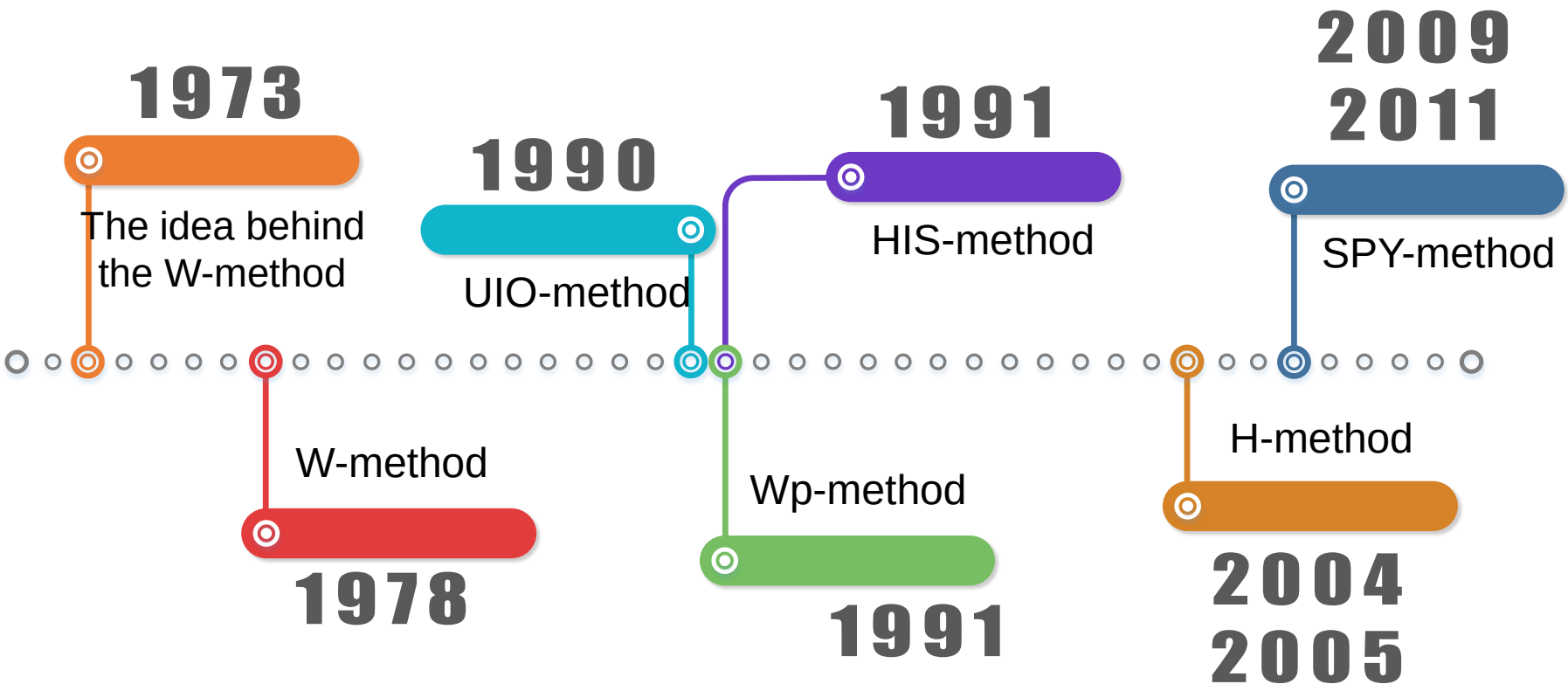
A transition fault is not necessary detected by a transition tour!!!

Black box testing (guaranteed killing transfer faults)

- Most methods for detecting transfer faults in initialized complete deterministic FSMs are based on W-method
- *Spec* is a complete deterministic reduced FSM with *n* states
- The upper bound *m* on the number of states of an implementation FSM is known
- The fault models

$<S, \cong, \mathfrak{I}_n>$ or $<S, \cong, \mathfrak{I}_m>$, $m \geq n$

Time-line for W-method and its derivatives



Isomorphic FSMs

Two FSMs *Spec* and *Imp* are isomorphic iff

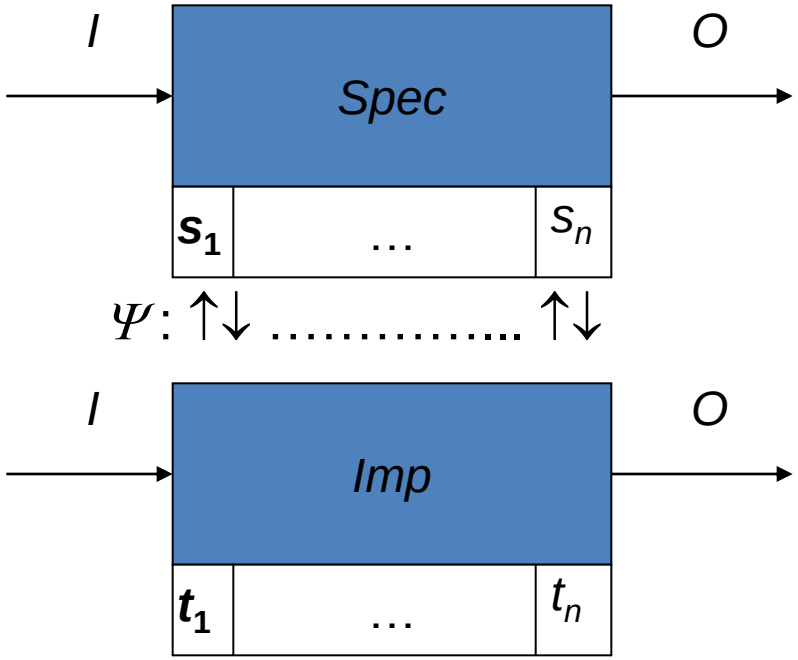
1. There exists one-to-one Ψ: $T \rightarrow S$ between states, $\Psi(t_1) = s_1$
2. The same Ψ is kept between transitions

$\lambda_{Imp}(t, i) = \lambda_{Spec}(\Psi(t), i)$

and

$\Psi(\delta_{Imp}(t, i)) = \delta_{Spec}(\Psi(t), i)$

Spec and *Imp* have the same number of states



Test suite derivation for detecting transfer faults (*m* = *n*)

Two states s_j and s_k of the specification FSM are *equivalent* if the FSM has the same output response at states s_j and s_k to each input sequence

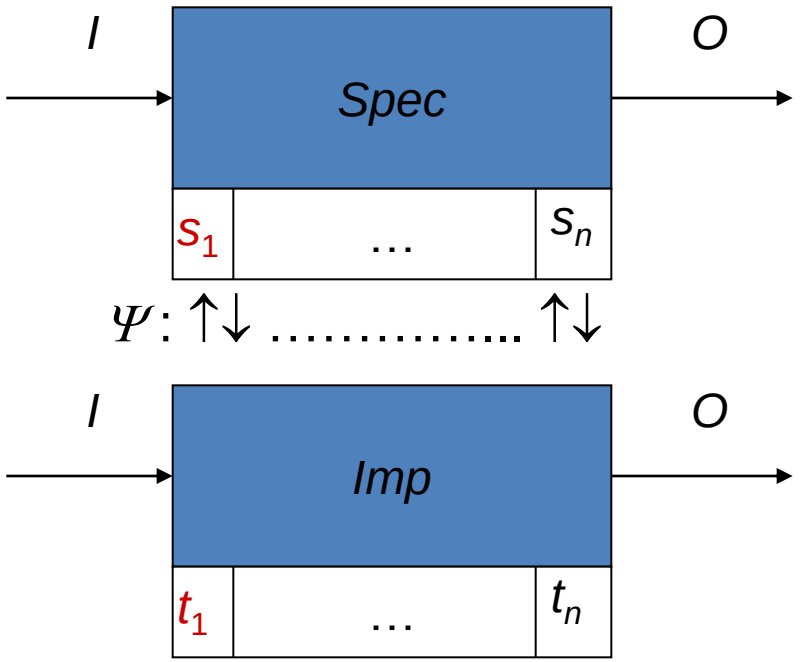
Proposition. Given complete deterministic reduced specification FSM *Spec* and a complete deterministic implementation FSMs with the same number of states, *Spec* and *Imp* are equivalent iff *Imp* is ***isomorphic*** to *Spec*

