Fault Model-Based Testing from State-Oriented Models

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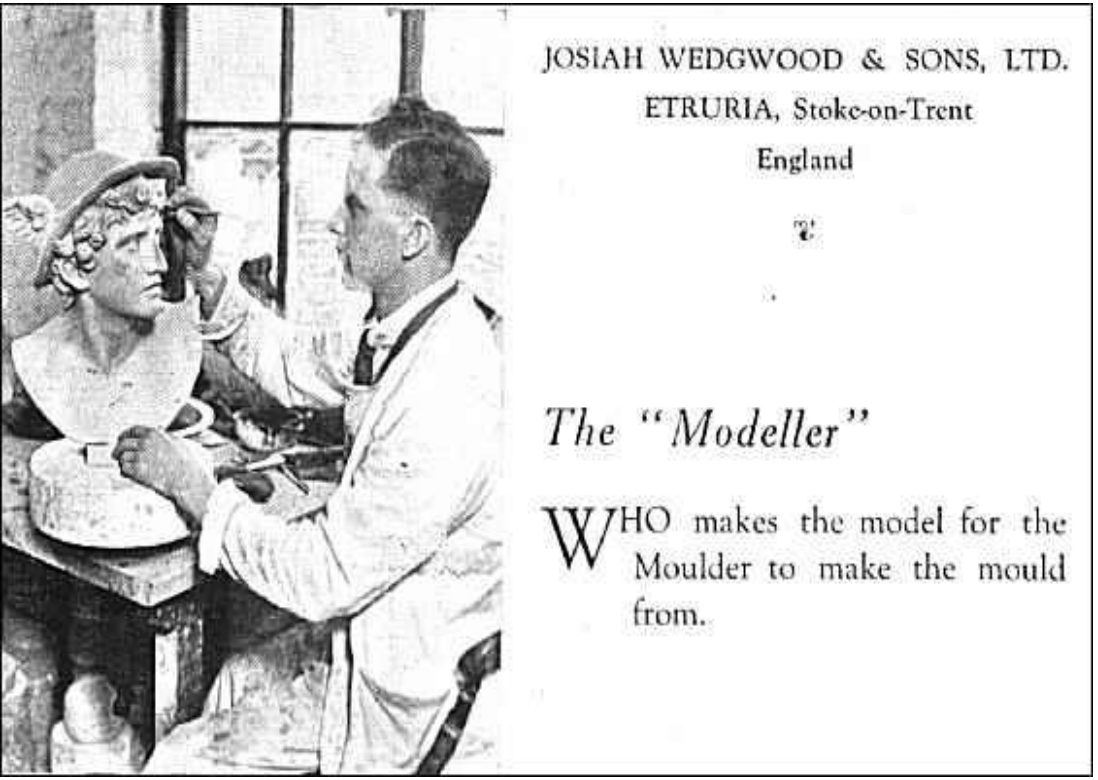
To Model or Not to Model, That is the Question

Testers become test modellers



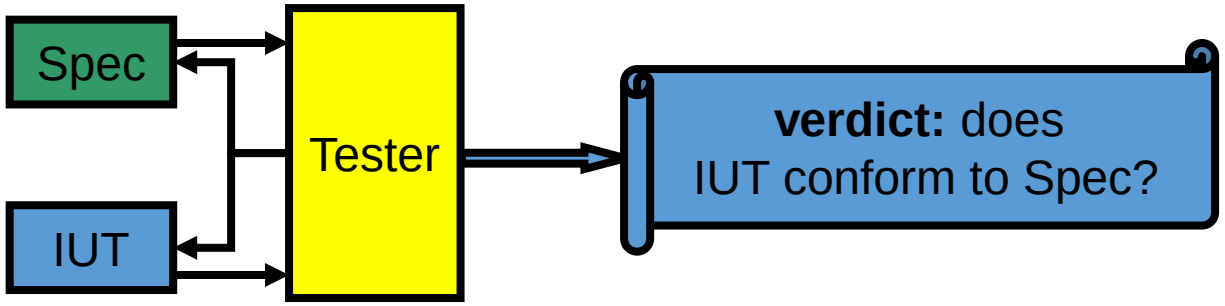
"Palais Idéal" is still built by many without any modelling

Given Test Model, What To Cover By Tests?

- Usual model/specification coverage
  - Executions
  - Structural elements
- Testing can be used to show the presence of bugs, but never to show their absence [Dijkstra]
- Yet can testing at least guarantee that no bugs of a predefined type are left?
- To achieve this fault models are needed
- Model coverage is not fault coverage

General Fault Model for Testing

(*Specification, Conformance Relation, Fault Domain*)



- Specification is a state-oriented model: Finite State Machine (FSM) or Input Output Transition System (IOTS)
- Fault domain is a set of Implementations Under Test (IUT) treated as black box and modelled by FSM or IOTS,
  it formalizes test assumptions
- Conformance relation is defined as a relation on FSM or IOTS

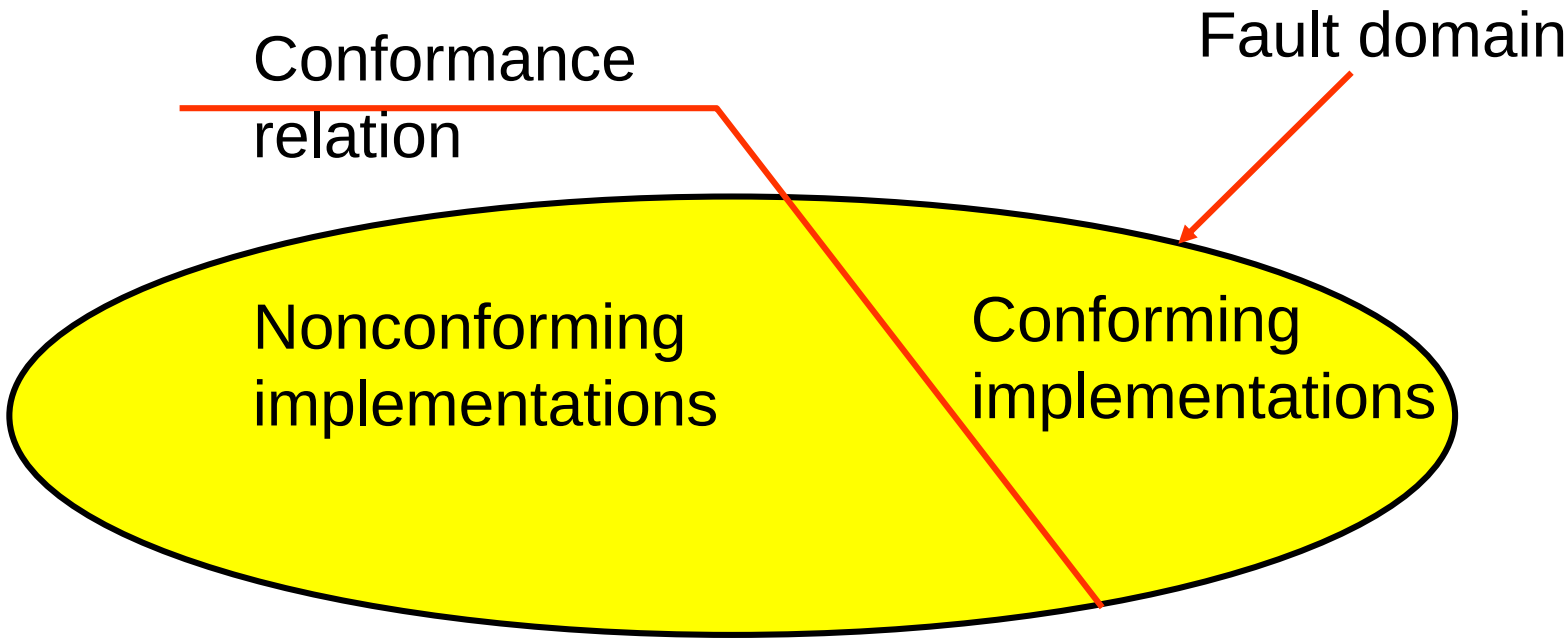
Complete Test Suite for Fault Model

- Test suite is *sound* if no conforming IUT from a given fault domain fails it
- Test suite is *exhaustive* if each nonconforming IUT from a given fault domain fails it
- Test suite is *complete* for a given fault model if it is both, sound and exhaustive

- Since life is short, complete test suite must be finite
- The first complete test suites called checking experiments have been studied since 1960s (model-based testing has started!)

Test Completeness and Fault Coverage

Complete test suite provides a full fault coverage within a given fault domain



a smaller fault domain usually requires a shorter complete test

The Holy Grail for Fault Model-based Testing

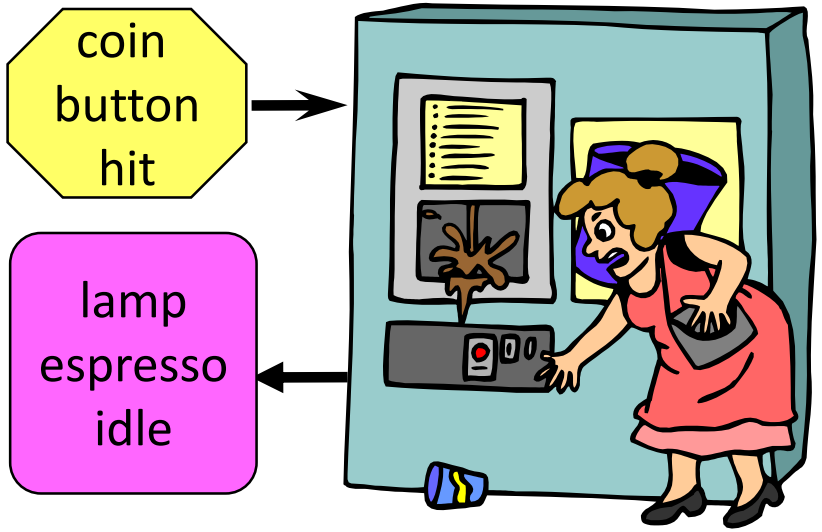
A method which given an instance of a fault model
generates a minimal complete test suite

Tutorial Aims at Explaining

- Diversity of FSM and IOTS models used for fault model-based testing
- Variety of fault models
- Basic ideas of constructing complete test suites for some fault models

Finite State Machines

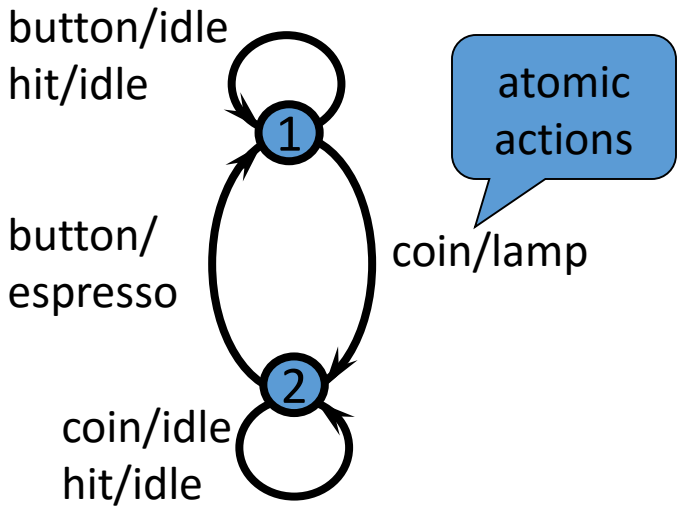
Typical Finite State Machine



Inputs: coin, button, hit

Outputs: lamp, espresso, idle

States: 1 (wait for coin), 2 (wait for button)



Specification FSM $A = (S, s_0, X, Y, \delta, \lambda)$

S - finite set of states, s_0 is initial state

X - finite set of inputs

Y - finite set of outputs

$\delta: S \times X \rightarrow S$ - transition function

$\lambda: S \times X \rightarrow Y$ - output function

Mealy machine

FSM can be viewed as a Finite Automaton

- each state is final (accepting)
- input-output pair is a symbol

Equivalence Relation

- Aka trace equivalence
- Let $A = (S, s_0, X, Y, \delta, \lambda)$
- States s and s' are *equivalent* if for each input sequence $\alpha \in X^*$ it holds that $\lambda(s, \alpha) = \lambda(s', \alpha)$
- States s and s' are *distinguishable* if there exists input sequence $\alpha \in X^*$ such that $\lambda(s, \alpha) \neq \lambda(s', \alpha)$; α is *distinguishing* sequence for s and s'
- The length of a distinguishing sequence for two states in (completely specified) FSM does not need to exceed the number of states
- A is *reduced* (minimal) if it has no equivalent states
- Each completely specified FSM has a unique reduced form

Conformance Relation for Mealy Machines

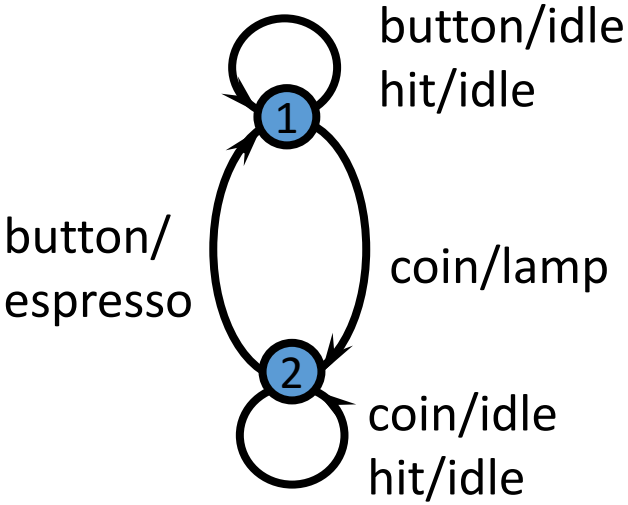
- Conformance relation is equivalence
- Conforming IUT is modelled by a machine equivalent to the specification machine
- For each nonconforming IUT there exists an input sequence distinguishing it from the specification machine; this is a test on which it fails

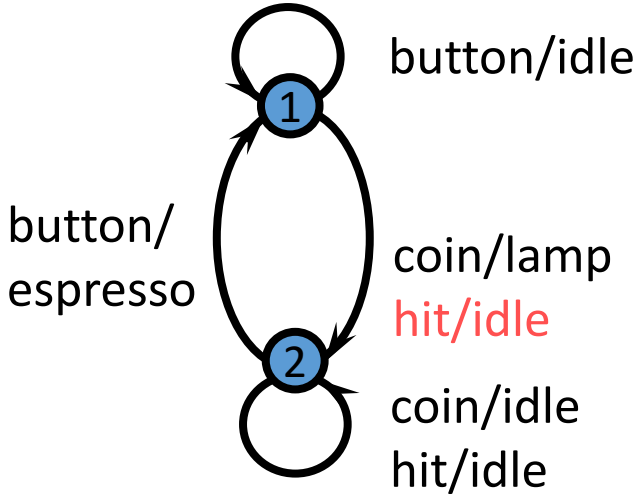
Faults in FSM Implementations

- Faults are modelled as mutants of a specification machine forming a fault domain
- Mutations mimic the implementation process
- Initialization fault – wrong initial state
- Output fault - wrong output of transition
- Transfer fault - wrong end state of transition
  - Creating additional states
  - Reducing or maintaining the number of states
- Transition fault - wrong output or end state of transition
- Mutants can have multiple faults (high order mutants)

