Complete Controllable Distributed Testing

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Challenges in Testing

- These include:
  - Scale
  - Concurrency
  - Distribution
  - The Oracle Problem (checking test output).
- Currently expensive, error-prone, mainly manual.
- Possible solution: model-based testing.

Formal languages used

- Typically have states and transitions between states triggered by actions.
- Many based on one of:
  - Finite state machines (FSMs)
  - Labelled transition systems (LTSs)
- Tools might translate models to either FSMs or LTSs.

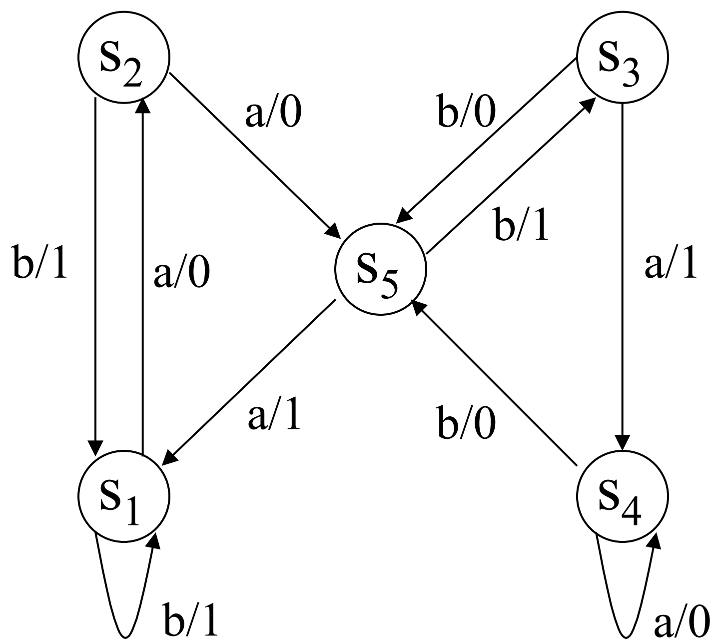
Assumptions

– Usually we only observe interactions between the system under test (SUT) and its environment - *black-box testing*.
– To reason about test effectiveness we assume:
  - The behaviour of the SUT can be expressed in the same language as the model.
– This allows us to define *implementation relations* between models.

Finite State Machines and MBT

Finite State Machines

- The behaviour of M in state s_i is defined by the (regular) set of input/output sequences (traces) from s_i



Implementation relations

- Assuming all models are completely-specified, these are:
  - Equivalence for deterministic FSMs.
  - Language inclusion for nondeterministic FSMs.

- There are efficient algorithms for deciding these properties, so:
  - If we know that the SUT behaves like FSM *N* and we have specification FSM *M* then we can determine whether *N* conforms to *M*.
- We will focus on: *deterministic FSMs*.

Fault Domains

- A set of models that represent potential behaviours of the system.
- Standard fault domains for testing from an FSM *M* with *n* states:
  – The SUT behaves like an unknown FSM *N* with at most *n* states.
  – The SUT behaves like an unknown FSM *N* with at most *m* states (some $m>n$).

Complete test suites

- A test suite *T* is m-complete when testing against *M* if:
  - For every FSM *N* with no more than m states, if N does not conform to *M* then there is a test sequence in T that demonstrates this.
    - Implicit: fixed input and output alphabets.

- If the SUT satisfies these conditions then such a test suite *determines correctness*:
  - If the SUT passes the test suite then either it is correct or has more than m states.

Existence of m-complete test suites

- We can produce an m-complete test suite:
  - For each FSM *N* with no more than m states we:
    - Determine whether *N* conforms to specification *M*.
    - If *N* does not conform to *M* then we add a test sequence that demonstrates this.

- These steps are computable (and there are finitely many FSMs to consider).

Smaller test suites

- There are more efficient algorithms.
- Many build test sequences from ‘parts’ that:
  - Reach a state *s*.
  - Distinguish two states *s* and *s’* (or distinguish every pair of states).