How to check if an implementation is isomorphic to *Spec*

1. To assure that a given implementation *Imp* has *n* states

2. To assure that for each transition of *Spec* there exists a corresponding transition in the FSM *Imp*

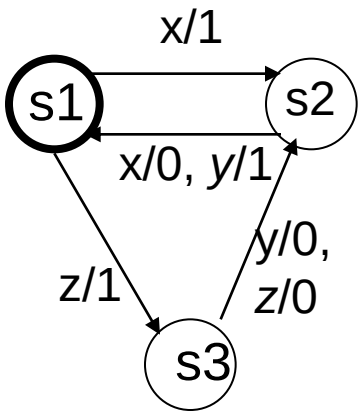
Checking states and transitions of *Imp*



! We forget about the infinite set of input sequences and check finite number of transitions

Reduced FSM

Given a complete deterministic reduced FSM, for every two different states there exists a sequence that distinguishes these states (separating sequence)



FSM is reduced
Separating sequences:
$\gamma(s1, s2) = x$
$\gamma(s2, s3) = y$
$\gamma(s1, s3) = z$

For each deterministic complete FSM there exists a reduced FSM with the same Input/Output behavior, i.e. a reduced FSM with the same set of traces

Conclusion: we can consider only reduced specification FSMs

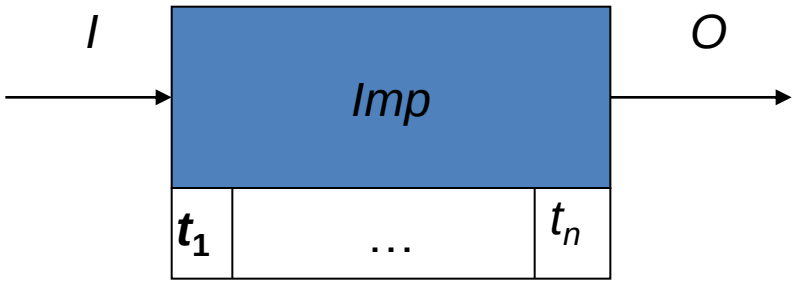
Separating sequences

As we do not directly observe states of *Imp*, we use separating sequences to draw some conclusions

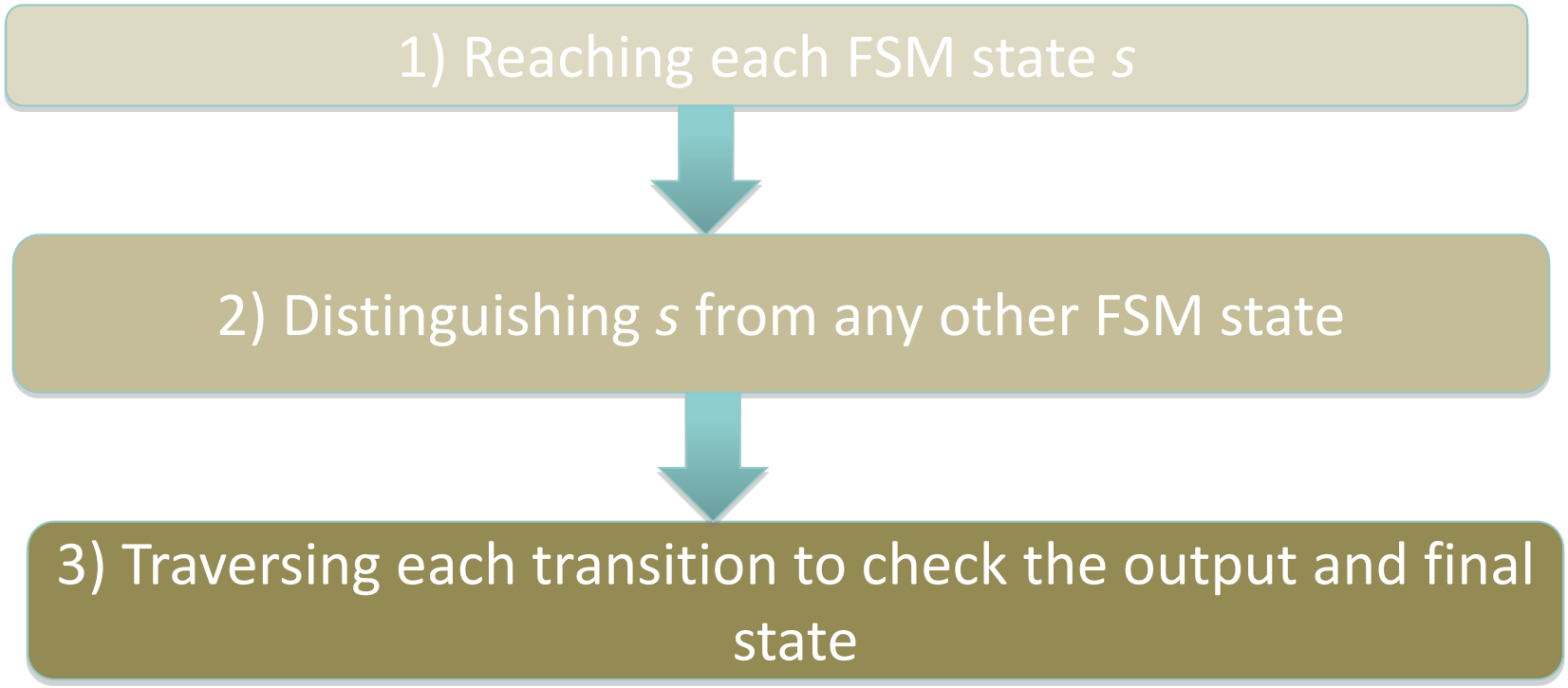
States s_j and s_k of *Spec* are separated by input sequence α if *Spec* has different output responses at s_j and s_k to α

If *Imp* produces different outputs to α then *Imp* is at two different states t_j and t_k when is applied

… $tj\ \alpha/\beta_1$ … … $tk\ \alpha/\beta_2$ …



When testing against FSMs …



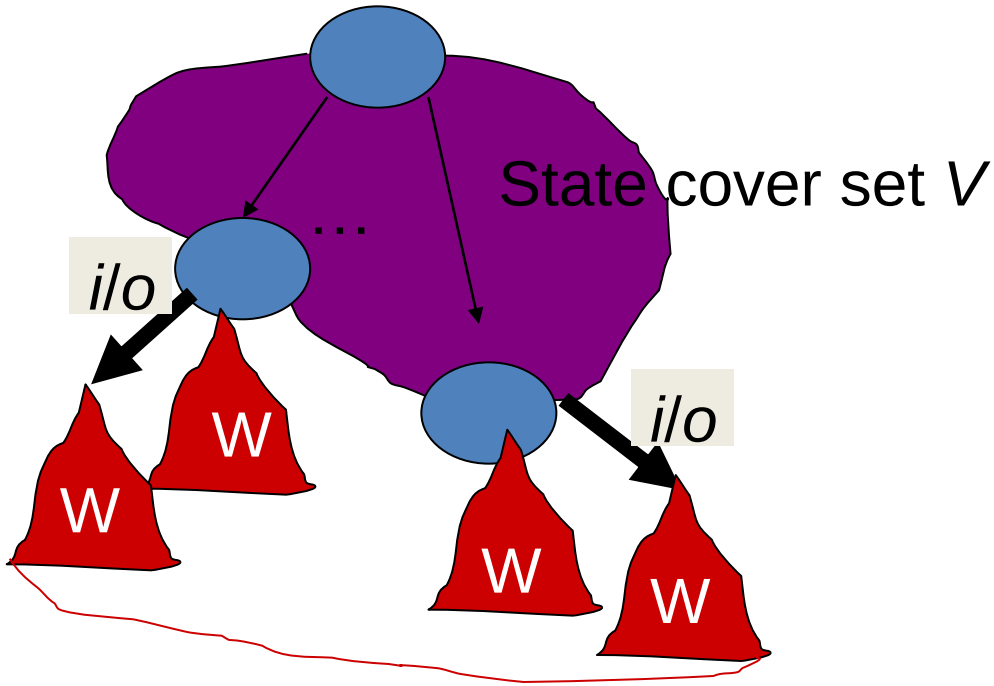
- 1) can be solved via an application of a transfer sequence
- 2) can be solved via an application of a separating sequence

W-method ($m = n$)

1. For each two states s_j and s_k of the specification FSM *Spec* derive a distinguishing sequence γ_{jk}
   Gather all the sequences into a set W that is called a *distinguishability* set
2. For each state s_j of the FSM *Spec* derive an input sequence that takes the FSM *Spec* to state s_j from the initial state
   Gather all the sequences into a set CS that is called a *state cover* set

W-method (2)

3. Concatenate each sequence of the state cover set V with the distinguishability set W: $TS_1 = V.W$
4. Concatenate each sequence of the state cover set V with the set iW for each input i: $TS_2 = V.I.W$



! The shortest test suites are derived when FSM has a *distinguishing* sequence

R. Dorofeeva, K. El-Fakih, S. Maag,R. Cavalli, N. Yevtushenko, “FSM-based conformance testing methods: A survey annotated with experimental evaluation,” Inform. & Softw. Tech., vol. 52, no. 12, pp. 1286–1297, 2010.