Mutation Testing with FSM

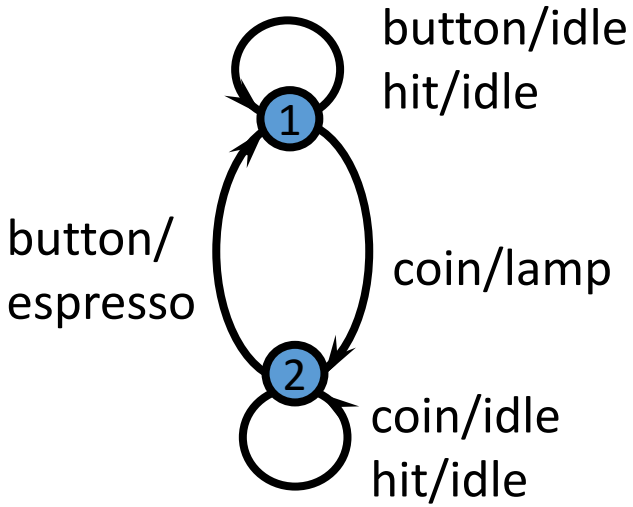
- Mutation testing is suggested first in 1964 for FSM; each mutant models specific type of hardware faults (stuck-at 0, 1)
- It predates software mutation testing
- Tests are obtained by mutant killing

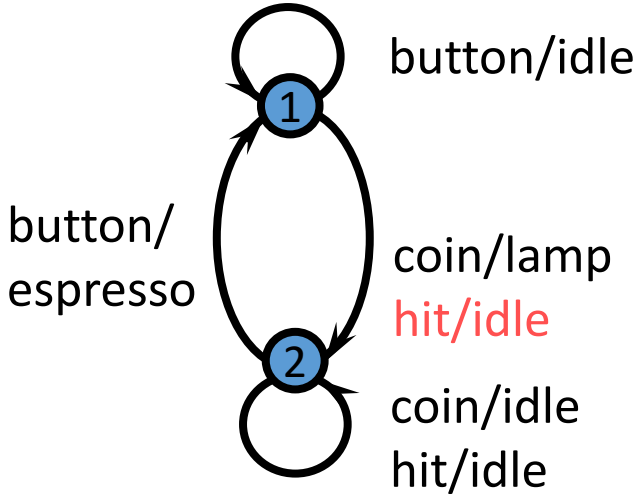




Mutant Killing

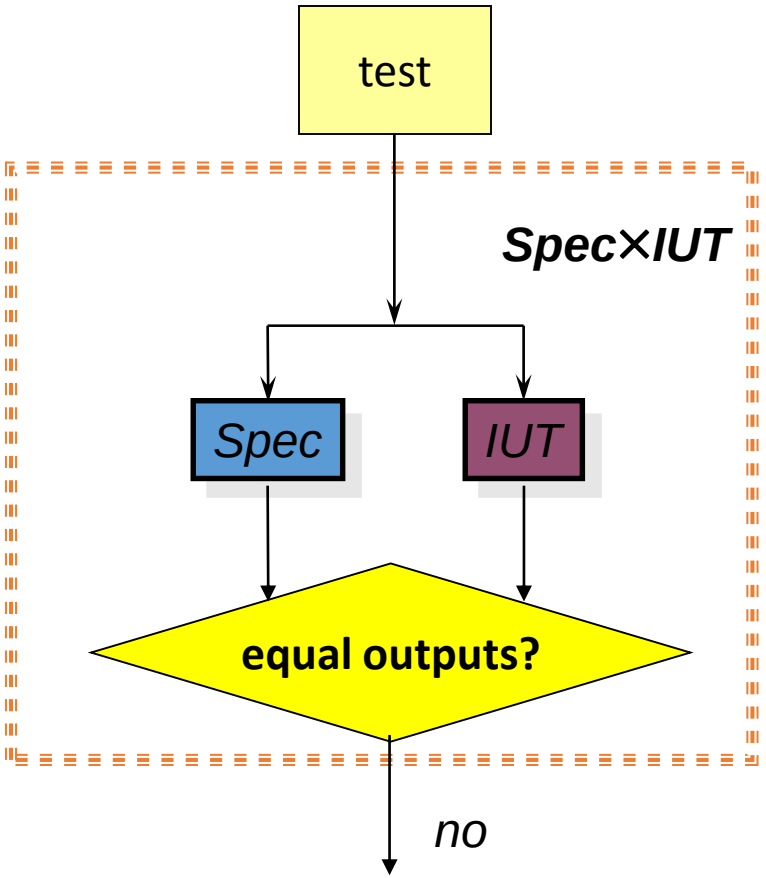
Test hit.button kills the mutant





FSM Mutant Killing

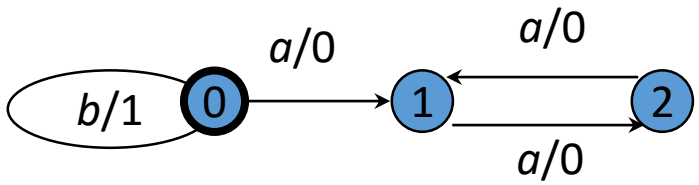
Spec and mutant *IUT*



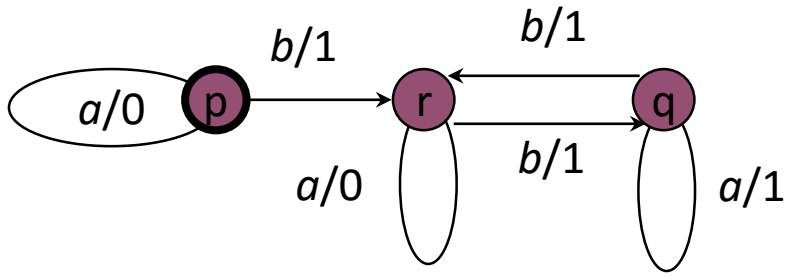
This is *FSM product* used, e.g., for verification purposes

Mutant Killing with FSM Product Equipped with Fail State

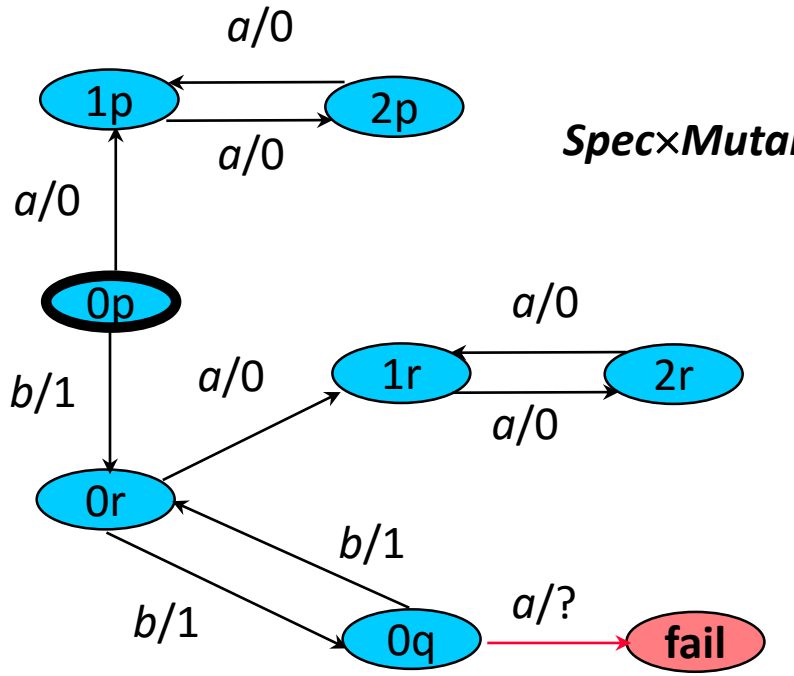
FSM *Spec*



FSM *Mutant*



Spec*×*Mutant



All ests distinguishing ***Mutant*** and ***Spec***
are given by the paths to the fail-state
bba, *bbbba* and so on. *b*{*bb*}**ba*
If the product has no fail-state, the mutant conforms to ***Spec***

General Fault Domain

- A set of mutants each modelling a particular test assumption
- A general fault domain is the universe of all machines with a predefined maximal number of states *m*
- The number of all Mealy machines with *m* states, *p* inputs, *o* outputs is

$$(m \times o)^{m \times p}$$

- Test assumption is that anything may go wrong, i.e., all transition faults, but the number of states in IUT does not exceed a chosen limit *m*
- Complete test suites for this fault domain are traditionally called checking experiments, aka m-complete test suites

Deriving Complete Test Suite for Enumerated Mutants

Fault domain is a list of arbitrary mutants

Step 1. For each mutant in a fault domain

- Construct the product
- Determine one or several tests killing the mutant

Step 2. Determine a minimal number of tests killing all mutants by solving a set cover problem

- More mutants need more tests
- Mutant enumeration can be avoided following the state identification approach (checking experiment)

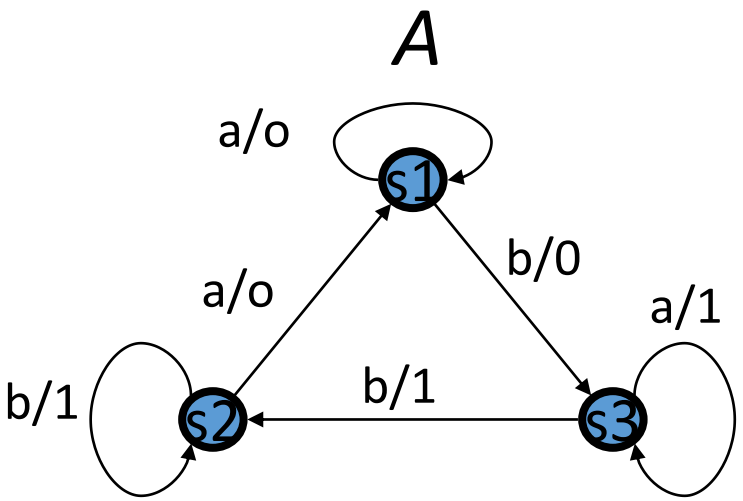
State Identification (Complete Tests for Initialization Faults)

- Fault domain is a set of mutants, each mutant is an instance of the specification machine $A = (S, s_0, X, Y, \delta, \lambda)$ initialized in a different state, i.e., $M_i = (S, s_i, X, Y, \delta, \lambda)$, $s_i \neq s_0$
- The number of mutants is $n - 1$, where n is the number of states in the specification machine
- A complete test suite $W(s_0)$ is a set of input sequences distinguishing s_0 from all the other states
- $W(s_0)$ is a *state identification experiment* for state s_0 or simply *state identifier* for s_0

Variety of State Identifiers

- Let $W(s_0)$, …, $W(s_{n-1})$ be state identifiers for $A = (S, s_0, X, Y, \delta, \lambda)$
- If $W(s_0) = \ldots = W(s_{n-1}) = W$ then W is a *characterization* set of A
- If $W(s_i)$ is a singleton then it is called a *UIO* sequence of s_i
  it provides an output signature of the state
- If a sequence is an UIO of all the states then it is a *distinguishing* sequence of A
- Family of *Harmonized* State Identifiers (HSI) $\{W(s_0), \ldots, W(s_{n-1})\}$ such that in each pair of state identifiers $W(s)$ and $W(s')$ there exist two sequences with a common prefix α, such that $\lambda(s, \alpha) \neq \lambda(s', \alpha)$

Example



	a	*b*
s_1	$s_1/0$	$s_3/0$
s_2	$s_1/0$	$s_2/1$
s_3	$s_3/1$	$s_2/1$

$W(s_1) = b$ is UIO

$W(s_3) = a$ is UIO

$W(s_2) = \{a, b\}$, s_2 has no UIO sequence

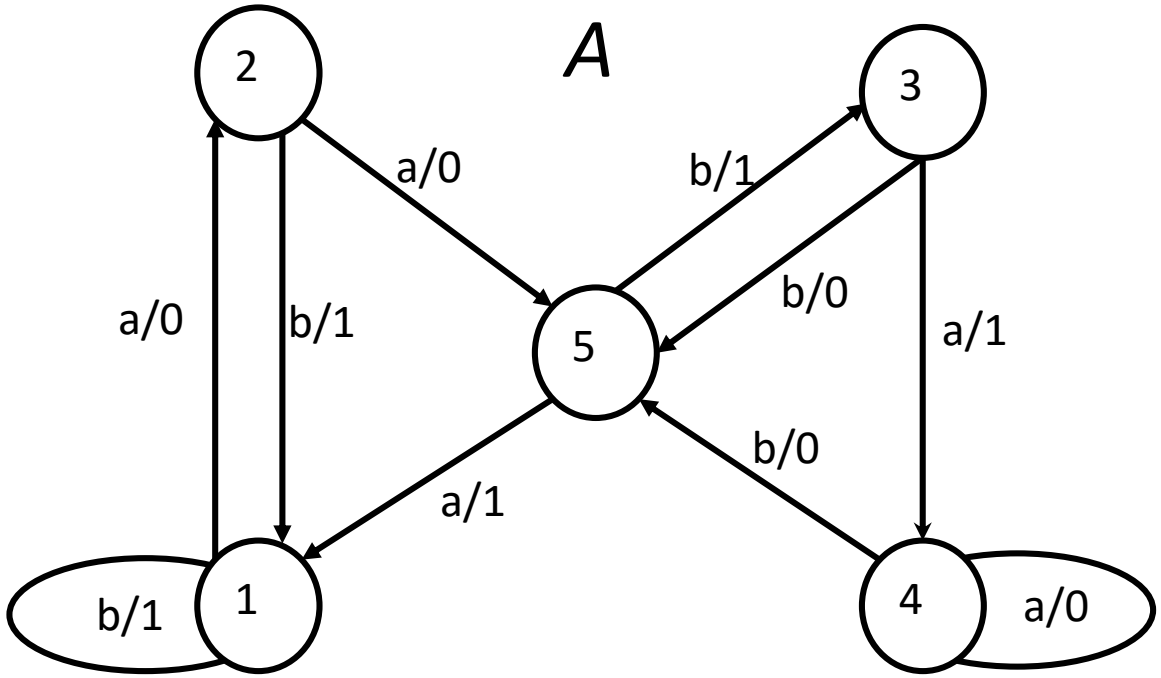
$\{a, b\}$ is a characterization set of A

A has no distinguishing sequence:

If we take a then states s_1 and s_2 are no longer distinguishable

If we take b then states s_2 and s_3 are no longer distinguishable

Distinguishing Sequence for FSM

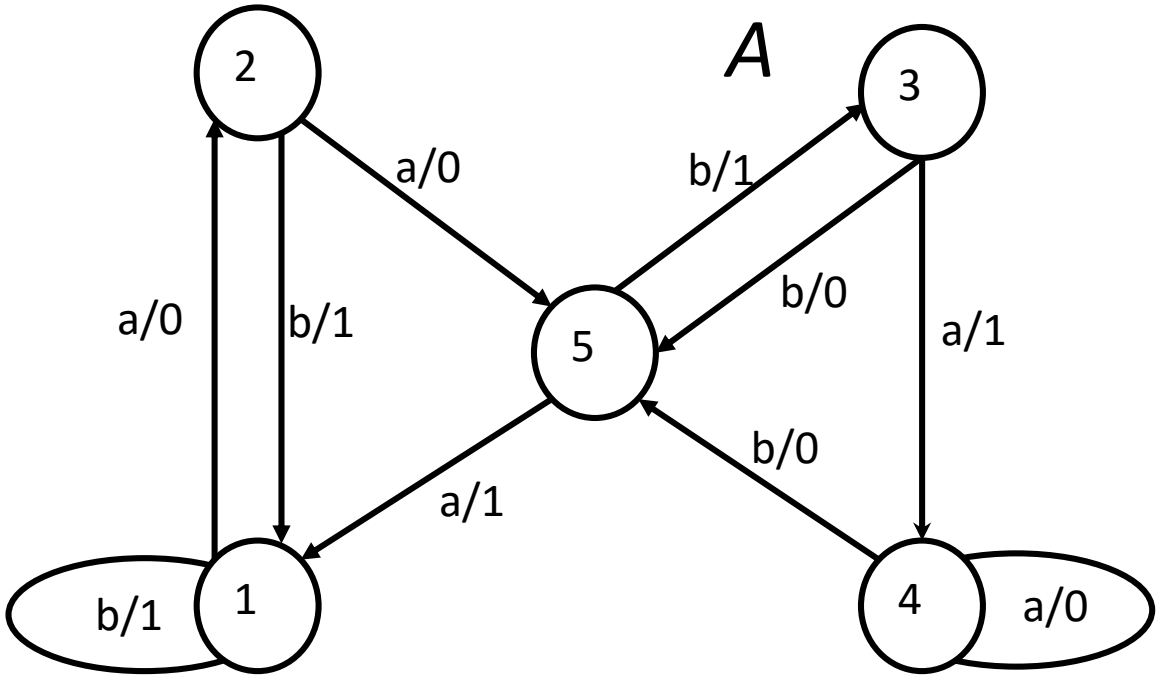


aba is a distinguishing sequence for *A*

Output sequences

	a	*b*	*a*
1	0	1	0
2	0	1	1
3	1	0	1
4	0	0	1
5	1	1	0

Example of Harmonized State Identifiers



Output sequences

	a	*b*	*a*
1	0	1	0
2	0	1	1
3	1	0	1
4	0	0	1
5	1	1	0

$W = \{aba\}$
$W(1) = \{aba\}$
$W(2) = \{aba\}$
$W(3) = \{ab\}$
$W(4) = \{ab\}$
$W(5) = \{ab\}$

Family of Harmonized State Identifiers $\{W(1), W(2), W(3), W(4), W(5)\}$

What Are State Identifiers For?

- Used by various methods which generate complete test suites for Mealy machines
- Characterization sets in the W-method
  (Vasilevskiy, 1973; Chow 1978, improved by Bochmann et al 1991, Wp-method)
- Distinguishing sequences in the DS-method
  (Hennie 1964; continuously being improved)
- UIO sequences in the UIOv-method
  (Vuong, 1989)
- Harmonized State Identifiers in the HSI-method
  (Petrenko & Yevtushenko, 1990; later H and SPY methods)

M-Complete Test Suite

- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is a reduced Mealy machine $A = (S, s_0, X, Y, \delta, \lambda)$, $|S| = n$
- Conformance relation is equivalence
- Fault domain is the universe of all machines with a predefined maximal number of states m
  - Fault do not increase the number of states, $m = n = |S|$
  - Faults may increase the number of states, $m \geq n = |S|$
- Test suite complete for such a fault model is called *m-complete* test suite

The Basic Idea of Constructing M-Complete Test Suites For FSM

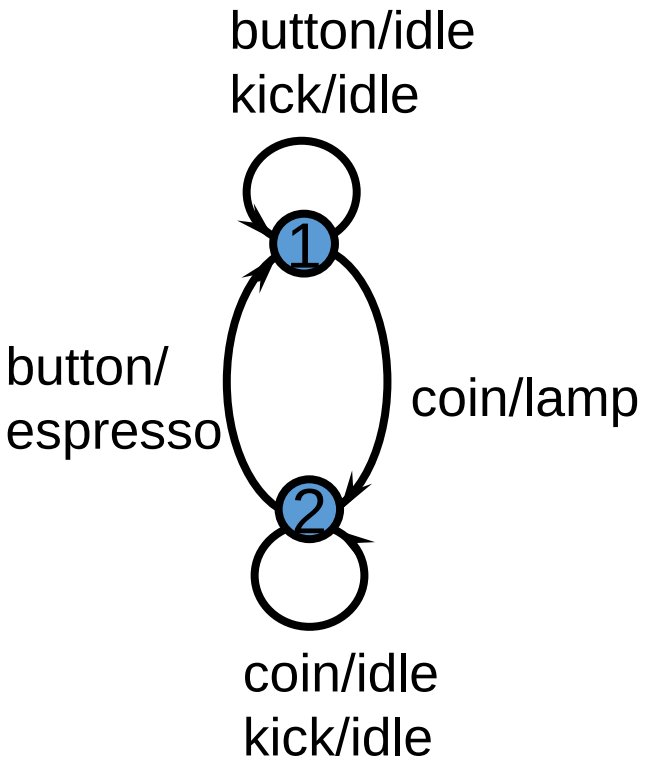
- Reach every state in any IUT from the fault domain
- Check each reached state using some state identifiers built from the specification FSM
- Execute all transitions from each reached state
- Check the end state of each transition using the same state identifiers
- Corresponding test fragments are
  - transfer sequences to reach states in the specification FSM
  - sets of sequences extending the transfer sequences to execute all transitions from IUT states
  - state identifiers

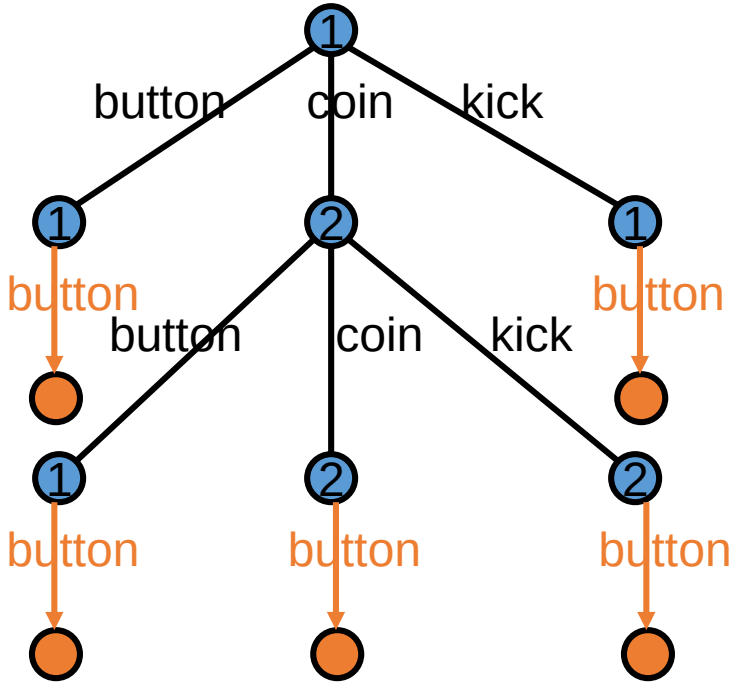
W-method for N-complete Test Suite

- $A = (S, s_0, X, Y, \delta, \lambda)$ with n states
- Determine a single transfer sequence for each state, obtaining a state cover $V = \{\alpha_0, \ldots, \alpha_{n-1}\}$, where $\alpha_0 = \varepsilon$, empty sequence;
- Determine a transition cover by adding each input to every transfer sequence in the state cover $V\!X = \{\alpha_i x \mid \alpha_i \in V, x \in X\}$
- Construct a characterization set W
- Concatenate sets $V \cup V\!X$ and W to obtain an n-complete test suite

$$(V \cup V\!X)W = \{\alpha\beta \mid \alpha \in (V \cup V\!X), \beta \in W\}$$

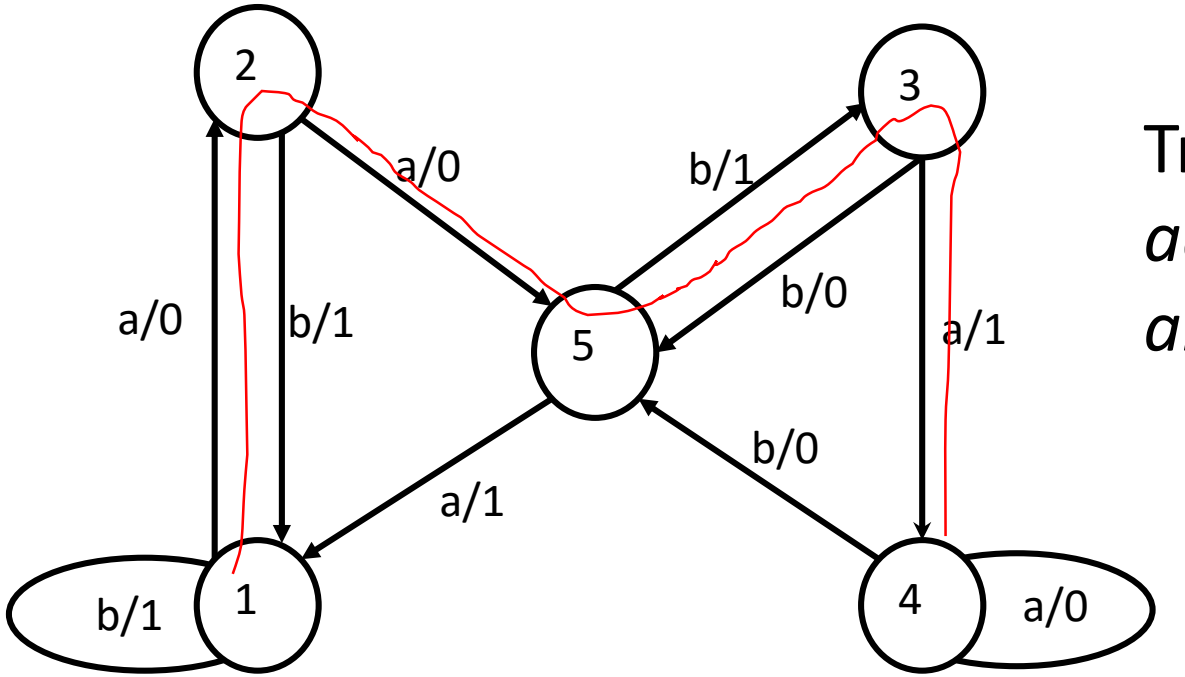
Example with W-method, I





button identifies the states, it is a DS
so is **coin**, but it is more expensive ☺

Example with W-method, II



State Cover $V = \{\varepsilon, a, aa, aab, aaba\}$

Transition Cover $VX = \{\varepsilon, a, aa, aab, aaba\}\{a, b\} = \{a, aa, aaa, aaba, aabaa, b, ab, aab, aabb, aabab\}$

Choose, e.g., $W = \{aba\}$

$(V \cup VX)W = \{\varepsilon, a, aa, aab, aaba, aaa, aabaa, b, ab, aabb, aabab\}\{aba\} = \{aba, aaba, aaaba, aababa, aabaaba, aaaaba, aabaaaba, baba, ababa, aabbaba, aabababa\}$

W-method for M-Complete Test Suite

- Fault domain is the universe of all machines with a predefined maximal number of states m, fault may increase the number of states, $m \geq n = |S|$
- The number of additional states in IUT can reach $m - n$; any additional state can be reached by an state cover extended with all input sequences of length at most $m - n$ in the set $X^{\leq(m - n)}$
- Transition cover then becomes $VX^{\leq(m - n)}X = VX^{\leq(m - n+1)}$
- M-complete test suite is then

$$VX^{\leq(m - n+1)}W$$

- N-complete test suite is a special case of m-complete test suite

$$VX^{\leq 1}W$$

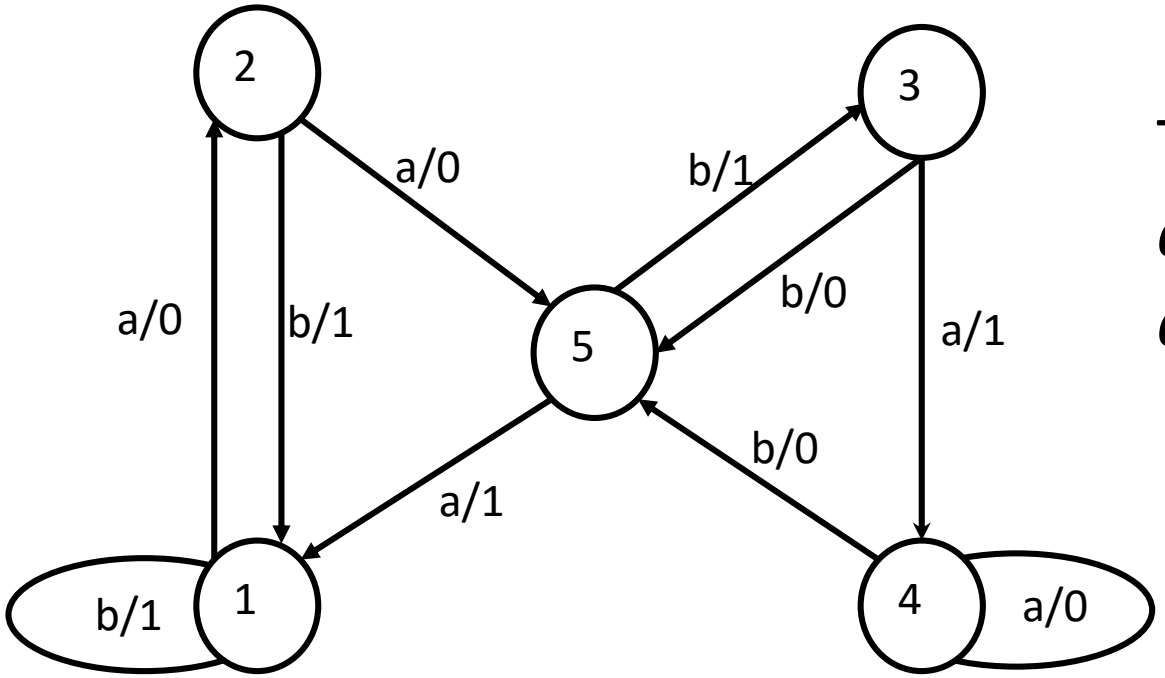
HSI-method

- It uses a family of harmonized state identifiers
  $F = \{W(s_0), \ldots, W(s_{n-1})\}$ instead of a single characterization set

$$VX^{\leq(m-n+1)}@F =$$
$$\{\alpha\beta \mid \alpha \in VX^{\leq(m-n+1)}, \beta \in W(\delta(s_0, \alpha)), W(\delta(s_0, \alpha)) \in F\}$$

- This method allows to define state identifiers for partially specified FSMs which may not have any characterization set

Example with HSI-method



State Cover $V = \{\varepsilon, a, aa, aab, aaba\}$

Transition Cover $VX = \{\varepsilon, a, aa, aab, aaba\}\{a, b\} = \{a, aa, aaa, aaba, aabaa, b, ab, aab, aabb, aabab\}$

HSI: $W(1) = W(2) = \{aba\}$
$W(3) = W(4) = W(5) = \{ab\}$

The resulting n-complete test suite is shorter than the one of W-method, since the latter always concatenates *aba*, while now its prefixes are used

How Complex are Complete Tests for CFSM?