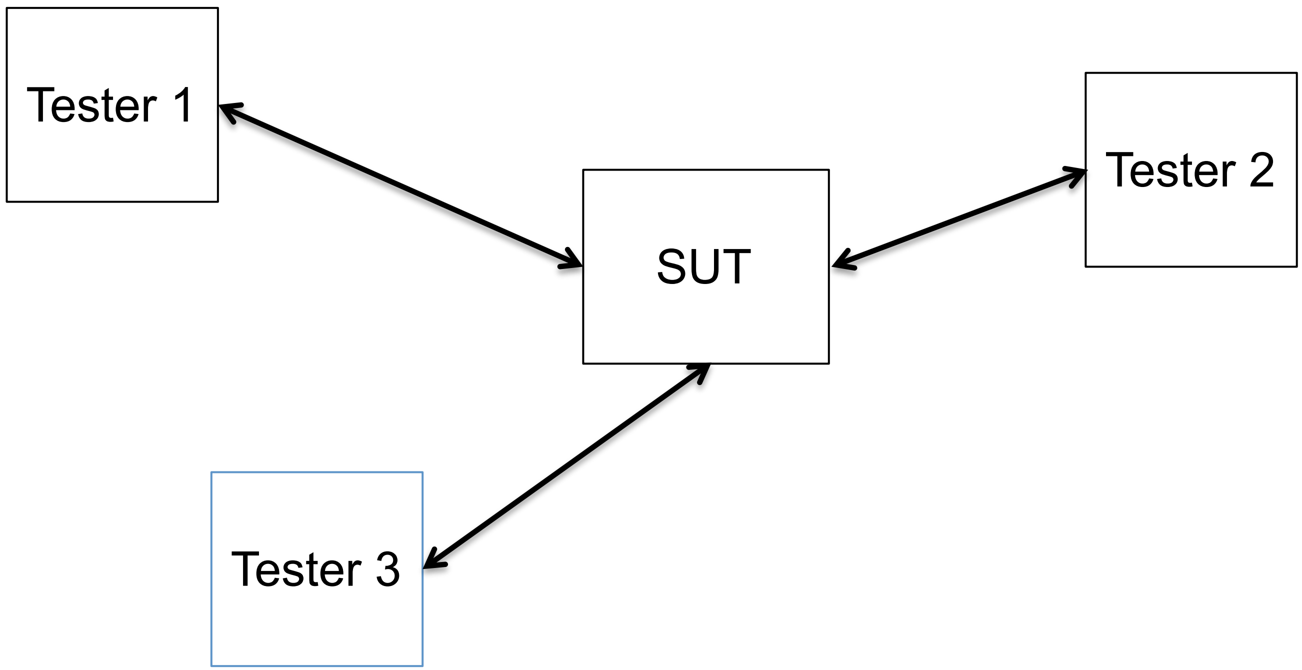
- For deterministic FSMs these ‘parts’ can be produced in low-order polynomial time.

Summary: using a single tester

- For (deterministic) FSM specification *M*:
  - We can efficiently decide whether an observation is allowed by *M* (the Oracle Problem).
  - We can efficiently produce tests to reach states or distinguish states.
  - We can efficiently decide whether an FSM *N* conforms to *M*.
  - We can generate an m-complete test suite for *M*.

Distributed Testing

The Architecture



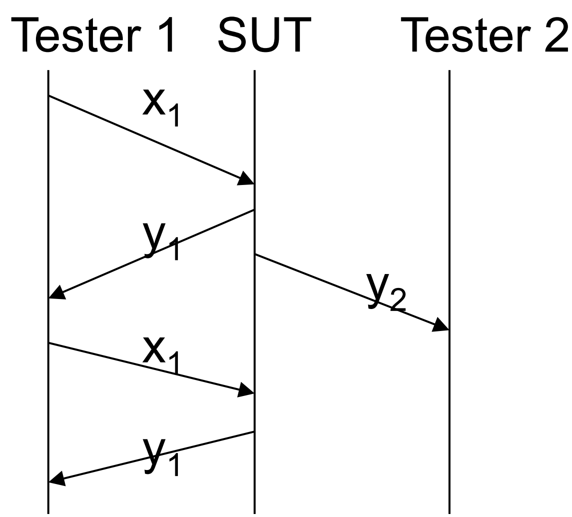
Distributed testing

- We have:
  - An SUT that interacts with its environment at physically distributed interfaces (ports).
  - A tester at each port.

- Will focus on the case where:
  - The testers do not interact with one another during testing and there is no global clock.
  - The testers log their observations and logs are combined after testing.