W-method (3)

4. Concatenate each sequence of the state cover set *V* with the set *iW* for each input *i*: $TS_2 = V.I.W$

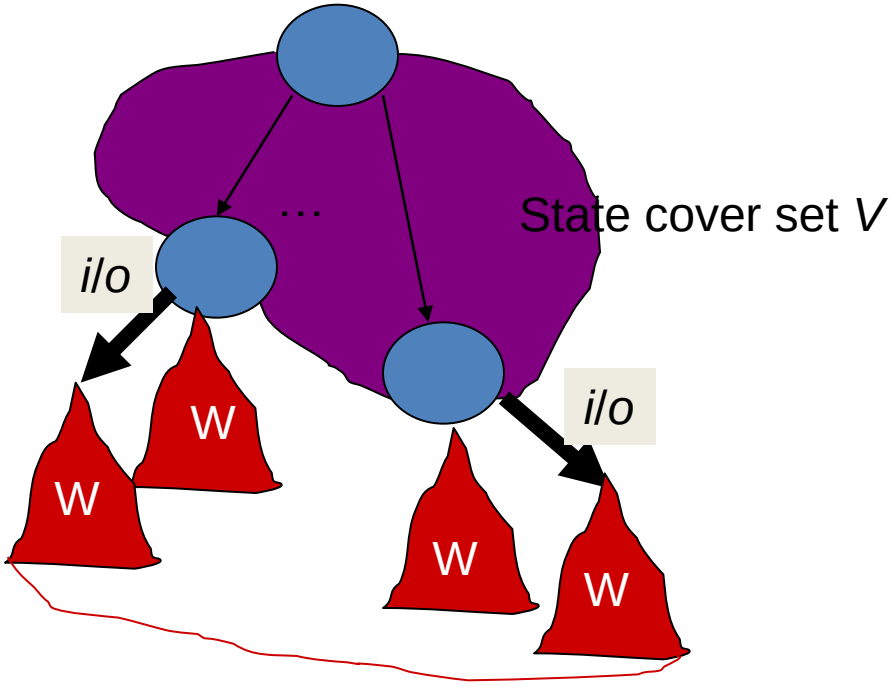
Proposition. If an implementation FSM *Imp* that passed TS_1 passes also TS_2 then one-to-one mapping Ψ satisfies the property:

$$\lambda_{Imp}(t, i) = \lambda_{Spec}(\Psi(t), i) \;\&\; \Psi(\delta_{Imp}(t, i)) = \delta_{Spec}(\Psi(t), i)$$

i.e., FSM *Imp* is isomorphic, and thus, is equivalent to *Spec*

W-method (4)

Test suite returned by W-method



All the sequences that are prefixes of other sequences can be deleted from a complete test suite without loss of its completeness

W-method (5)

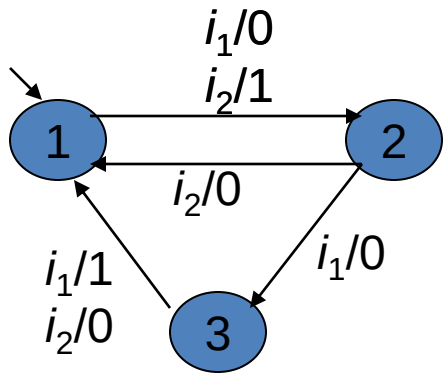
When a state cover *V* is prefix closed, while the distinguishability set *W* is suffix closed, the set

$$V.I.W$$

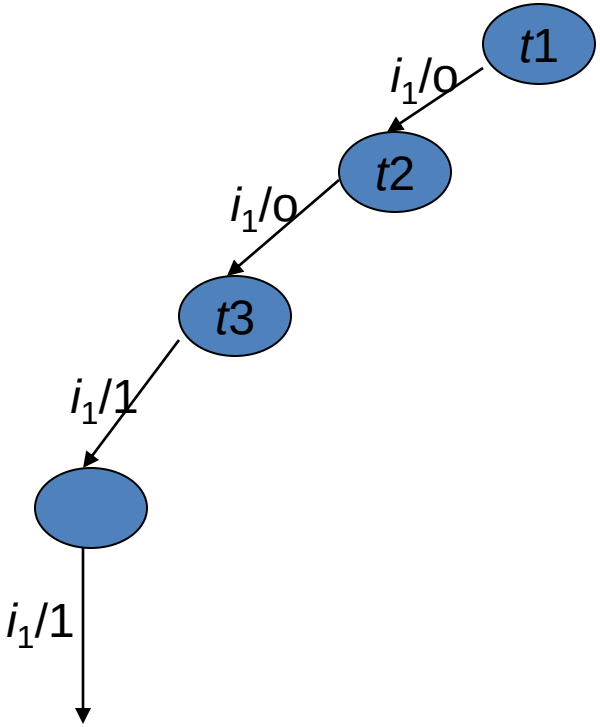
is a complete test suite for the case when the IUT has not more states than the specification

Example

FSM with three states



State identification

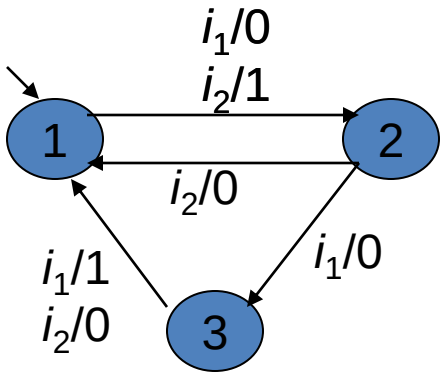


Output to $i_1 i_1$

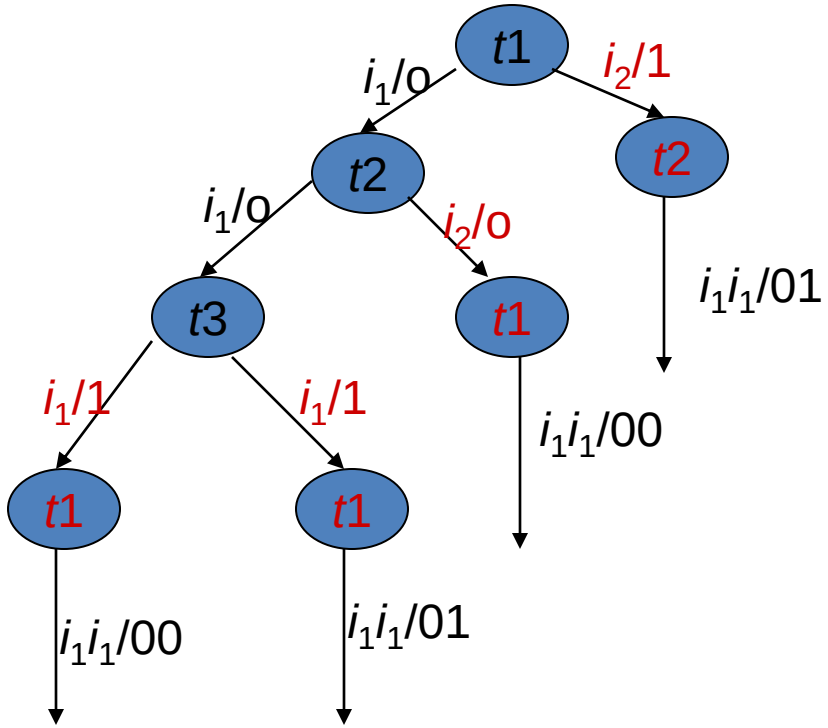
1: 00
2: 01
3:10

Example (2)

Spec



Complete test suite



Experimental results for W-method

State num.	Input num.	Output num.	Trans. num.	Average length
30	6	6	180	2545
30	10	10	300	3393
50	6	6	300	5203
50	10	10	500	6773
100	10	10	1000	17204