- Given FSM with n states, any two non-equivalent states can already be distinguished by at most n-1 inputs
- We need no more than n-1 input sequences to obtain a characterization set/HSI
- The length of n-complete test is at most pn^3, where p is the number of inputs
- The length of m-complete test is exponential $p^{m-n+1}n^3$, $m \geq n$

Mealy Machine is Completely Specified

- $A = (S, s_0, X, Y, \delta, \lambda)$

  S - finite set of states, s_0 is initial state

  X - finite set of inputs

  Y - finite set of outputs

  $\delta: S \times X \rightarrow S$ - transition function

  $\lambda: S \times X \rightarrow Y$ - output function

- There are partially specified (partial) machines

FSM Redefined

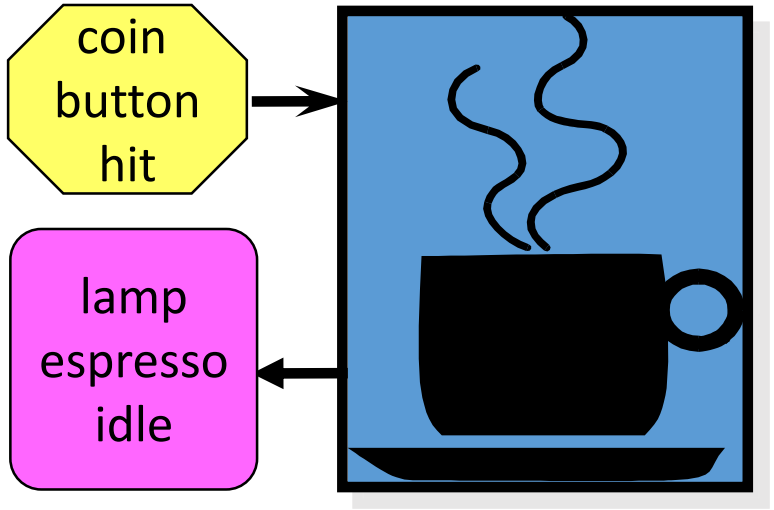
- FSM $A = (S, s_0, X, Y, D, \delta, \lambda)$
  - S - finite set of states, s_0 is initial state
  - X - finite set of inputs
  - Y - finite set of outputs
  - $D \subset (S \times X)$ - specification domain
  - δ: $D \rightarrow S$ - transition function
  - λ: $D \rightarrow Y$ - output function

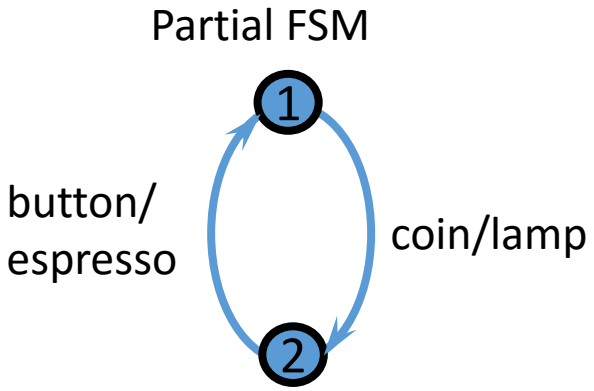
Complete FSM if $D = S \times X$; *partial* FSM (PFSM) if $D \subset (S \times X)$

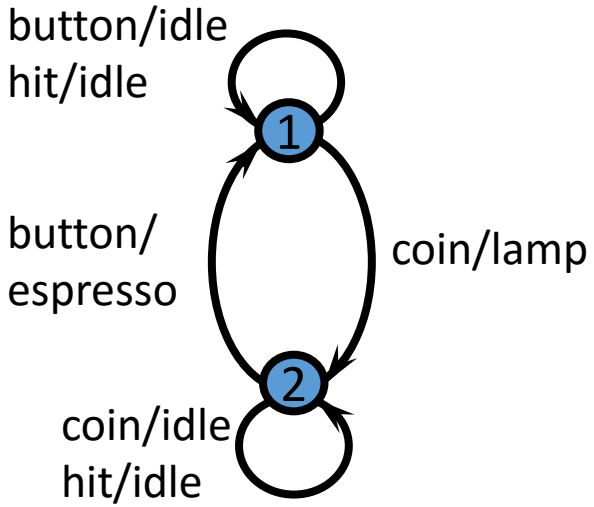
Acceptable input sequences in X^* traverse defined transitions

$\Omega_A(s)$ denote the set of all acceptable input sequences for state s

Example







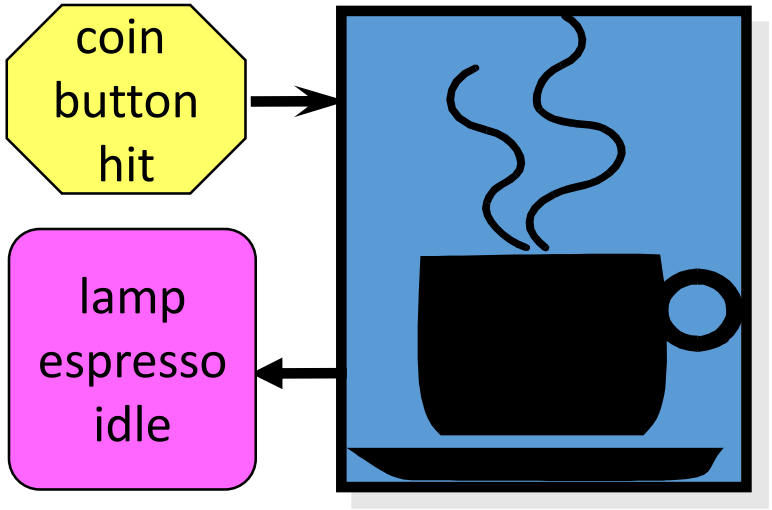
Acceptable sequences – (coin.button)*
It is a partial test model, but FSM implementations are completely specified

How Missing Transitions Can Be Treated?

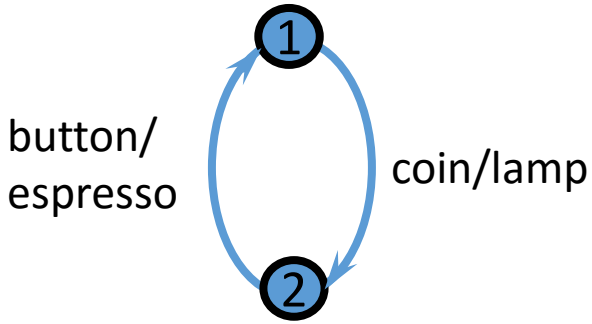
The behavior is not specified for some states and inputs, i.e., some transitions are missing

- *Implicitly defined* transitions
  - self-loops with the output “null/idle”, inputs are ignored (angelic completion)
  - Transitions lead to a sink state with the output “error”
- *Undefined by default* transitions, i.e., don’t care transitions lead to a chaos sink state with all outputs (demonic completion)
- *Forbidden* transitions
  - The environment cannot provide certain input sequences, e.g., testing via context (see slides later)
  - Certain tests are not allowed (Chernobyl)
  - Input variables can change only one at a time

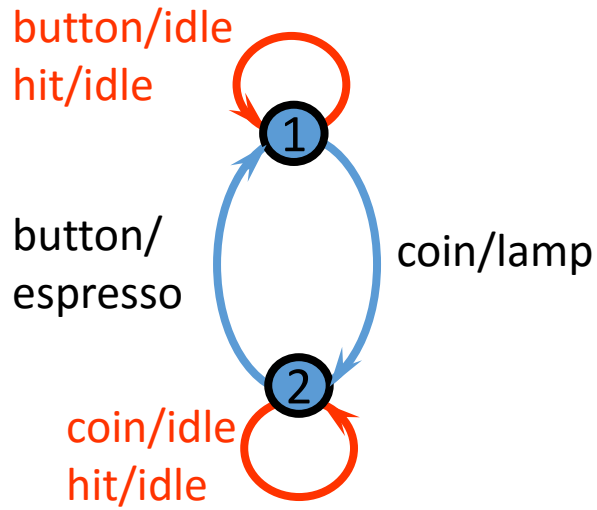
Example



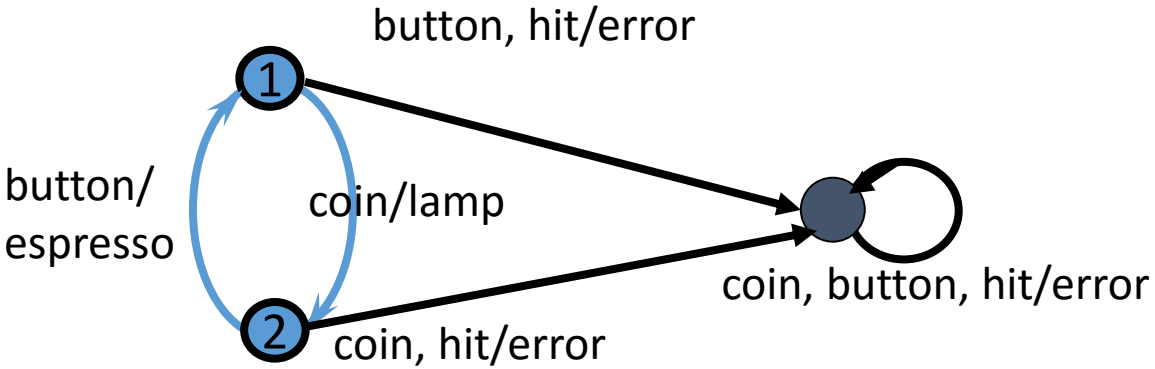
Partial FSM

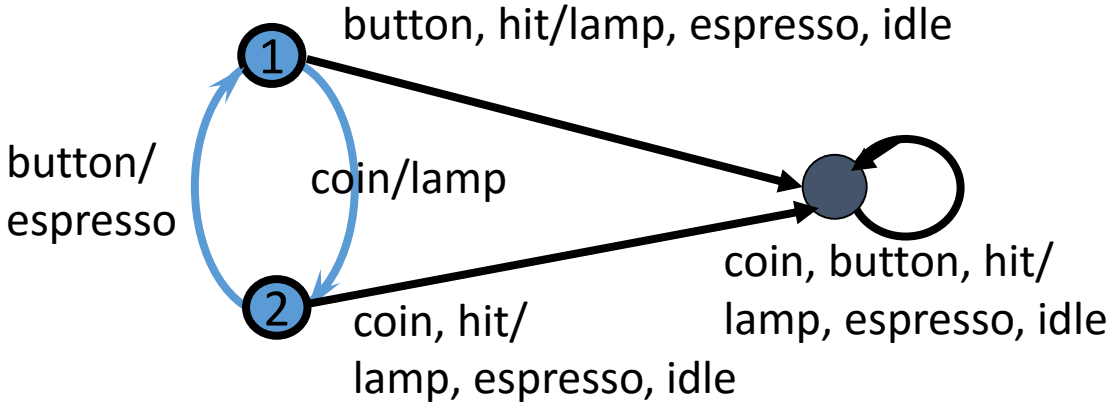


Implicitly defined transitions



Undefined by default transitions





Testing from Partial FSM

- Input enableness is usually assumed for implementations
- Following a chosen completeness assumption implicitly defined and undefined by default transitions become explicitly defined and a partial FSM is sometimes replaced for testing by a complete FSM
- Do we actually know how PFSM was completed in IUT?
- Partial FSM with forbidden transitions cannot be replaced by any complete FSM
- The equivalence conformance relation needs to be weakened and fault models adapted

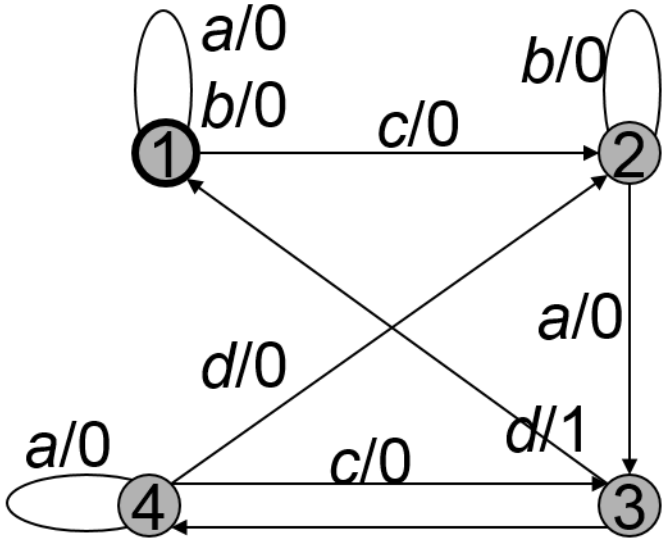
PFSM Relations

- $A = (S, s_0, X, Y, D, \delta, \lambda)$
- States s and s' are *compatible* if each input sequence acceptable in both states produces the same output sequence
  $\Omega_A(s) \cap \Omega_A(t) = \varnothing$ or $\lambda(s, \alpha) = \lambda(s', \alpha)$ for all $\alpha \in \Omega_A(s) \cap \Omega_A(s')$
- s' is *quasi-equivalent* to s if they are compatible and sequences acceptable in s are also acceptable in s'
  $\lambda(s, \alpha) = \lambda(s', \alpha)$ for all $\alpha \in \Omega_A(s)$ and $\Omega_A(s') \supseteq \Omega_A(s)$
- States s and s' are *distinguishable* if there exists $\alpha \in \Omega_A(s) \cap \Omega_A(s')$ such that $\lambda(s, \alpha) \neq \lambda(s', \alpha)$
- The length of a distinguishing sequence for two states does not need to exceed "n choose 2" = $n(n\text{-}1)/2$; cf. n for complete FSM
- A is *reduced* if it has no compatible states
- Compatibility is not transitive so partial FSM can have several reduced forms as opposed to complete FSM