Consequences

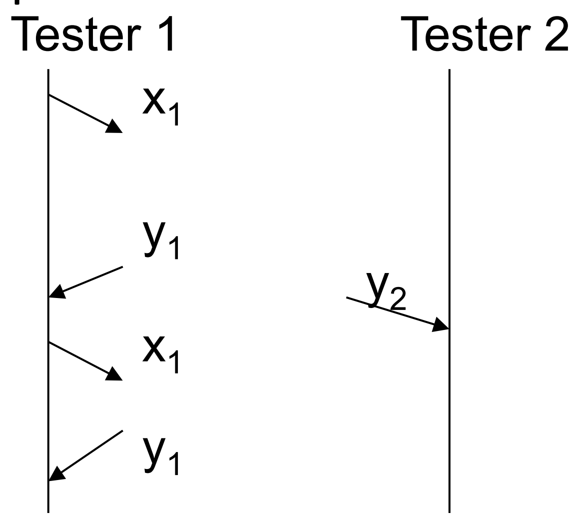
- Each tester observes only the sequence of interactions (*local trace*) at its port



- The tester at port 1 observes $x_1y_1x_1y_1$ and the tester at port 2 observes y_2 only.

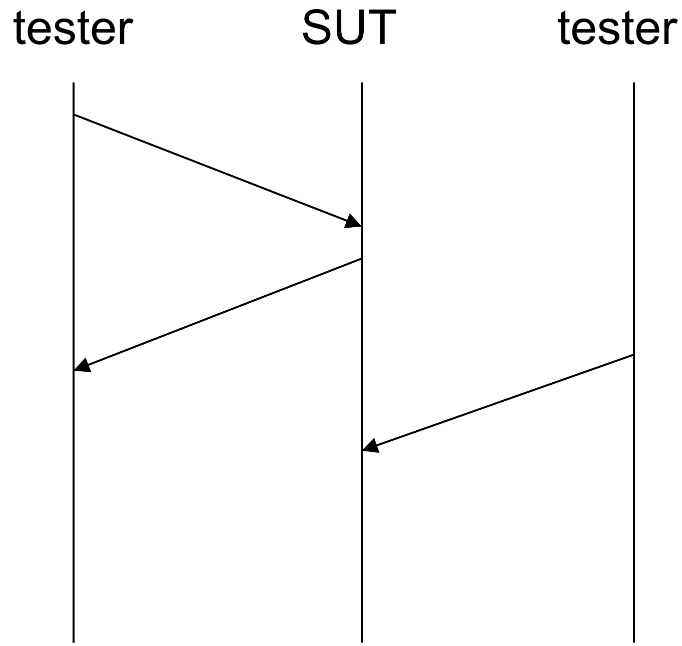
What the testers observe

- Given global trace z, the tester at p observes a local trace $\pi_p(z)$.