Experimental results (conclusion)

Theoretically:

Length is $O(kn^3)$ where

k – number of inputs

n - number of states

Experiments show:

- tests are much shorter than corresponding theoretical upper bounds
- test suites are fast generated (compared with explicit enumeration)

STILL LONG ENOUGH

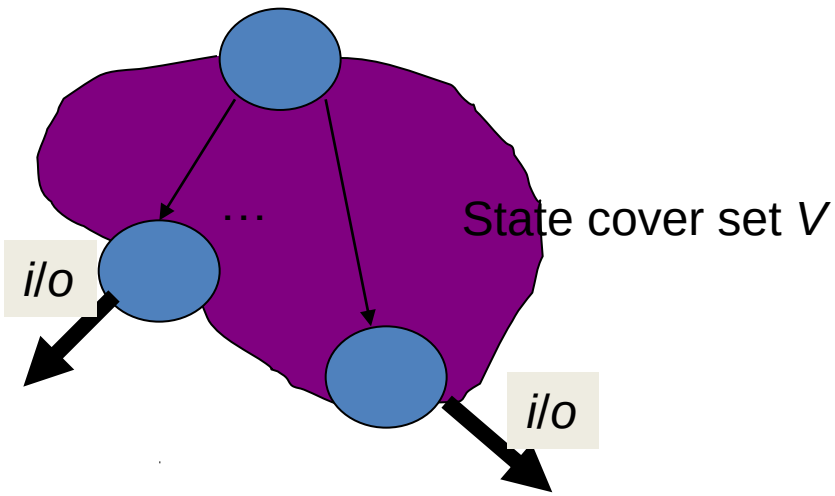
Studying W-method

Conclusions:

1. The set *V.I* is presented in each complete test suite

(each transition at each state must be traversed)

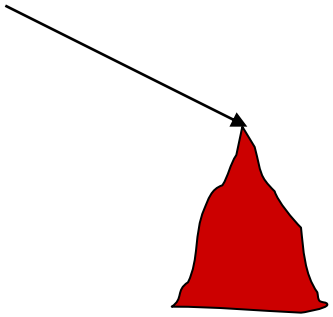
2. The length of a complete test suite significantly depends how states are identified, i.e., on the choice of state identifiers



Modifications of W-method

1. DS-method
2. UIO-method
3. Wp-method
4. UIOv-method
5. HSI-method

Depending how a set of separating sequences is defined



! H-method allows to identify states with separating sequences derived on-the-fly
! SPY method allows to check transitions after different transfer sequences of a state cover set

H- and SPY-methods

- *H-method*

Allows to use different state identifiers when checking different transitions

Conclusion: State identifiers can be derived on the fly

- *SPY-method*

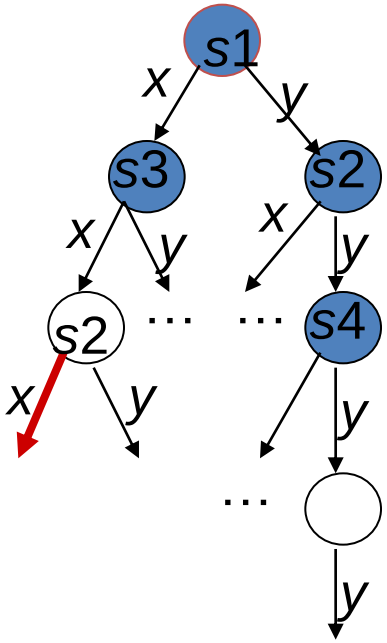
Allows to use different input sequence when reaching a state where a transition is checked

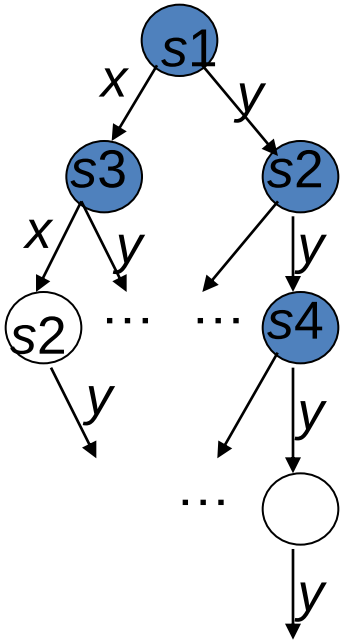
Conclusion: Transfer sequences can be derived on the fly

! Still there are no necessary and sufficient conditions for a test suite to be complete

Using different state identifiers in H-method

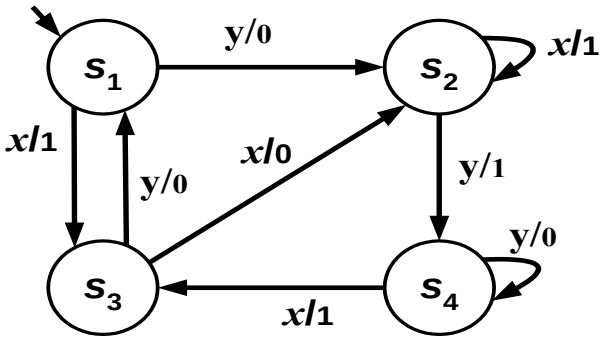
$W_2 = \{y\}$, $W_3 = \{x\}$ but $H_2 = \{x, y\}$, $H_3 = \{x, y\}$



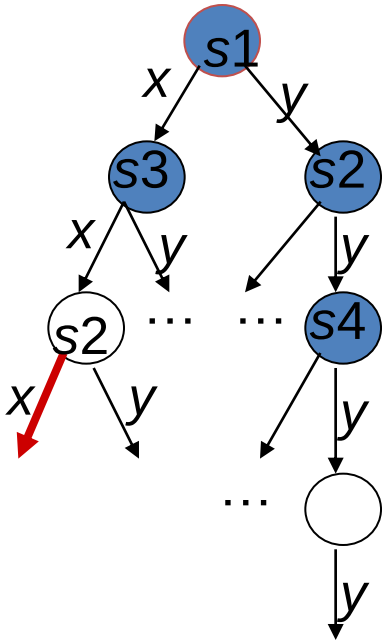


H-method (illustration)

Spec

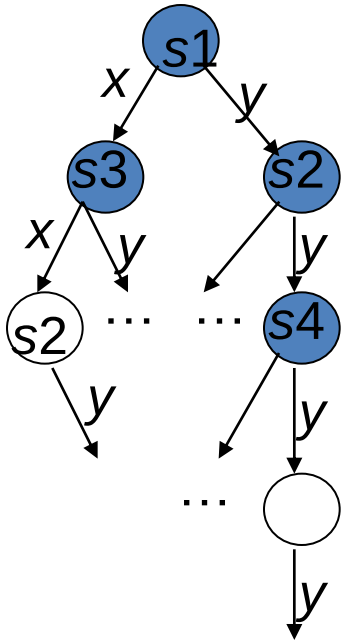


HIS-method



$L = 41$

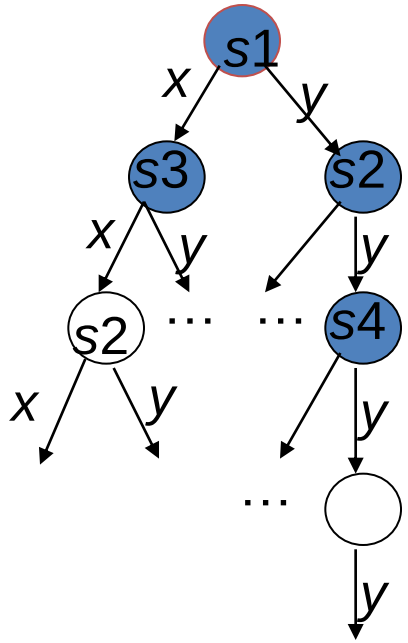
H-method



$L = 25$

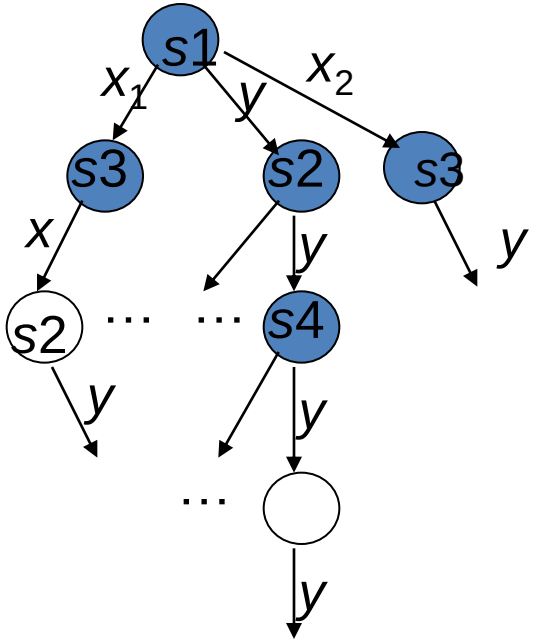
SPY-method (illustration)