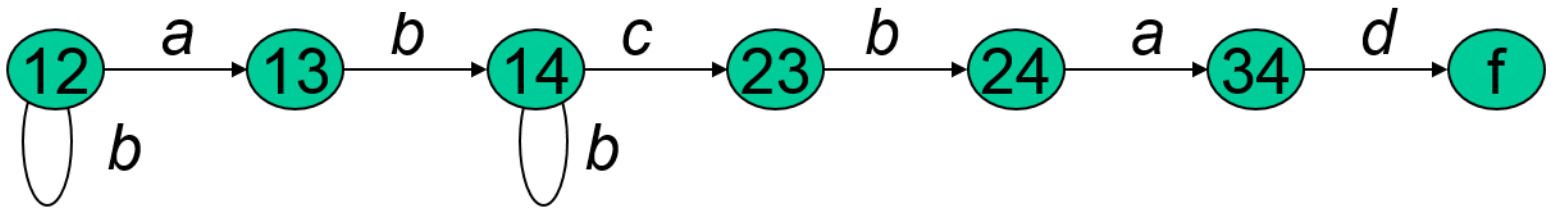
Upper Bound for Distinguishing Sequences in PFSM

Determining a sequence distinguishing states 1 and 2

The bound "*n* choose 2" is tight



	a	b	c	d
1	1/0	1/0	2/0	
2	3/0	2/0		
3		4/0		1/1
4	4/0		3/0	2/0



M-Complete Test Suite for PFSM

- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is a partial not necessarily reduced FSM
  $A = (S, s_0, X, Y, D, \delta, \lambda)$
- Conformance relation is quasi-equivalence,
  since all IUTs are complete machines
- Fault domain is the universe of all complete machines
  with a predefined maximal number of states m
- The bound m cannot be lower than the number of pairwise distinguishable states in A which can be smaller than $n = |S|$

Building m-Complete Test Suite for PFSM

- State identification approach fails because of compatible states
- State-Counting approach (Petrenko & Yevtushenko, 1989, 2000) generalizes the state identification approach
- The idea is based on the above example:
  determine all acceptable input sequences from each state such that each state of the specification is traversed at least *m* times
- The value of *m* can be reduced if the specification has
  - quasi-equivalent or
  - distinguishable states, so state distinguishing sequences can be employed

Mealy Machine is Deterministic

- $A = (S, s_0, X, Y, \delta, \lambda)$

  S - finite set of states, s_0 is initial state

  X - finite set of inputs

  Y - finite set of outputs

  $\delta: S \times X \rightarrow S$ - transition function

  $\lambda: S \times X \rightarrow Y$ - output function

- There are nondeterministic machines

FSM Redefined Again

$A = (S, s_0, X, Y, T)$

S - finite set of states, s_0 is the initial state

X - finite set of inputs

Y - finite set of outputs

T - transition relation $T \subseteq S \times X \times Y \times S$
quadruple $(s, x, y, s') \in T$ is a transition

A is *complete* if for each $(s, x) \in S \times X$ it has at least one transition

deterministic if for each $(s, x) \in S \times X$ it has at most one transition

nondeterministic if for some $(s, x) \in S \times X$ it has several transitions

observable if for each $(s, x, y) \in S \times X \times Y$ it has at most one transition;
non-observable FSM can be made observable by determinization

Is Nondeterminism Really a Problem in Testing?

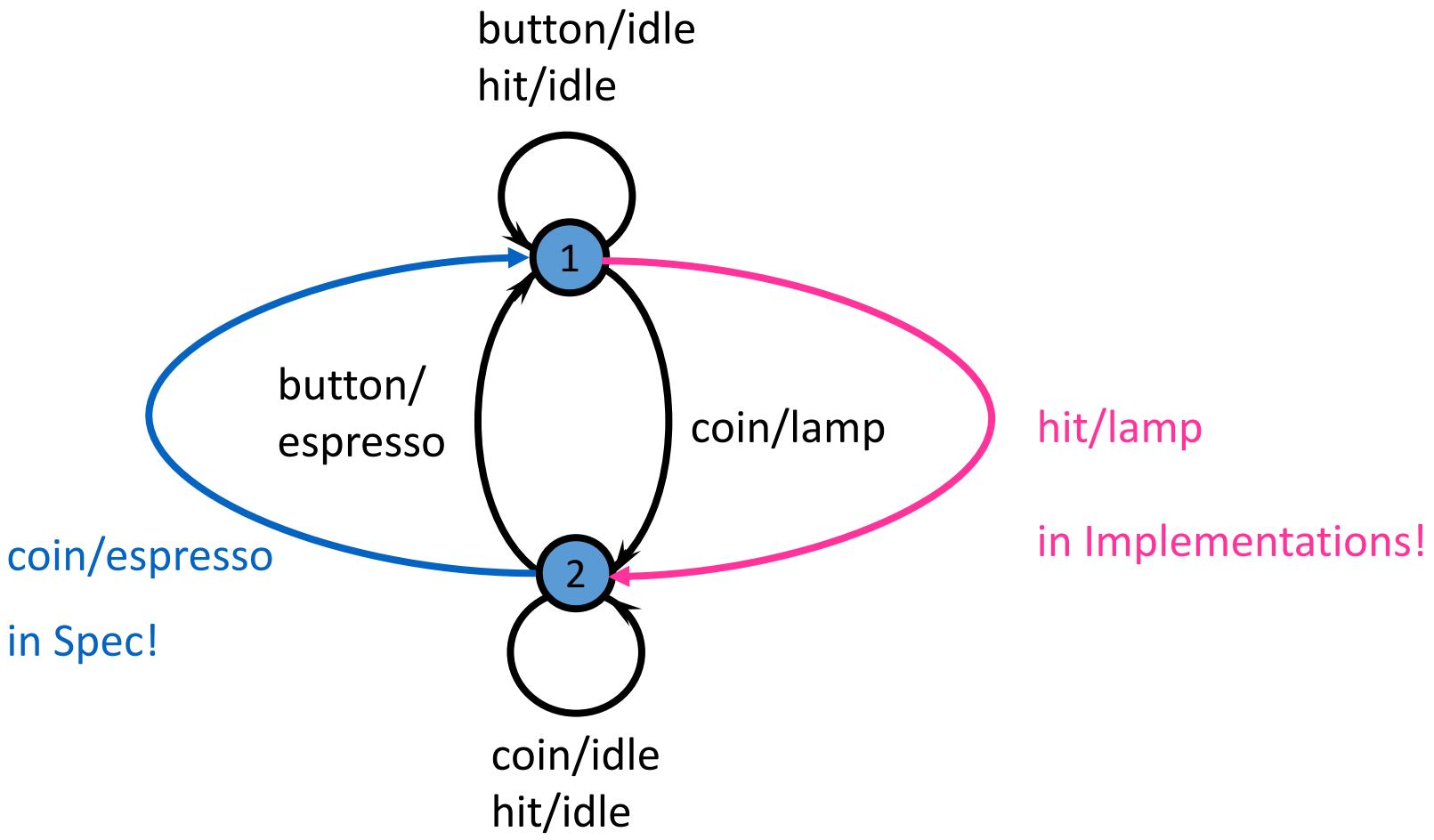
- Nondeterminism contradicts the general feeling that computer systems are deterministic, so we might wonder whether there is any real meaning to use the term nondeterminism, or whether it is a useful, but essentially meaningless, formal trick (A. J. Dix, 1990)

- It is a good practice to design systems for testability, and one important aspect of testability is that you can reproduce test results many times, and this implies that the system should be as deterministic as possible. The issue of testing nondeterministic systems is therefore, albeit real, relatively minor at least in the current practice (A. Huima, 2011)

Various Sources of Nondeterminism

- Concurrency modelled by interleavings
- Abstractions, under-specification (undefined by default transitions), options, uncertainty
- Asynchronous communication, unknown delays
- Partial controllability
- Partial observability
- Distributed interfaces: the actual order of events is unknown
- Random choice implemented in some applications

NFSM Example



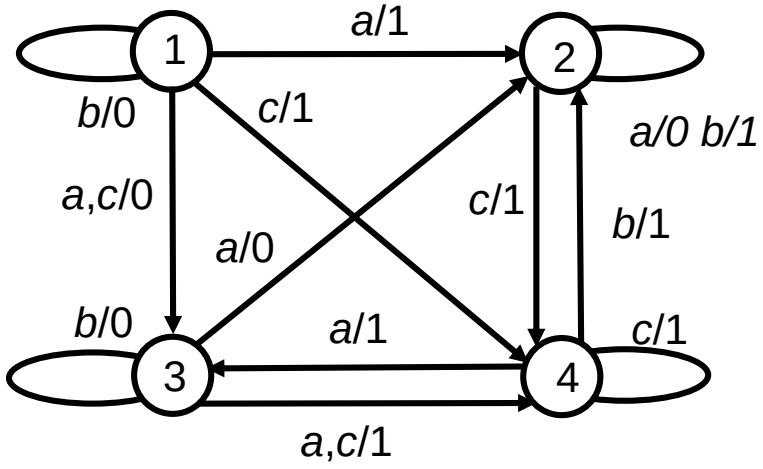
Testing NFSM is a Challenge

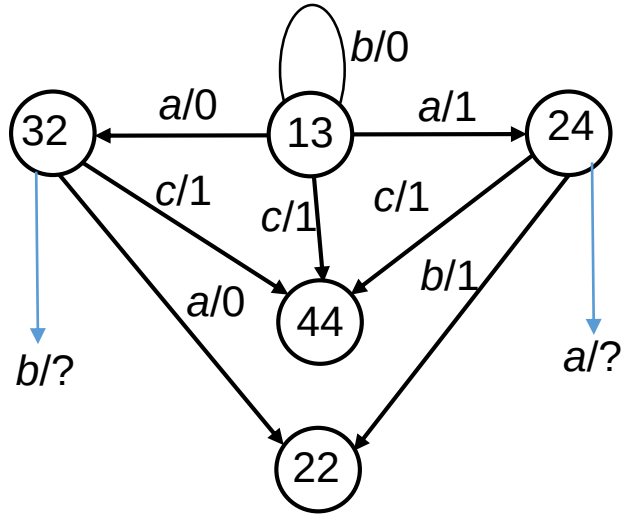
- In NFSM input sequence can produce several output sequences and bring the machine into different states
- Two main test scenarios
  - Specification is nondeterministic, but IUT is deterministic
  - Both, specification and IUT, are nondeterministic
- Testing nondeterministic IUT requires some fairness/all weather assumption:
  there exists *k* such that, if input sequence is applied to IUT *k* times,
  the tester concludes that all possible output sequences are observed
- Testing becomes adaptive, so tests are also NFSM as opposed to DFSM tests which are input sequences

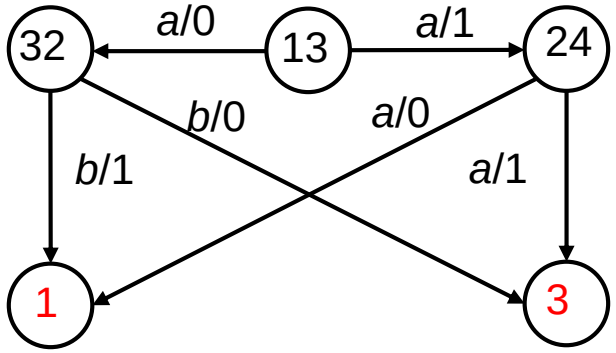
NFSM Relations

- FSM $A = (S, s_0, X, Y, T)$
- States s and s' are (trace) *equivalent* if their sets of traces coincide, i.e., $Tr(s) = Tr(s')$
- s and s' are *distinguishable* if $Tr(s) \neq Tr(s')$, there exists input sequence $\alpha \in X^*$ such that $out(s, \alpha) \neq out(s', \alpha)$
  α is distinguishing sequence for s and s'
- s is a *reduction* of s' if $Tr(s) \subseteq Tr(s')$, trace inclusion
- s and $s'$are *r-compatible*, if they have a common reduction, i.e., there exists a state of a complete FSM that is a reduction of both states
- s and s' are *r-distinguishable*, if they have no common reduction, i.e., no state of any complete FSM can be a reduction of both states
  - several input sequences may be needed
  - the bound is n^2

Example of R-distinguishability







Specification NFSM

Fragment of the product for states 1 and 3

Adaptive test r-distinguishing states 1 and 3

Adaptive tests r-distinguishing states are called *separators*

Fault Models for NFSM

- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is NFSM $A = (S, s_0, X, Y, T)$
- Case 1
  - Fault domain is the universe of all **NFSMs** with a predefined maximal number of states m
  - Conformance relation is trace equivalence
- Case 2
  - Fault domain is the universe of all **NFSMs** with a predefined maximal number of states m
  - Conformance relation is trace inclusion
- Case 3
  - Fault domain is the universe of all **DFSMs** with a predefined maximal number of states m
  - Conformance relation is trace inclusion

M-Complete Test Suite for NFSM and Equivalence Relation

- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is a reduced NFSM $A = (S, s_0, X, Y, T)$
- Conformance relation is trace equivalence
- Fault domain is the universe of all NFSMs with a predefined maximal number of states m
- M-complete test suite can be obtained by mimicking steps of the W-method for DFSM

$$VX^{\leq(m-n+1)}W$$

Fault Model for NFSM and Reduction Relation

- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is an NFSM $A = (S, s_0, X, Y, T)$
- Conformance relation is reduction
- Fault domain is the universe of all NFSMs and DFSMs with a predefined maximal number of states m, not less than the number of pairwise r-distinguishable states
- Multiple test execution only if the fault domain includes NFSMs
- Characterization set W for the equivalence relation cannot be used, separators play its role

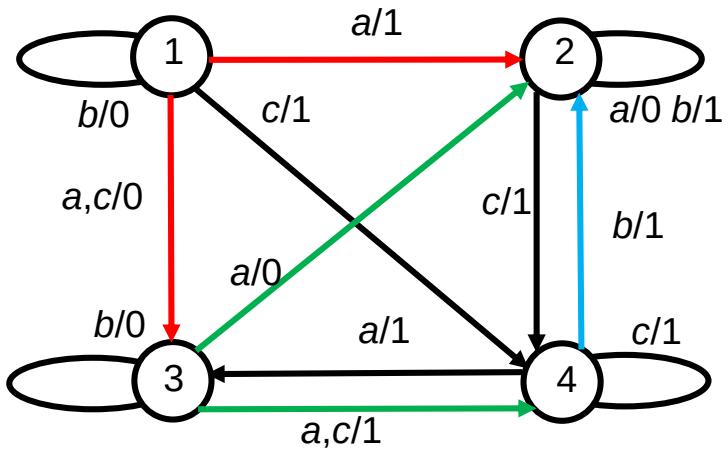
Recall the Basic Idea of Constructing m-Complete Test Suites

- Reach every state in any IUT from the fault domain
- Check the reached state using some state identifiers
- Execute all transitions from each reached state
- Check the end state of each transition using the same state identifiers
- Fragments of complete test suite
  - transfer sequences to reach states in the specification FSM
  - sets of sequences extending the transfer sequences to execute all transitions from IUT states
  - state identifiers

Challenges of Constructing Transfer Sequences

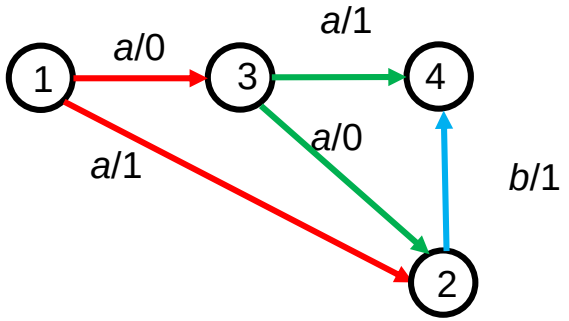
- Transfer sequences to reach states in the specification FSM if it is nondeterministic?
- State reachability for NFSM
  - Reachable by preset transfer input sequence (deterministically reachable)
  - Reachable by adaptive tests, i.e., adaptive preambles (definitely reachable)
  - No adaptive homing test exists
- Some states of NFSM $A = (S, s_0, X, Y, T)$ may not even be implemented in an IUT conforming wrt reduction relation, since it is allowed not to have all the traces of A

State Preamble Example



How state 2 can be reached?