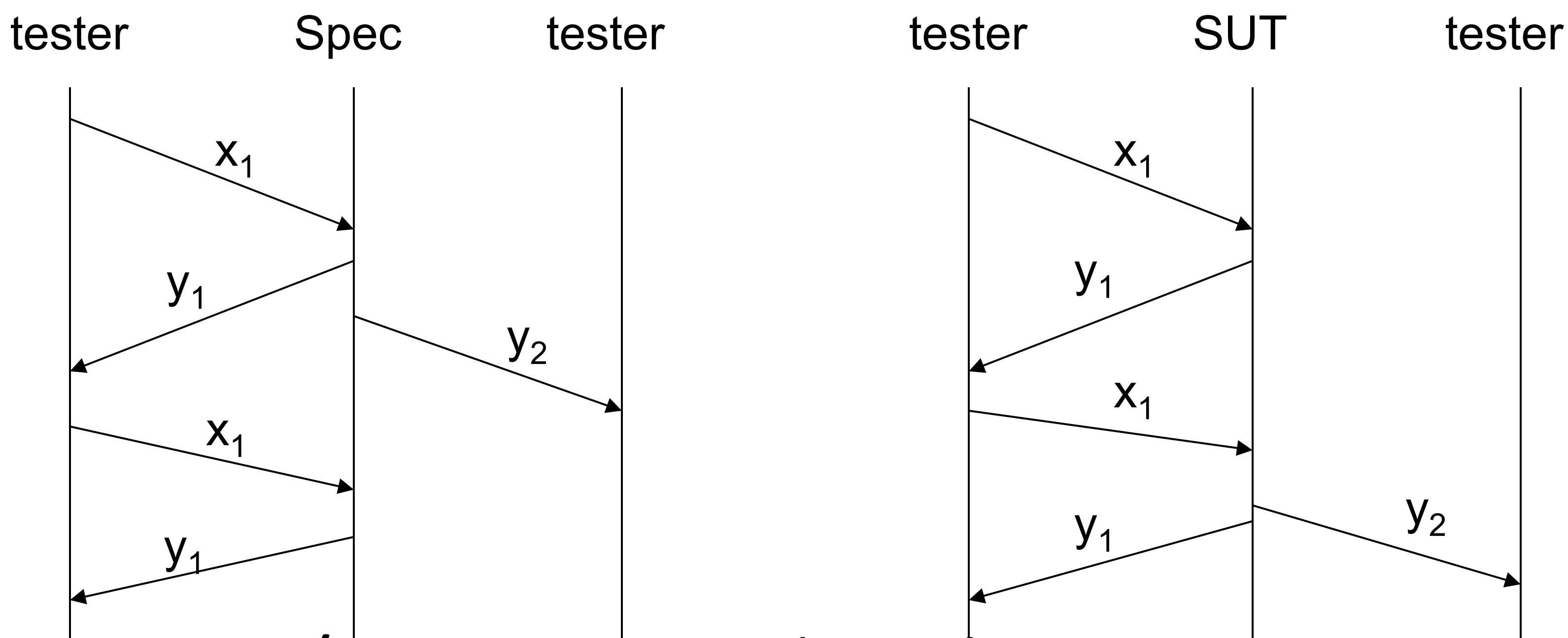
Controllability problems

- This test has a controllability problem: introduces nondeterminism into testing.



Observability problems

- The following look the same



- Testers/users cannot 'map' output to input

Equivalent global traces

- Since we only observe local traces:
  – Global traces *z* and *z'* are indistinguishable if their projections are identical: the local traces are the same. We denote this: $z \sim z'$

$$z \sim z' \Leftrightarrow \forall p \in \mathcal{P}.\pi_p(z) = \pi_p(z')$$

- The following are equivalent under ~

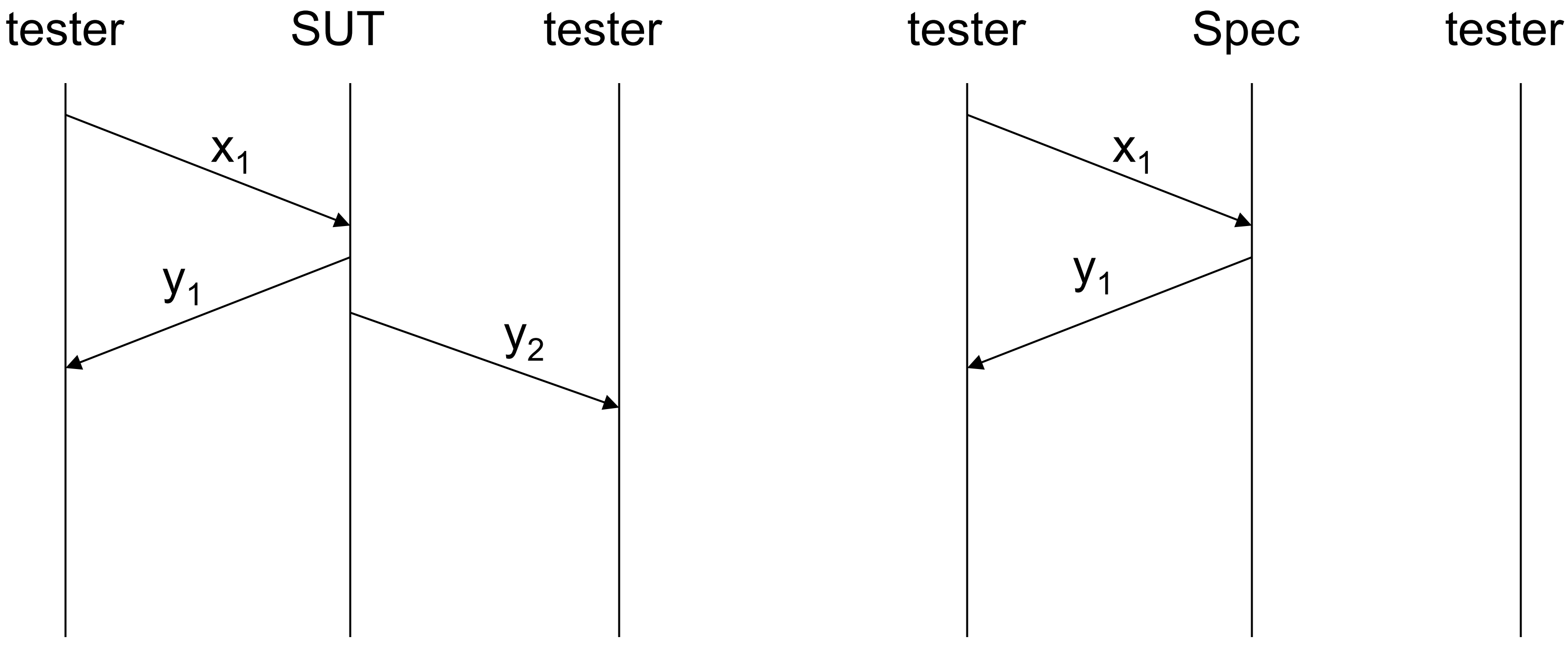
  $x_1/(y_1,y_2)x_1/(y_1,-)$

  $x_1/(y_1,-)x_1/(y_1, y_2)$

- Both have $x_1y_1x_1y_1$ at port 1 and y_2 at 2.