HSI-method



$L = 41$

SPY-method



$L = 26$

Experimental results

State num.	Input num.	Output num.	Trans. num.	Wp	H, SPY
30	6	6	180	1626	1105
30	10	10	300	2175	1568
50	6	6	300	3261	2142
50	10	10	500	4305	2852
100	10	10	1000	10503	6880

Conclusions

1. As it is known, the DS-method returns shortest test suites

But: less than 10% of specifications possess a DS

2. H- and SPY- methods return tests that are comparable with those returned by DS-method

And: can be applied to any reduced (partial or complete) specification

3. The test quality is very good

4. Test suites returned by all above methods are still too long for real systems: the abstraction level should be carefully chosen

Experimental results (2)

A number of protocols have been considered

- SCP
- POP3
- Time
- TCP
- …

Java implementation of each protocol has been developed and the μjava tool has been used for the mutant derivation

All the tests returned by HIS method detect 100 % of implementation faults injected by the μjava tool

The ratio between test suite length returned by different methods is almost the same as for randomly generated FSMs

Faults can increase the number of states of an implementation FSM

Faulty implementation can have more states than the specification

m – number of states of *Imp*

n – number of states of *Spec*

$m > n$

- *Fault model* $<\mathcal{S}, \cong, \mathfrak{I}_m>$

A single transfer fault in the specification EFSM of a Simple Connection Protocol (SCP) can transform the corresponding FSM into an FSM with more states

W - method and its modifications

1. State cover set *V* is augmented with all input sequences of length $m - n$
2. State idenitifiers are applied according to a given method

! The length of a test suite becomes exponential w.r.t. the number of *Spec* inputs

!! Experiments show almost the same relationship between length of test suites returned by different modifications of W - method

Publications

1. Chow, T.S. 1978. Test design modeled by finite-state machines. IEEE Transactions on Software Engineering, 4(3): 178--187.
2. Lee D. and Yannakakis, M. 1996. Principles and methods of testing finite state machines-a survey. Proceedings of the IEEE, 84(8): 1090--1123.
3. Lai, R., 2002. A survey of communication protocol testing. The Journal of Systems and Software. 62:21--46.
4. M.Dorofeeva, K.El-Fakih, S.Maag, A.Cavalli, N.Yevtushenko. FSM-based conformance testing methods: A survey annotated with experimental evaluation. Information and Software Technology, 2010, 52, (12), pp. 1286-1297.
5. A. Simao, A. Petrenko, N. Yevtushenko. Generating reduced tests for FSMs with extra states // LNCS 5826, P. 129—145.
6. M. Forostyanova. Tree automata based test derivation method for telecommunication protocol implementations. Trudy ISP RAS, 2014, N 6.
7. A. Ermakov, N. Yevtushenko. Increasing the fault coverage of tests derived against Extended Finite State Machines. Proceedings of Seventh Workshop Program Semantics, Specification and Verification: Theory and Applications, 2016

Minimizing FSM-based tests for conformance testing

The test quality is very good

BUT

Test suites returned by all above methods are too long

Question: how to shorten test suites, preserve some fault coverage without explicit enumeration of faulty FSMs

Solution: to consider user-driven faults

How to reduce the length of a test suite

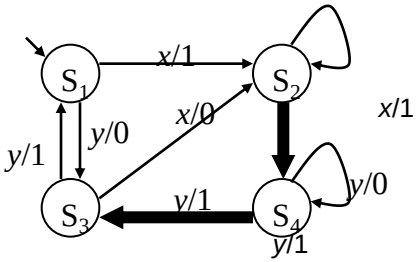
Solution: To partition the set of transitions of the specification FSM into clusters and check only transitions of one cluster at each step

Incremental testing or testing *user-driven faults*

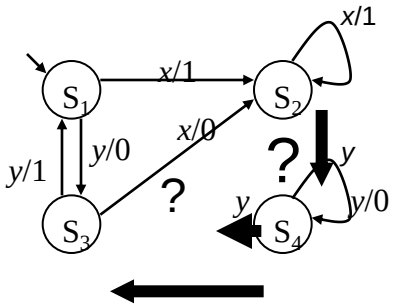
Experimental results are very promising especially for the case when faults can increase the number of states of the specification

Incremental testing or user-driven faults

Only some transitions should be checked



An implementation is assumed to be known up to the transitions that should be checked



Other transitions are not changed

Fault model for incremental testing

Fault model - <*Spec*, ≅, Sub(*MM*)>

Spec is a complete deterministic specification FSM

MM is a mutation (nondeterministic FSM) where

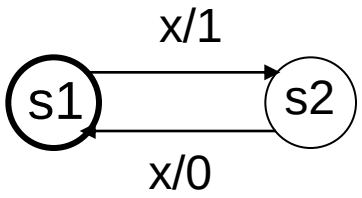
unmodified transitions are as in the specification while

modified transitions are chaos transitions

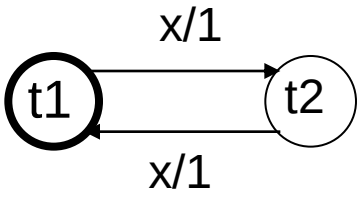
! A bit more tricky when m > n but this is enough for today lecture

Fault domain for incremental testing (2)

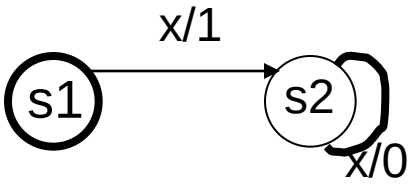
Initial $Spec_{in}$



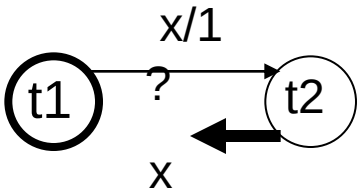
Initial Imp_{in}

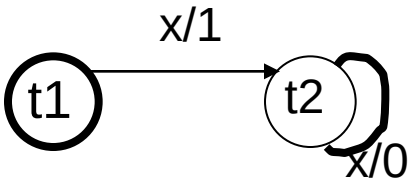


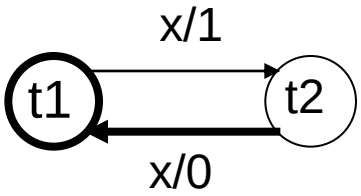
Modified *Spec*

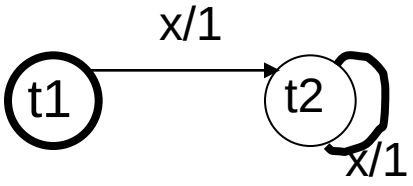


Possible implementations









Complete test suite

Incremental complete test suite has to detect each nonconforming implementation where all unmodifed specification transitions are known

↓

The fault domain has the finite number of FSMs

$$FD = \{Imp_1, \ldots, Imp_k\}$$

Number of mutant FSMs = $(n \cdot p)^t$

n – number of states, p – number of outputs, t – number of modified transitions

When is it enough to check only modified transitions?