Here is a preamble



Building m-Complete Test Suite For NFSM

- Preambles are used to reach definitely reachable states
- Traversal sequences are determined as in case of partial DFSM, such that each state of the specification is traversed no more than *m* times
- The parameter *m* can be reduced if the specification has
  - r-compatible states or
  - r-distinguishable states
- State separators used for state identifiers

The SC-method by Petrenko & Yevtushenko
(recent versions in 2011 and 2014)

M-Complete Test Suites Come at a Price

- Scalability and expressiveness
  - M-complete tests may explode
  - All the ingredients of the FSM model are finite, as a result such a model without extensions may become to be too big to construct and execute tests
  - FSM model does not support the use of variables/parameters
- How we can deal with this
  - Generate tests incrementally
  - Use communicating FSMs
  - Use mutation machines to specify fault domains as subsets of the universe of all FSMs
  - Consider extended FSM models

Incremental Generation of Complete Test Suite

- The idea is to find sufficient conditions for p-completeness
- Given a test suite determine additional tests which satisfy these conditions
- Increment *p* and iterate until the desired value is reached or the size of the obtained test suite reaches a predefined limit

- See the P-method, see Petrenko & Simao, “Fault Coverage-Driven Incremental Test Generation”, 2009

M-Complete Test Suites Come at a Price

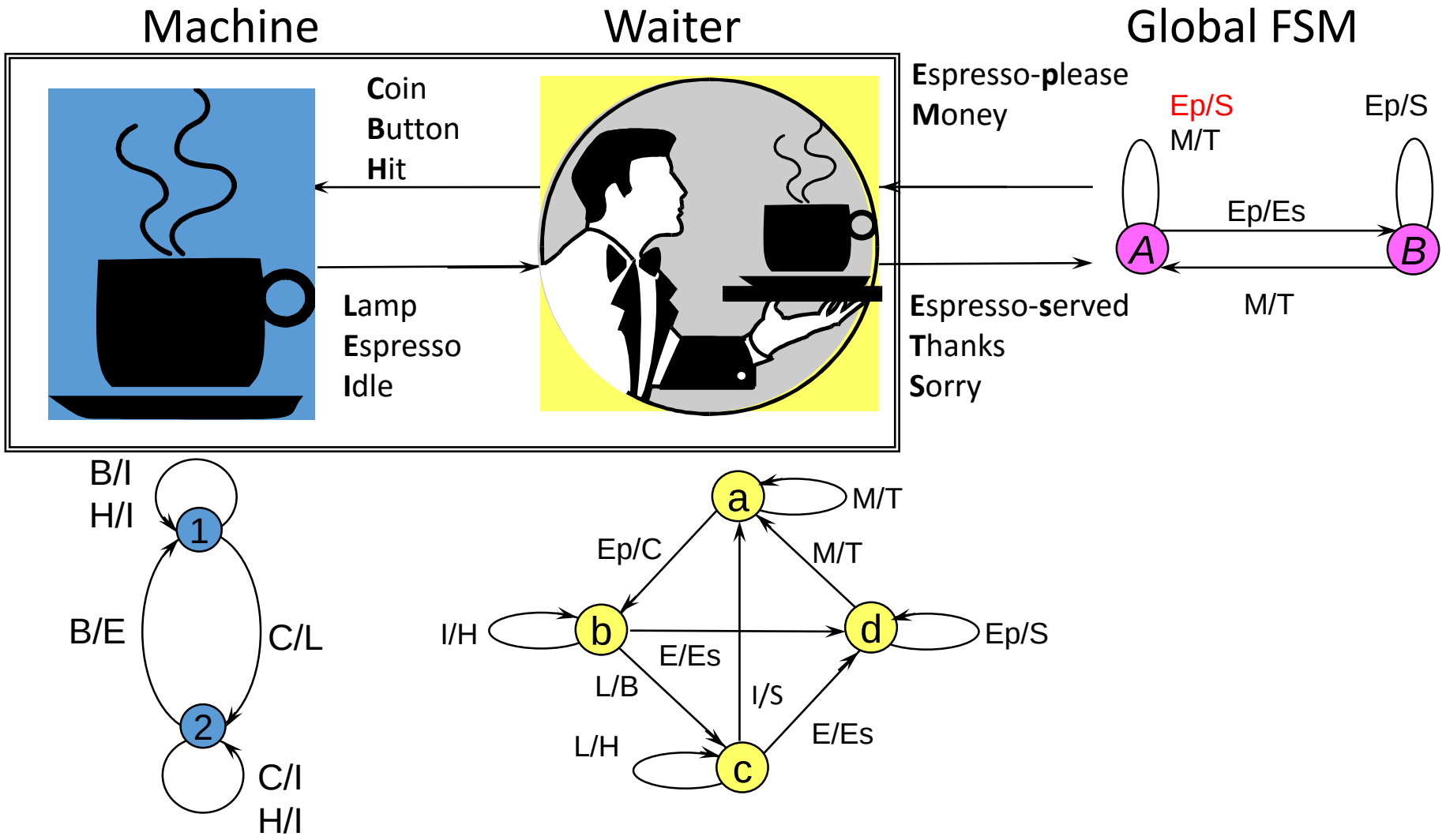
How to deal with this

- Generate tests incrementally
- Use communicating FSMs
- Use mutation machines to specify fault domains as subsets of the universe of all FSMs
- Consider extended FSM models

Testing Communicating FSMs

- Given a system of ComFSM, derive a (complete) test suite using external inputs and outputs
- Variety of testing scenarios
  - faults in individual FSMs or in channels
  - some FSMs are fault-free
  - internal actions are observable or not
  - distributed testing with synchronized testers

Example of Communicating FSMs

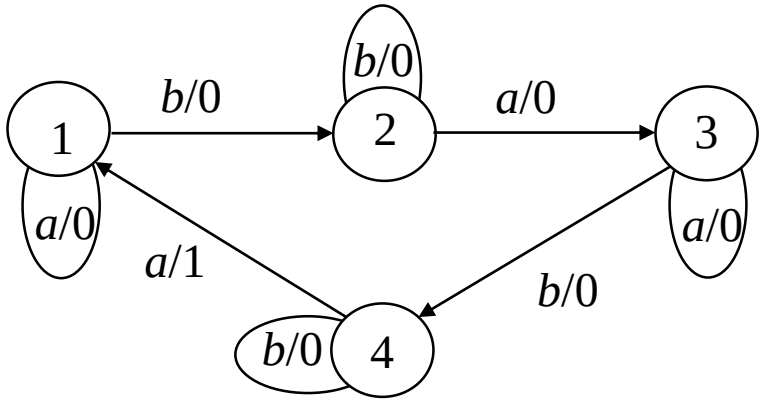


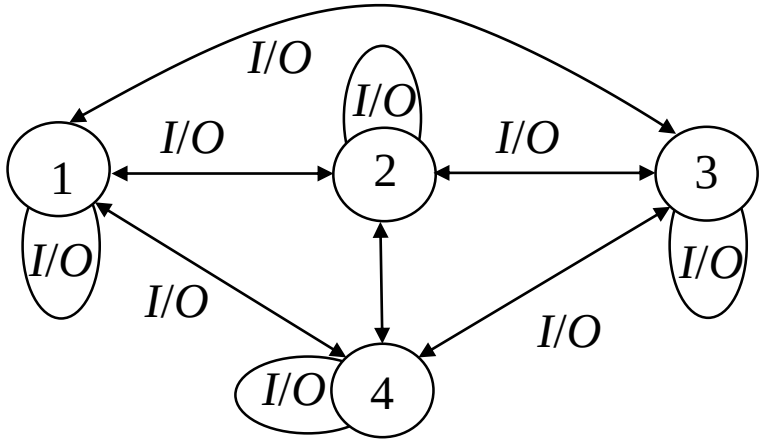
M-Complete Test Suites Come at a Price

How to deal with this

- Generate tests incrementally
- Use communicating FSMs
- Use mutation machines to specify fault domains as subsets of the universe of all FSMs
- Consider extended FSM models

Using Mutation Machines to Specify Fault Domains





$I/O = \{x/y \mid x \in X,\ y \in Y\}$

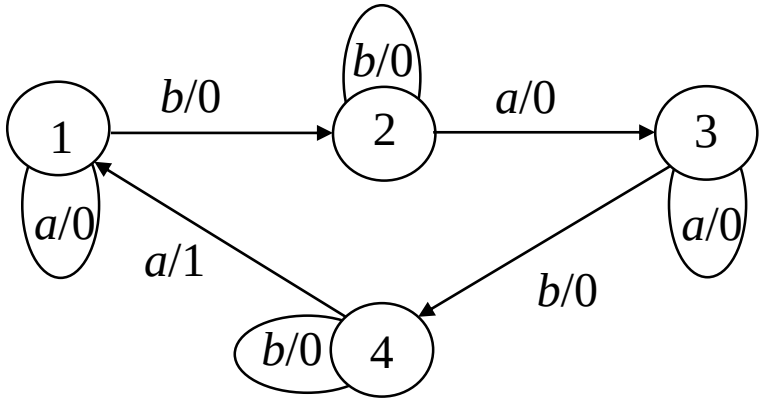
Chaos FSM, which represents all possible mutants in the fault domain with at most 4 states

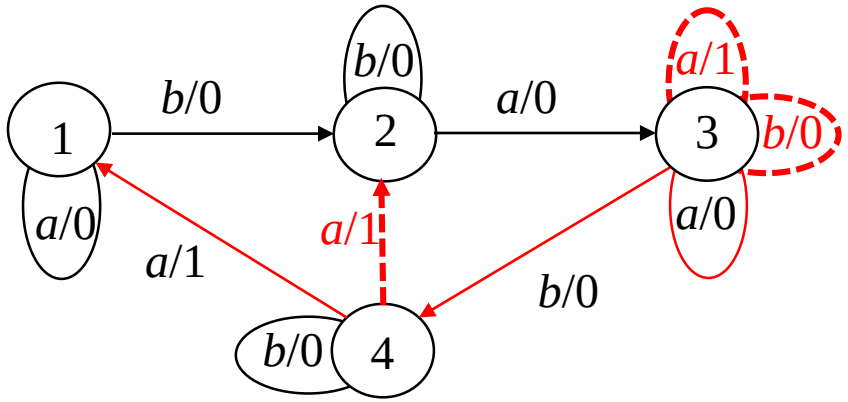
It is called a *mutation machine*, each deterministic submachine is a mutant

Their number is $(|S| \times |O|)^{|S| \times |I|} = (4{\times}2)^{4\times2} =$ 16,777,216

4-complete test suite for this fault model kills all the mutants

Example of Restricted Fault Domain





The mutation machine has 6 suspicious transitions in red
3 mutated transitions in dash lines (output fault and two transition faults
The fault domain includes 8 deterministic submachines, so 7 mutants
they can be enumerated as in mutation testing

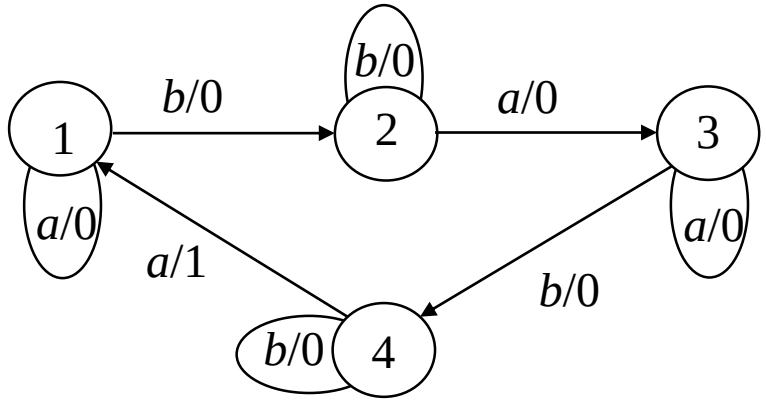
Testing Based on Mutation Machines

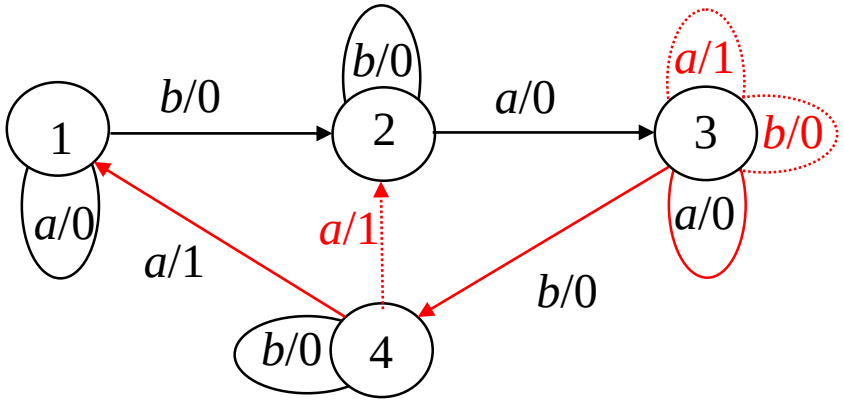
- Fault model is (Specification, Conformance Relation, Fault Domain)
- Specification is a DFSM $A = (S, s_0, X, Y, \delta, \lambda)$
- Conformance relation is equivalence
- Fault domain is the set of all deterministic submachines of A
- Test generation methods using state identification facilities can be adopted to deal with non-chaotic mutation machines
- See our papers co-authored with Koufareva, Yevtushenko and Grunskiy

- Test completeness can be checked for this fault model
- The idea is to use again an FSM product
- See our paper “Multiple Mutation Testing from FSM”, FORTE 2016