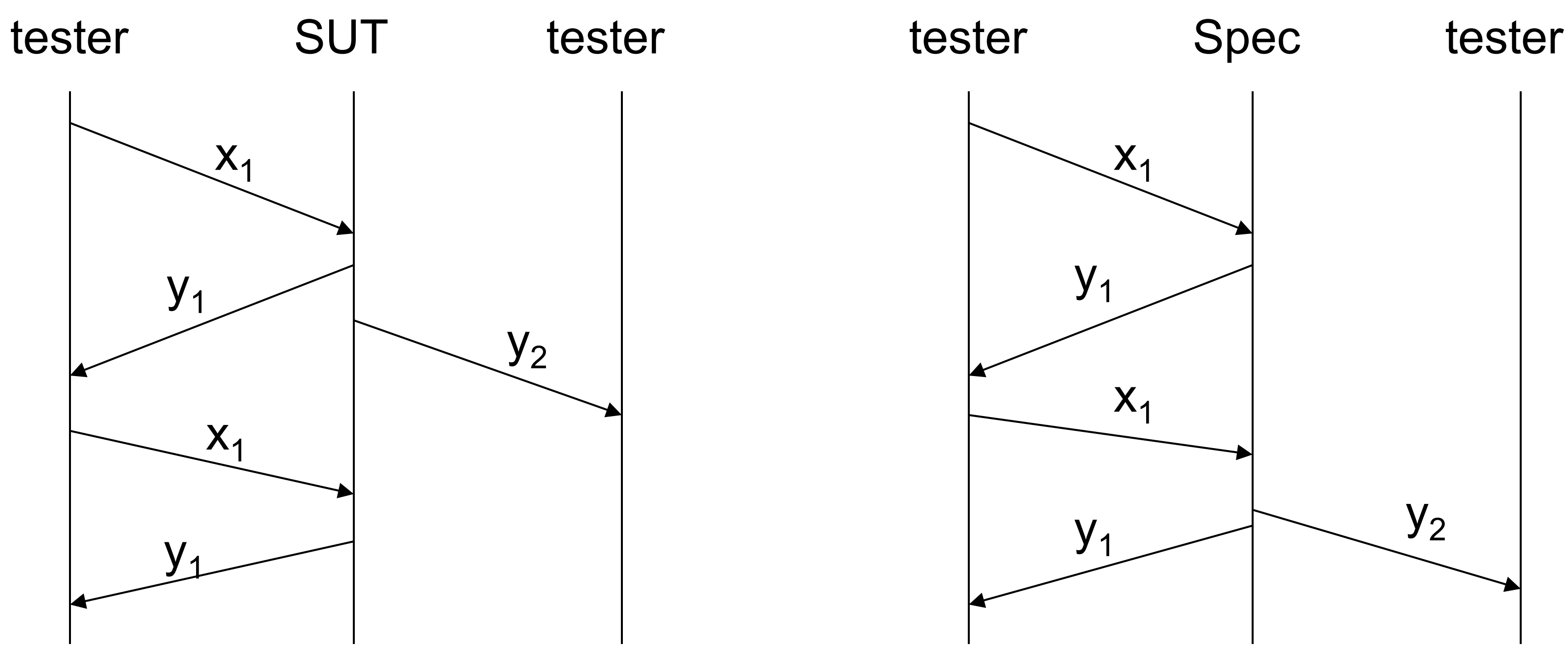
A simple output fault

- Input x_1 detects the fault.