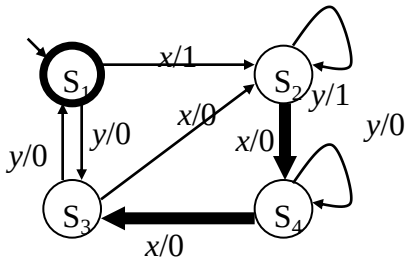
1. When the final state of each modified transition has a state identifier in the unmodifed part of the modified *Spec*

2. When each modifed transition is reachable through unmodified transitions in the modifed *Spec*

! Solution: to derive partitions in order to satisfy the above properties

Final state of each modified transition has a state identifier in the unmodifed part

Example: add two new transitions



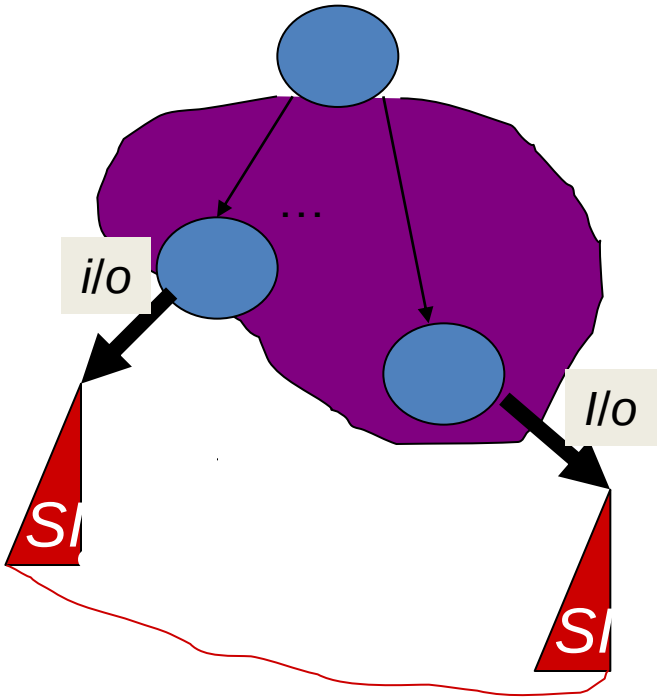
yy is a DS in the unmodifed part

TS = {*r.x.x.yy*, *r.xx.x.yy*}

Compare: *HSI*_length = 25

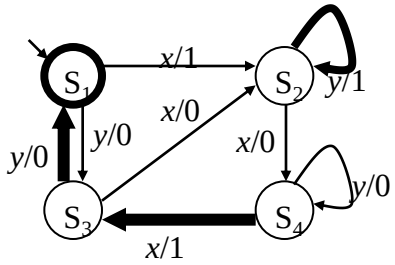
If the whole *Imp* is tested

Only modifed transitions are tested

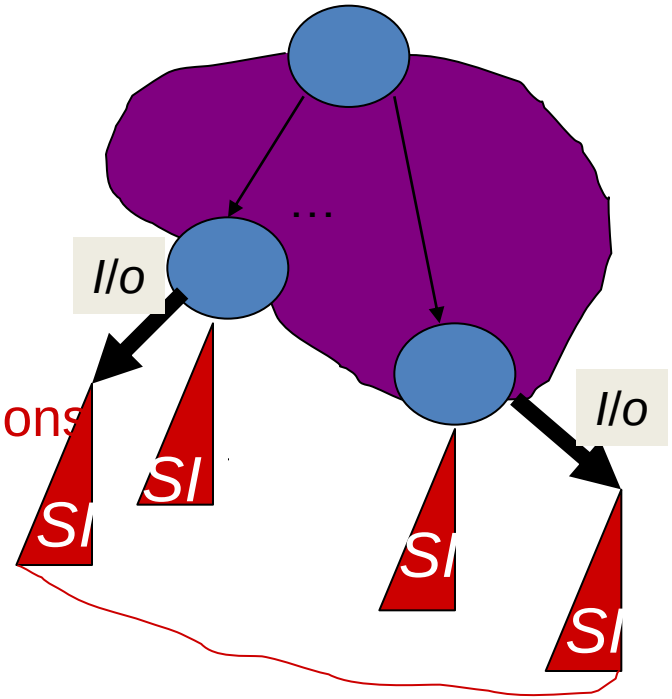


All states are reachable through unmodified transitions

Example



Only modified transitions are tested



State *s*3 has no state identifier in the unmodified part but each state is reachable through unmodified transitions
yy is a DS

Compare: length = 15
HSI_length = 25

General procedure

1. For each state that is reachable via unmodified transitions identify the state and check only modified transitions from this state
2. For each state that has a state identifier in the unmodified part identify the state (if reachable via modified transitions) and check modified transitions
3. For all other states, identify the state and check each outgoing transition
4. Delete sequences that do not traverse modified transitions

Step 3 can be improved

Experimental results

s	i	HSI length	0-5% modif	5-10% modif	10-15% modif	15-20% modif
20	10	2992	93	337	490	785
20	20	5818	148	477	999	1513
30	10	5333	135	518	957	1450
35	10	6588	148	539	1013	1537
40	5	3737	89	345	636	887

Experimental results (2)

Ratio *H* = HSI_length/IncrTest_length

0-5 % modif	5-10 % modif	10-15 % modif	15-20 % modif
36.0	11.3	6.1	4.0

The ratio slightly increases when the number of transitions increases

Implementation can have more states than the specification

A faulty implementation can have more states than the specification

m – number of states of *Imp*

n – number of states of *Spec*

$m > n$

State cover of *Imp*

Question: As a modified *Imp* inherits some transitions from the *Spec*, possibly there exists a shorter set than $V.Pref(I^{m-n})$ that is a state cover set of each possible *Imp*?

Reply: Yes, a state cover set $V.Pref(I^{m-n})$ can be reduced

Experimental results

n (*Spec*)	*m* (*Imp*)	Input_ num	Modif %	Incr_ length	HSI_ length
20	21	4	30	343	3773
20	22	4	20	339	17238
40	41	8	30	1014	?
40	42	8	30	1060	?

Conclusions

Incremental test derivation methods return much shorter test suites

Future work (for example):

Based on incremental testing methods

to derive a test suite that detects single and double output/transition faults of *Spec*

Publications

1. K. El-Fakih, N. Yevtushenko, and G. v. Bochmann. FSM-based incremental conformance testing methods", *IEEE Transactions on Software Engineering*, 204, 30(7), 425-436.
2. K. El-Fakih, M. Dorofeeva, N. Yevtushenko, G.v. Bochmann. FSM based testing from user defined faults adapted to incremental and mutation testing. Programming and Computer Software, 2012, Vol. 38, Issue 4, pp. 201 - 209

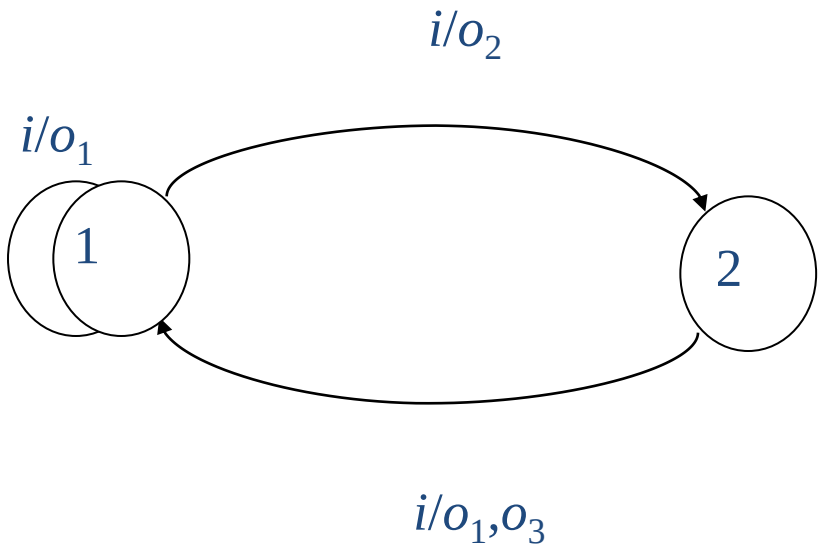
Testing non-initialized FSMs

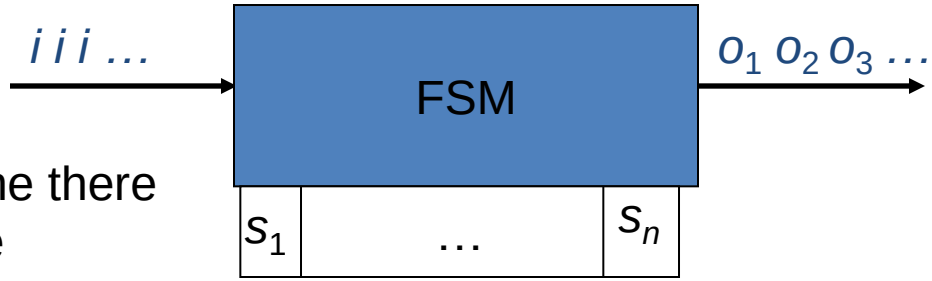
No reliable reset
or
The reset is very expensive

Finite State Machine (FSM)

$\mathcal{S} = (S, I, O, h_S)$ is an FSM

- S is a finite nonempty set of states with the initial state s_0
- I and O are finite input and output alphabets
- $h_S \subseteq S \times I \times O \times S$ is a behavior relation





Two complete non-initialized FSMs are *equivalent* if for each state of one machine there is an equivalent state in another machine

Checking sequences [Hennie64]

- Non-initialized FSMs
- The fault model <*Spec*, $\cong$, $\Im_n$> where *Spec* is a reduced strongly connected complete deterministic FSM that has a distinguishing sequence

An input sequence α is a *checking sequence* if for each FSM *Imp* with at most *n* states that is not equivalent to *Spec*, *Spec* and *Imp* have different output responses to α

! α separates (distinguishes) *Spec* from any non-equivalent FSM with at most *n* states

Checking sequences (2)

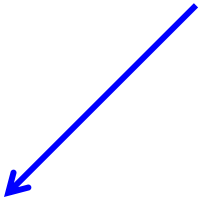
- The method for deriving a checking sequence is the same: to reach each state and to traverse each transition; states are identified using a distinguishing sequence

! It is much harder to reach a state without a reliable reset

! The length of a distinguishing (separating) sequence (if it exists) is exponential w.r.t the number of states of the specification FSM

How to decrease the complexity?