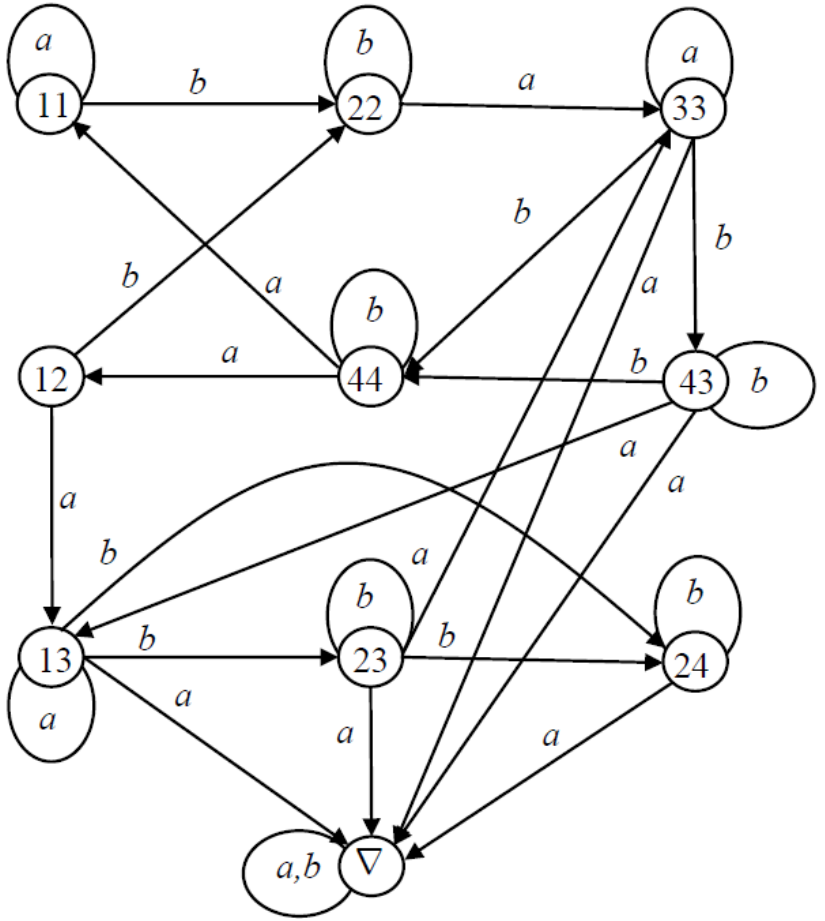
Distinguishing Automaton

Specification FSM





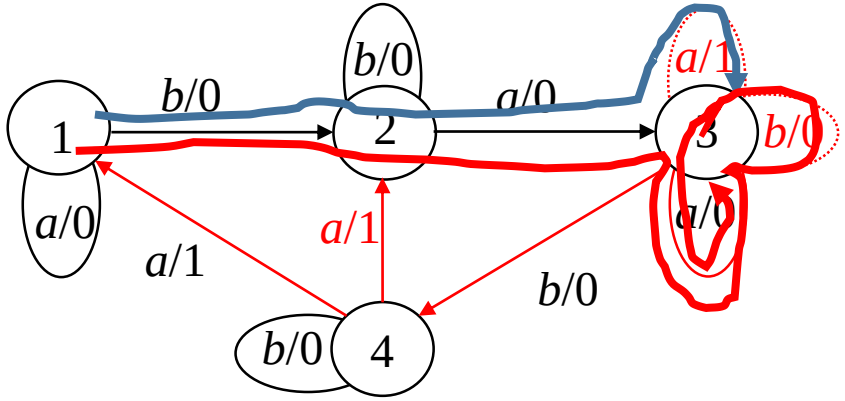
Mutation FSM

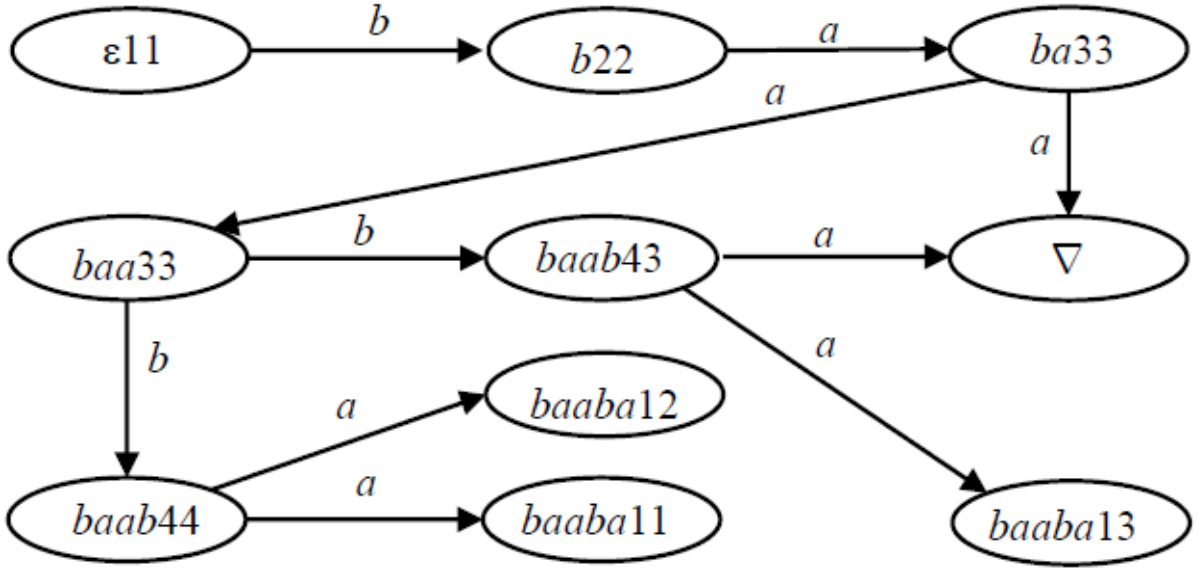


Mutation Coverage Analysis

The idea is to determine constraints on transitions in all the mutants killed by a test case

Example: *baaba*





two revealing executions

Any mutant Is killed by the test *baaba* if it includes suspicious transitions (**3, a, 1, 3**) **OR ((3, a, 0, 3) AND (3, b, 0, 3) AND (3, a, 0, 3))**
The negated constraint characterizes the survived mutants

Checking Test Completeness for a Given Fault Model

Input: a test suite *TS* for a specification and mutation machine

1. For each $\alpha \in TS$, build the disjunction of constraints excluding the α-revealing executions
2. Build the conjunction of the obtained disjunctions and add the constraint that excludes the solution defining the specification machine
3. Check the satisfiability of the constraint by calling a solver
4. If it is not satisfiable terminate with the message "*TS* is complete", otherwise check whether the mutant defined by a solution is conforming
5. If it is nonconforming terminate with the message "*TS* is incomplete", otherwise add the constraint that excludes the conforming mutant and go to Step 3

Experimental Results for Randomly Generated Mutation Machines

A specification for an automotive controller with 336 transitions

	M_{hvac}	M_{+20}	M_{+100}	M_{+428}	M_{+764}
Mut. Trans.	46	66	146	474	810
Mutants	6.9×10^{10}	5.5×10^{16}	3.1×10^{38}	2.2×10^{108}	3.9×10^{163}
Tests	36	55	140	369	1111
Sec.	3	7	24	86	1013

M-Complete Test Suites Come at a Price

How to deal with this

- Generate tests incrementally
- Use communicating FSMs
- Use mutation machines to specify fault domains as subsets of the universe of all FSMs
- Consider extended FSM models

Extended FSM Models

- FSM can be extended with variables, parameters, guards and operations on them (time can also be added)
- Once internal variables are used the number of complete states may become unbounded, so FSM methods are not applicable
- Fault model-based testing of extended FSMs (EFSMs) has not yet reached the level of maturity of that of the classical FSMs
- Mutation approach with mutation operations is applicable
- EFSM equivalence is in general undecidable
- This motivates investigation of special classes of EFSMs for which complete test suites could be derived (FSM with Symbolic Inputs, see our paper in ICTSS 2015)

Complete Test Generation for FSM Needs More Research

- M-complete test suite for partial non-observable NFSM?
- Complete test suites using mutation machines?
- Complete test suites for an arbitrary fault model?
- General types of Extended FSM?

Input/Output Transition Systems

Outline

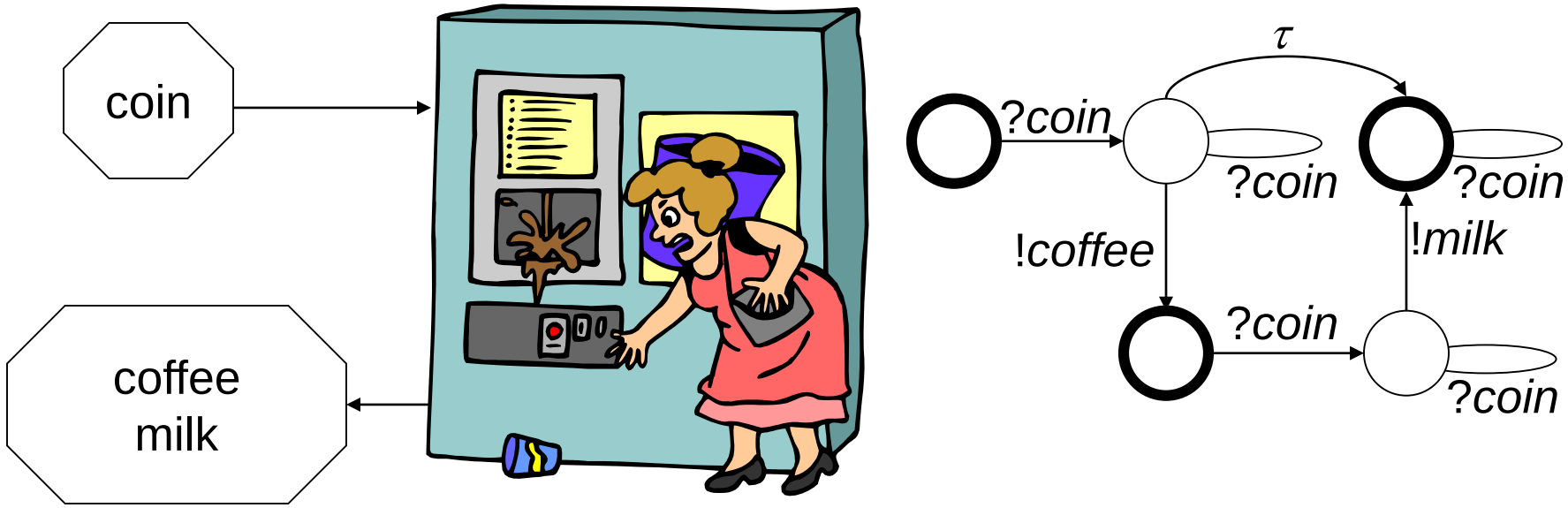
- Informal discussion of IOTS
- For formal definitions and ioco based testing theory,
  see the HSST 2014 tutorial, Tretmans, “Model-Based Testing - There is Nothing More Practical than a Good Theory”
- The ioco conformance relation and problems of using it
- Asynchronous testing
- Special IOTS classes for which complete test suites are suggested
  - Mealy IOTS
  - Input-eager IOTS

Labeled Transition Systems

- Difference between inputs and outputs is abstracted away
- LTS is a finite automaton, every state is accepting
- LTS communicate by rendezvous
- Actions are controllable, “refusal” is observed

- Several refusal-based conformance relations and test methods exist, see Glabbeek, “The linear time-branching time spectrum”, 1990

Example of Input/Output Transition System



State is quiescent if no output is enabled Its observation needs timer

Inputs may occur at states that are not quiescent

Rich choice of conformance relations which use traces, quiescent traces, suspension traces

Input Enableness of IOTS

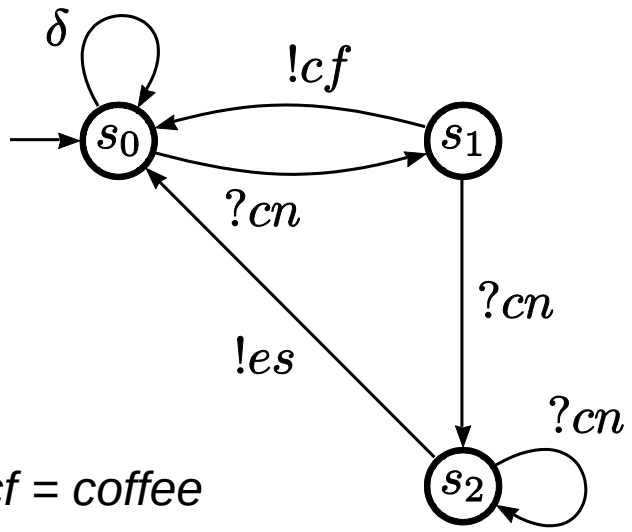
- IOTS is LTS with Input-Output and always enabled inputs
- I/O automaton, interface automaton
- Interpretation of unspecified transitions similar to partial FSM
  - Implicitly defined transitions: inputs lead to a sink state with the output “error”
  - Undefined by default transitions: don’t care transitions lead to a chaos sink state with all outputs (demonic completion)
  - Forbidden transitions: the environment cannot provide some input sequences

IOCO Relation and Test Generation

- *i* ioco-conforms to *s* iff
  - if *i* produces output *x* after trace σ, then *s* can produce *x* after σ
  - if *i* cannot produce any output after trace σ, then *s* cannot produce any output after σ (quiescence δ)
- Test generation algorithm: apply the following steps recursively, non-deterministically:
  - Terminate with **pass**
  - Give a next input to the IUT
  - Check the next output of the IUT
- If it is executed infinitely long, a complete test suite is obtained, but it is not finite
- If it yields a finite test suite its fault coverage is unknown
- Most of the existing work is on test purpose-based test generation and not on fault coverage
- Variety of ioco-like relations retaining its main features

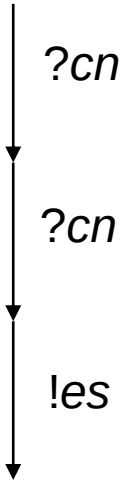
The Use of IOCO for Testing is Problematic

For general type of IOTS tests for this relation need to block outputs, may not be sound and controllable