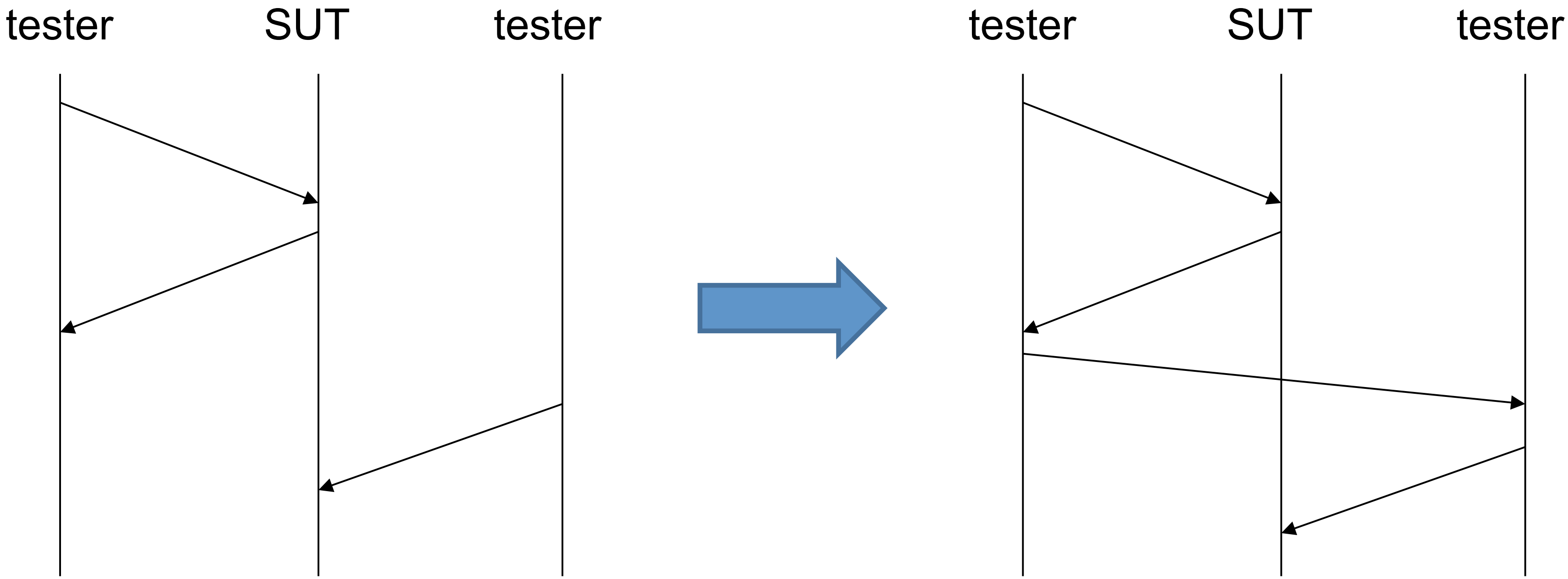
Test effectiveness is not monotonic

- However: x_1x_1 does not detect the fault.



Using an external network

- *Sometimes* we can overcome controllability and observability problems.



Distributed Testing and Deterministic Finite State Machines

An allowed behaviour

- Given specification M, a trace σ is allowed if

$$\exists \sigma' \in L(M) . \sigma' \sim \sigma$$

An implementation relation for distributed systems

- We say that FSM N conforms to FSM M if:
  - Every global trace of N is indistinguishable from a global trace of M.

$$\forall \sigma \in L(N) \exists \sigma' \in L(M) . \sigma' \sim \sigma$$

The language defined by an FSM

- With distributed observations, this is:

$$\mathcal{L}(M) = \{\sigma' | \exists \sigma \in L(M) . \sigma' \sim \sigma\}$$

- So, a behaviour is correct if

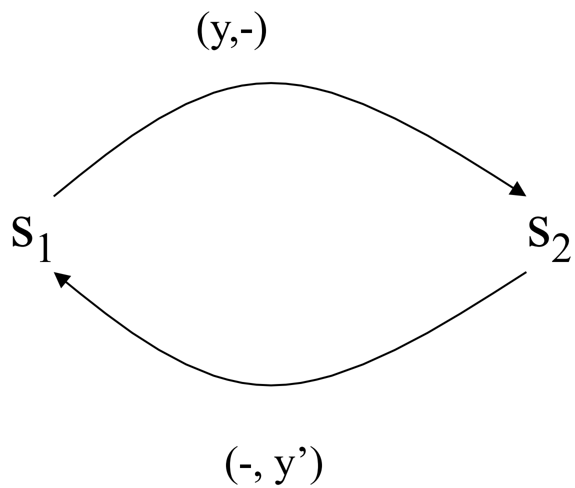
$$\sigma \in \mathcal{L}(M)$$

- N conforms to M if and only if

$$L(N) \subseteq \mathcal{L}(M)$$

The language need not be regular

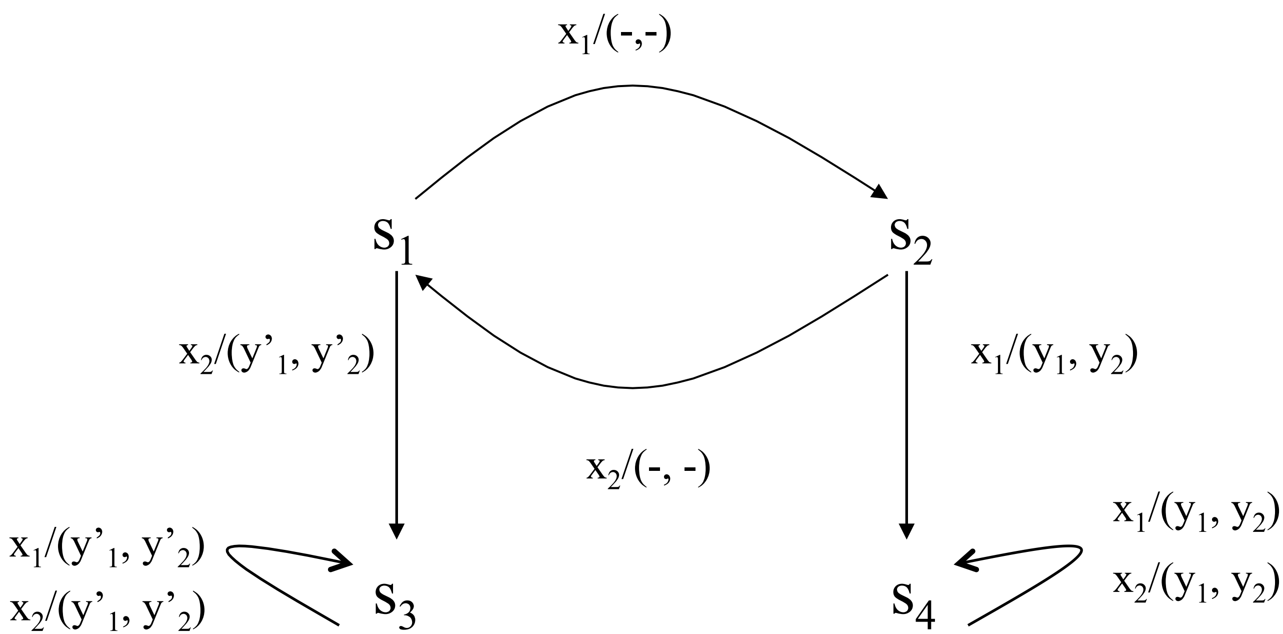
- The following ‘cheats’ – does not have any inputs.



- Clearly, $\mathcal{L}(M)$ is not regular.

The language need not be regular

- Following shows this (take the intersection with $\{x_1^*\}\{x_2^*\}$).



The Oracle Problem in Distributed Testing

- We observe projections

$$\sigma_1, \ldots, \sigma_m$$

- We want to know whether the following holds:

$$\exists \sigma \in L(M). \forall p \in \mathcal{P}. \pi_p(\sigma) = \sigma_p$$

- Essentially, a membership problem.

$$\sigma_1 \ldots \sigma_m \in \mathcal{L}(M)$$

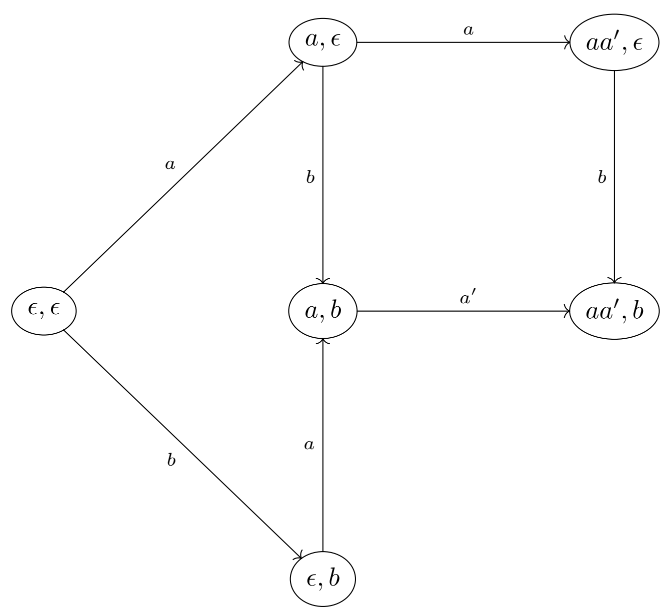
- It is *decidable*, since we could:
  - Form all interleavings of the projections.
  - For each such global trace, determine whether the global trace is allowed by the specification.
- This leads to a combinatorial explosion.