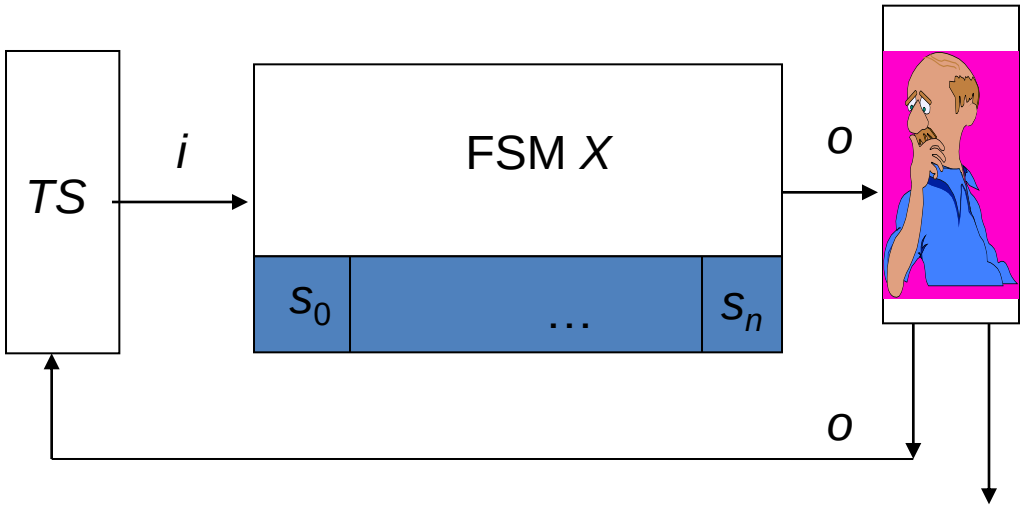
Switching **from preset to adaptive** test derivation strategy
Research groups of M. Yannakakis, R. Hierons , H. Yenigün, A. Simão, A. Petrenko, N. Yevtushenko,



Providing **effective heuristics**
Research groups of A. Zakrevskiy, H. Yenigün, R. Brayton, A. Cavalli

Adaptive testing for FSMs

Next input depends on the responses to previous inputs



Next input depends on the output to previous inputs
The length of adaptive checking sequence is less than the length of preset sequences

Conclusion: adaptive checking sequences are shorter than preset

Publications

1. Lee, D., Yannakakis, M.: Testing finite-state machines: state identification and verification. IEEE Trans. on Computers, 43(3), pp. 306-320 (1994)
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Conclusions

- FSMs are useful for deriving high quality test suites; however, as FSM specifications have many states, tests are too long
- The problem is how to extract FSM from an informal specification
- Usually an extracted FSM is partial and non-deterministic

Non-classical FSMs

Unfortunately, FSMs extracted from real systems are not complete and deterministic

- Partial deterministic
- Complete non-deterministic
- Partial non-deterministic
- Non-observable

How to derive tests?

Partial specification

1. *Spec* can be partially specified;

Imp is a complete FSM

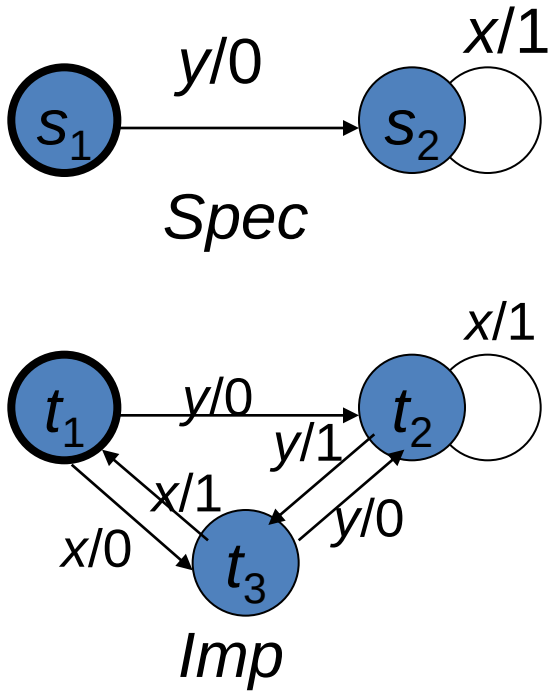
2. To complete *Spec* adding loops for undefined transitions with output ‘IGNORE’.

3. *Imp* conforms to *Spec* iff *Imp* is quasi-equivalent to *Spec* , i.e., has the same behavior for defined input sequences

Quasi-equivalence relation

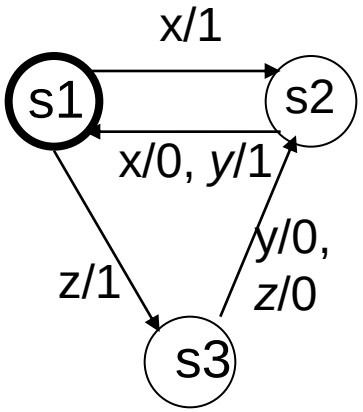
A complete FSM *Imp* is *quasi-equivalent* to *Spec* if their output responses coincide for each input sequence that is defined in the *Spec*

A partial *Spec* and a complete *Imp*



W-, Wp-, UIOv-methods cannot be used

W-, Wp, UIOv- methods cannot be generally used as not each partial FSM has the distinguishability set W



Distinguishability set
does not necessary exist

HIS, H, SPY still can be applied,
Moreover, *Spec* is not required to be reduced

Non-deterministic FSMs (NFSMs)

Tabular Representation of a NFSM

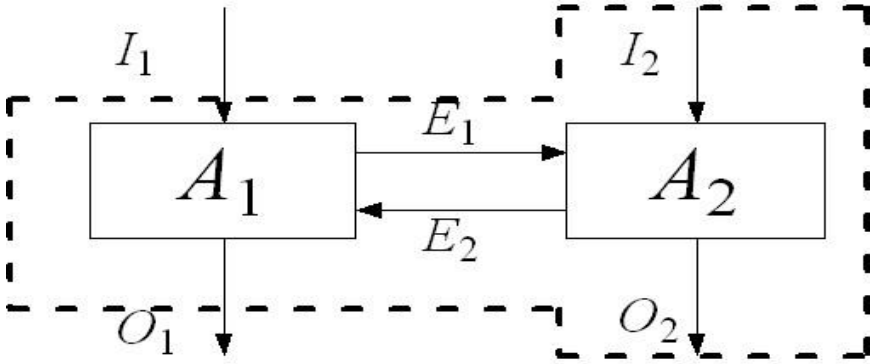
Input/ state	*a*	*b*
x	*a* / 0,1,2,3	*a* / 1,2
y	*b* / 1,2	*a* / 0 *b* /3

States: { a, b }
Inputs: {*x*, *y*}
Outputs : {0, 1, 2, 3}

At state a under the input *x*, we have four transitions
(*a*, *x*, 0, *a*), (*a*, *x*, 1, *a*), (*a*, *x*, 2, *a*), (*a*, *x*, 3, *a*)

Why non-determinism ?