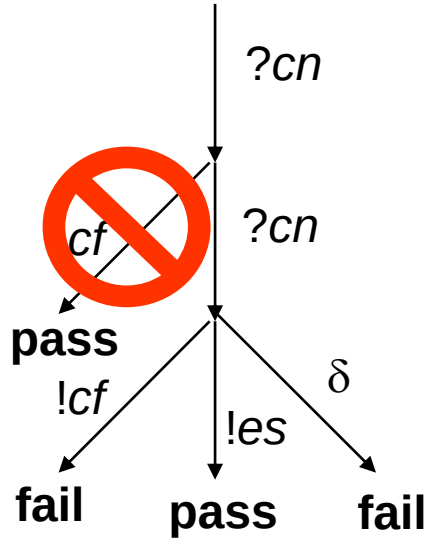


!cf = coffee
!es = espresso
?cn = coin
δ = quiescence

Test Purpose



Synchronous Test



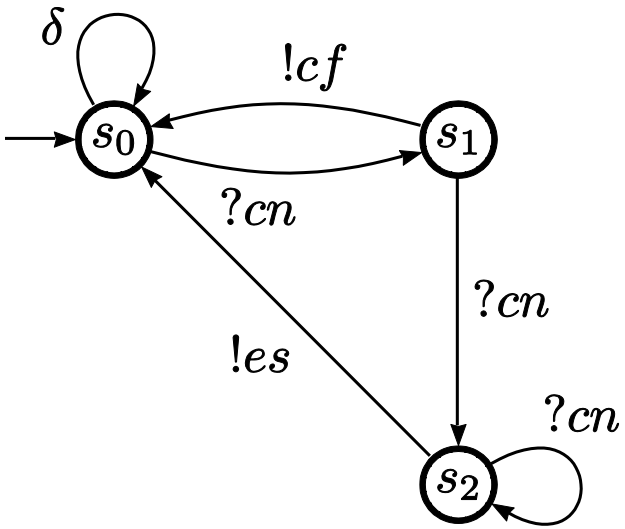
IOCO-based test blocks outputs according to version 1996 and TGV

To Block or Not to Block, That is the Question

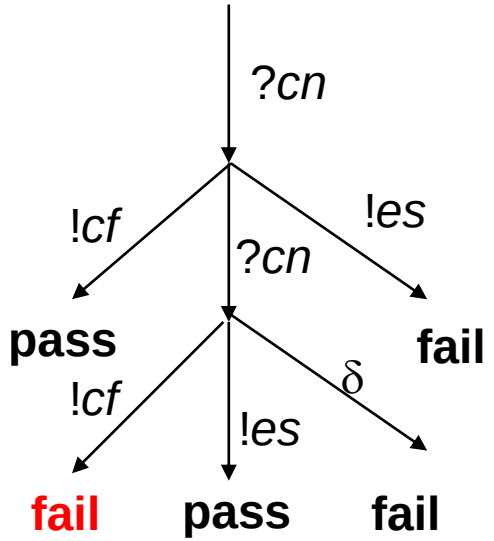
We define input-output transition systems to model systems with inputs and outputs, in which outputs are initiated by the system and never refused by the environment, and inputs are initiated by the system's environment and never refused by the system, see Tretmans,"Model based testing with labelled transition systems", 2008

- TGV, TorX, SpecEx, UPPAAL/TRON rely on blocking?

Example of Uncontrollable Tests



!*cf* = *coffee*
!*es* = *espresso*
?cn = *coin*
δ = *quiescence*

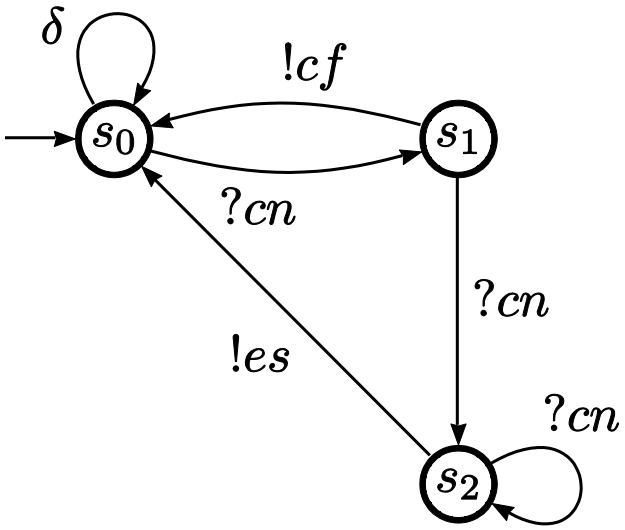


IOCO-based test
according to version 2008
is input-enabled
(SpecEx, but not TGV)

Input Enabledness of Test Cases?

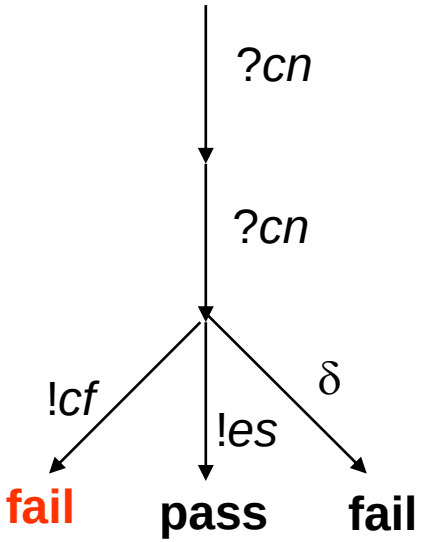
- Contradicts to
  - We will not allow test cases with a choice between input and output nor a choice between inputs [1996]
  - A test case is *controllable* if no choice is allowed between input and output or between inputs [TGV, FSM]
- If outputs cannot be blocked/preempted they could be stored in queues
- It is queued or asynchronous testing

Example of Unsound Tests



!*cf* = *coffee*
!*es* = *espresso*
?*cn* = *coin*
δ = *quiescence*

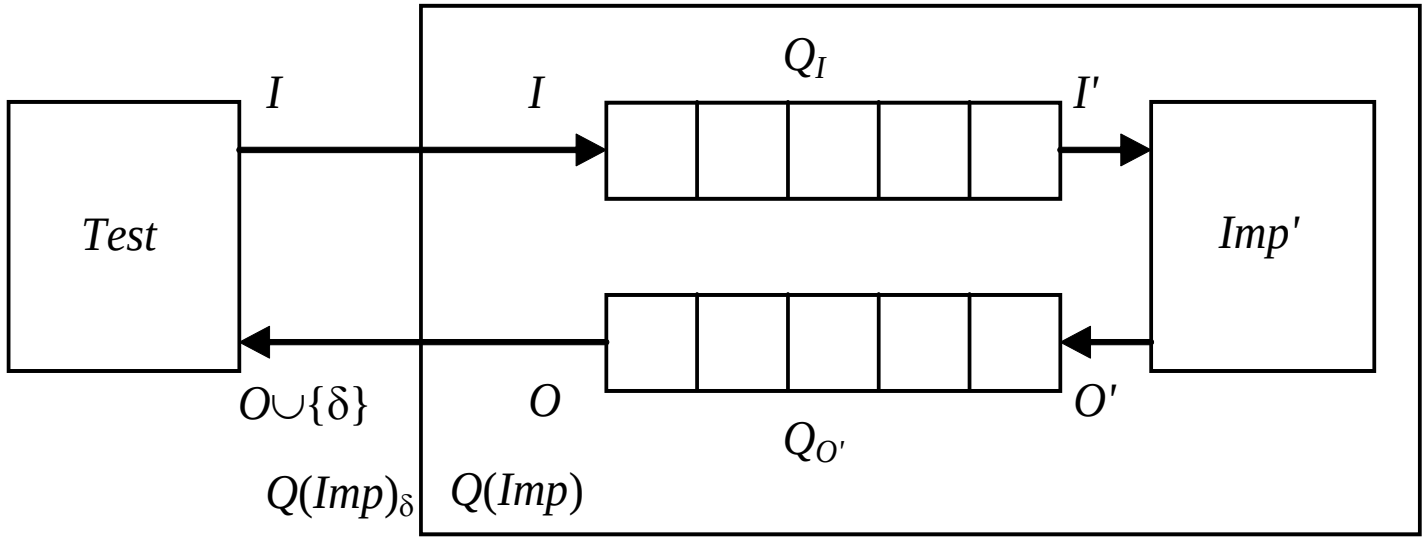
Unsound Asynchronous Test



Unsoundness is due to distortion
in observing outputs via queue

iocof, ioconf, mioco, rtioco, iocor, sioco, hioco, …, altsim

Asynchronous Testing for Output Faults



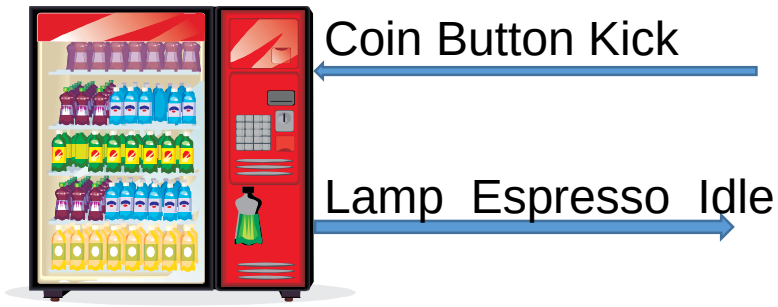
- Huo & Petrenko, “Transition Covering Tests for Systems with Queues”, STVR 2009
- Hierons, “Implementation Relations for Testing Through Asynchronous Channels”, 2012

Mealy IOTS

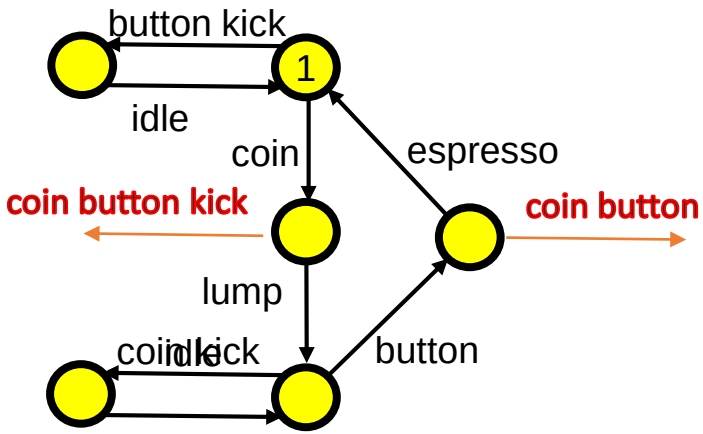
Without I/O conflicts, both models have the same behaviour

IOTS is then a Mealy IOTS

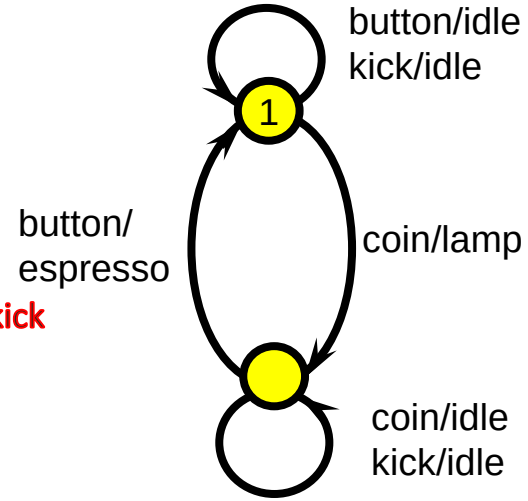
All the FSM methods generating complete tests are fully applicable



Input/Output Transition System



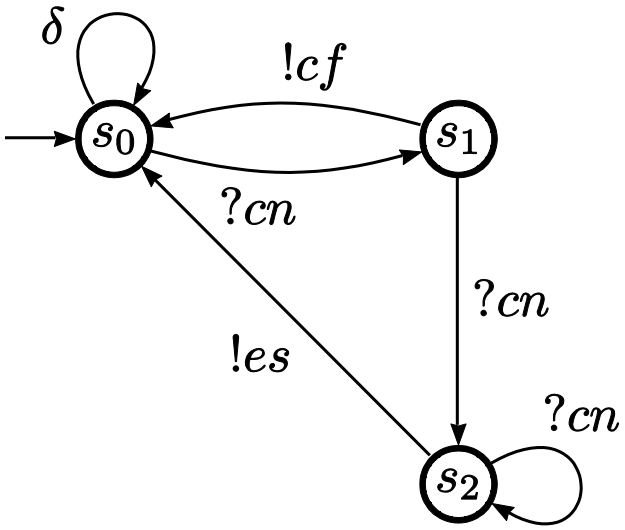
Finite State Machine

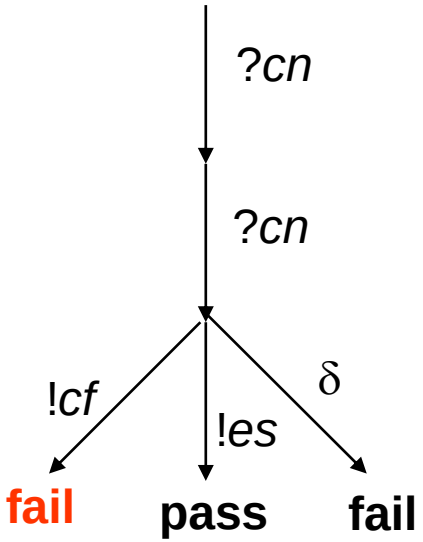


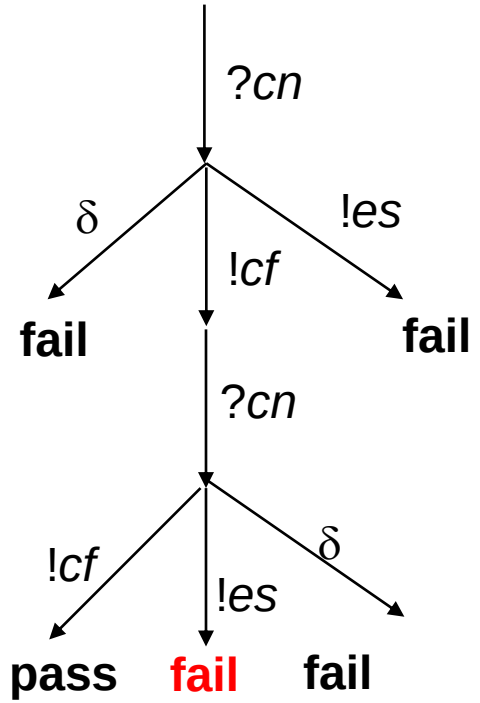
Input-eager IOTS

- Assume that each implementation IOTS when it is state with the input/output conflict, it does not produce any output if its input queue contains an input. We call such IOTS ***input-eager***
- Fault model is (Specification, Conformance Relation, Fault Domain)
  - IOTS with *n* input states
  - IOCO
  - The set of all input-eager IOTSs with at most *n* input states
- n-complete test suite can be generated by constructing test fragments similar to those for NFSM
- Simao & Petrenko, “Generating Complete and Finite Test Suite for ioco: Is It Possible?”, MBT 2014

Example of Sound Tests for Input-eager IOTS







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?*cn* = *coin*
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Complete Test Generation for IOTS Needs More Research

- Asynchronous testing for faults other than output faults?
- IOTS needs to be minimal to adopt state identification approaches, how to minimize it?
- M-complete test generation for general type of IOTS?
- Mutation machine for IOTS?
- Any way of dealing with I/O conflicts other than assuming input-eagerness or using queues?
- IOTS with extensions?

The Quest for the Holy Grail Goes On