- For example, when we have limited Controllability or Observability as in Remote Testing



- Due to the optionality
- Due to the abstraction level
- …

Input/Output Traces of an FSM

	a	*b*
x	*a* / 0, 1, 2, 3	*a* / 1, 2
y	*b* / 1, 2	*a* / 0 *b* /3

At state a, for input trace *x* , output traces:

***out*(*a*, *x*) = {0 , 1 , 2 , 3}**

At state a, for input trace *x.y*, output traces are :

***out*(*a*, *x.y*) = { 0.1 , 0.1 , 1.1 , 1.2 , 2.1 , 2.2 , 3.1 , 3.2 }**

(I/O)Traces of an FSM: all I/O sequences that can be derived from the initial state of the FSM

More Coformance Relations Between nondeterministic FSMs

- **FSMs *P* and *S* are *indistinguishable* if**

$$\forall \alpha \in I^* \; (out_P(p_1,\alpha) = out_S(s_1,\alpha))$$

- **FSMs *P* and *S* are *non-separable* if**

$$\forall \alpha \in I^* (out_P(p_1,\alpha) \cap out_S(s_1,\alpha) \neq \emptyset)$$

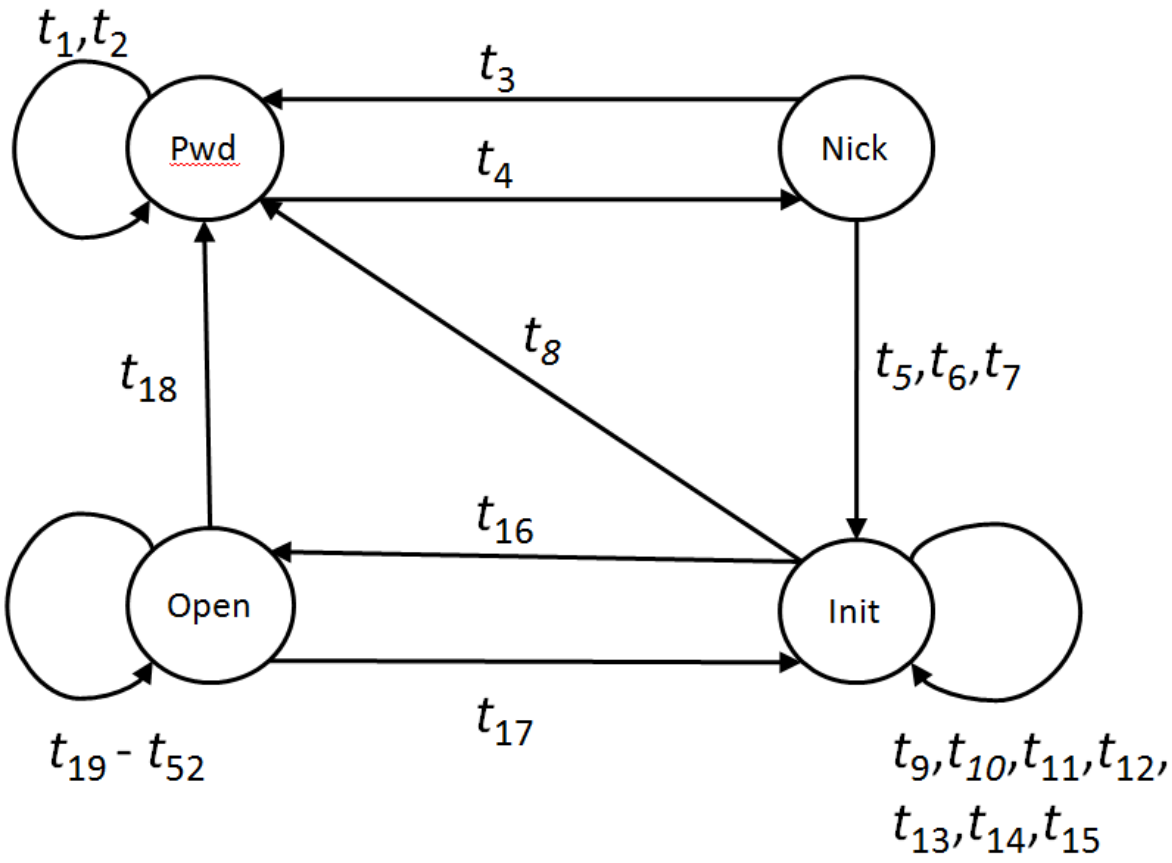
- **FSMs *P* and *S* are *r-compatible* if there exists**

  a complete FSM is a reduction of both FSMs, *P* and *S*

! There are methods for deriving complete test suites w.r.t. various conformance relations for NFSMs

!! Sometimes all-weather-conditions have to be used

IRC protocol



[*RFC2812*]

Inconsistencies detected

- Wrong code reply to the command *NICK* with the empty parameter (without nickname)
- Wrong server processing when using already occupied nickname
- Command MODE is wrongly processed

PASS(2)/NULL NICK(1)/{431}
PASS(2)/NULL NICK(3)/NULL USER(3,0,5)/001 NICK(3)/{433}
PASS(2)/NULL NICK(3)/NULL USER(3,0,5)/001 MODE(1,7)/{461}

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Complexity problems for nondeterministic FSMs

Some primitive complexity into…

Time

Space

…This is what it counts for an algorithm *A*…

n is the size of the input of a problem **P**

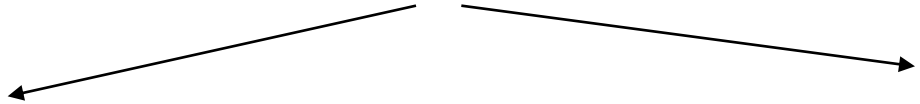
1) ***Time*** – can be considered as the number of primitive operations, in the worst case, to solve the problem

// number of transitions of the corresponding Turing machine

2) ***Space*** – can be considered as the size of memory to be used, in the worst case, to solve the problem

// the length of a tape in use of the corresponding Turing machine

What is good and what is bad?



When the time is polynomial

- There exists an algorithm that solves the problem in a polynomial time
- The problem is in P then

When the time is not polynomial

- Maybe, there exists an algorithm that verifies the solution in a polynomial time?

Then the problem is in NP

- Or maybe there exists an algorithm that solves the problem using a polynomial space?

Then the problem is in PSPACE

! P is good, for small degrees of the polynomials ☺

NP and PSPACE – not really

Bad… very bad ‘news’

Most of the problems in Model based testing are PSPACE-complete

In particular…

The problem of checking the existence of a distinguishing sequence for complete deterministic FSMs

The problem of checking the existence of a distinguishing sequence for complete nondeterministic FSMs

The problem of checking the existence of a homing / synchronizing sequence for complete non-reduced (non-)deterministic FSMs

Test sequences and checking sequences are somewhat hard to derive…

How to decrease the complexity?

Utilizing scalable representations allows to 'hide' the complexity
Research groups of R. Brayton, R. Jiang, A. Mischenko, T. Villa, J. Tretmans, V. Kunz, H. Yenigün

Providing **effective heuristics**
Research groups of A. Zakrevskiy, H. Yenigün, R. Brayton, A. Cavalli, A. Simão

Considering specific types of bugs in the software, i.e., specific fault models
Research groups of J. Offut, F. Wotawa, N. Yevtushenko

Switching **from preset to adaptive** test derivation strategy
Research groups of M. Yannakakis, N. Yevtushenko, A. Petrenko, A. Simão, R. Hierons

How to decrease the complexity (2)?

Simplifying a derivation of test sequences

1) ***Using scalable representations***

Logic circuits, for example?

2) ***Considering proper FSM classes***

1-distinguishing, merging free,…

3) ***Developing effective heuristics***

Check if a given FSM has a submachine with ‘good’ transfer and distinguishing properties

4) ***Switching from preset to adaptive test derivation strategy***

Already saw that this can help when deriving checking sequences even for deterministic FSMs

…

Each of the above is good for appropriate FSM classes

Conclusions

- **Theoretically**: almost all the problems in software testing that provide the guaranteed fault coverage have terrible (exponential or more!!!) complexity
- **Practically**: methods and tools for decreasing the complexity seem to be promising

New models (or new heuristics) need to appear and new methods and tools need to be provided to decrease the complexity

We do have something for the future work ☺

Working together with

Original results presented here were obtained in collaboration with research groups lead by

Prof. Ana Cavalli (and scientific group under her supervision)

Prof. Khaled El-Fakih

Prof. A. Petrenko (Canada and Russia ☺)

Prof. Ades Simão

Prof. H. Yenigün

PhD Natalia Kushik

Scientific group of Tomsk State University

Thank you!