Solving the Oracle Problem

- We observe projections $\sigma_1, \ldots, \sigma_m$
- We can form a finite automata whose language is the set of corresponding global traces (the oracle problem is then FA intersection).
- A state is a vector whose *i*th component is the latest event from σ_i

Example

- Two ports, local traces aa’, b.



How this works (1)

- We define a partial order < on events in σ: a < a' if (from the observations) we know that a must have been before a'.
- In this case:
  - Two events are related iff they are at the same port.
- Important property:
  - For a to occur we must have all events before a (under <).
  - Downwardly closed sets correspond to sets of events that can form a prefix of a trace equivalent to σ.
- Note – label events to make them unique if required.

How this works (2)

- We can also construct the FA as:
  - States are downwardly closed sets of event.
  - {} is the initial state
  - The complete set of events is the final state.
  - There is a transition from set E to set E’ with event e iff {e} = E’ \ E.

- The number of states of the FA is the product of the lengths of the σ_i (plus 1)
- So, exponential space is required.

- However, polynomial time if *m* is bounded above.

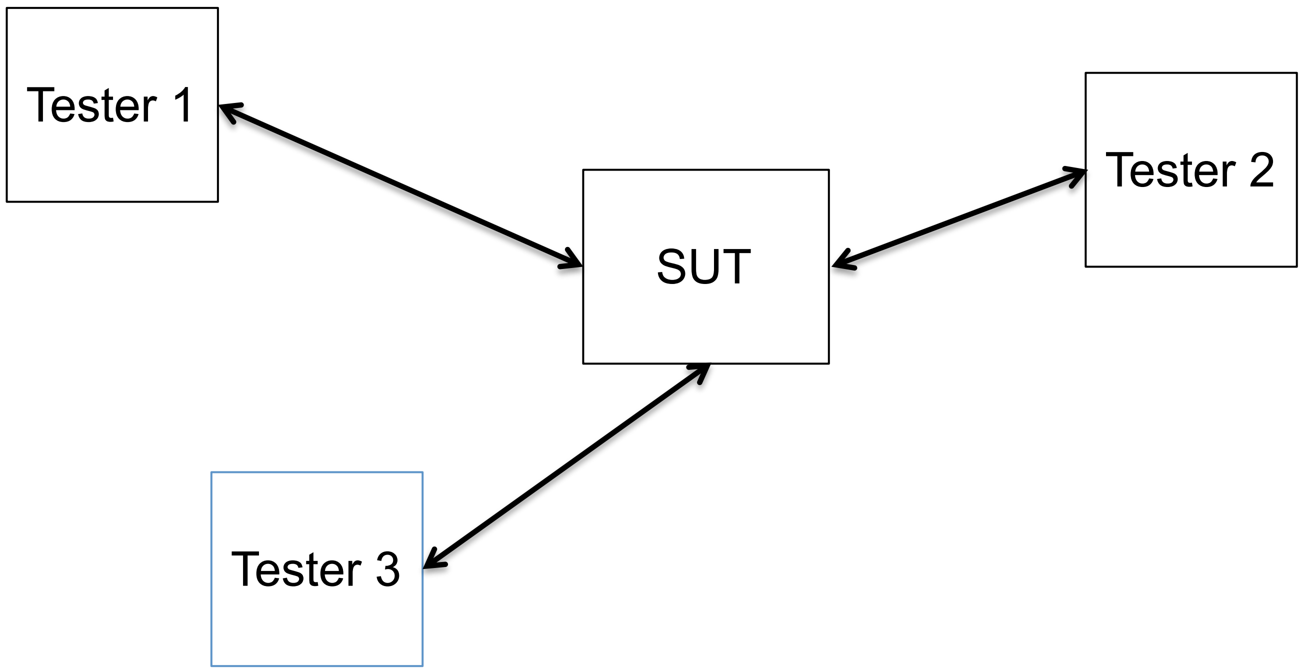
Results

- For single port: Oracle Problem can be solved in low order polynomial time.
- For DFSMs in distributed testing:
  - Can be solved in polynomial time for controllable test sequences; otherwise NP-complete.
- For NFSMs:
  - NP-complete even for controllable testing.
- However, problems become polynomial if we place bounds on the number of ports.

Distinguishing states and FSMs

- Let us suppose that:
  - *M* is the specification
  - *N* models a potential (and possibly faulty) implementation
- We want to know whether N conforms to M.
- Equivalently, we want to know whether two states can be distinguished.

Independent testers



- We have separate, independent, testers.
- At any point:
  - The FSM being tested has a current state.
  - Each local tester has observed a local trace.
- There are infinitely many possible combinations of the above.

Single port systems

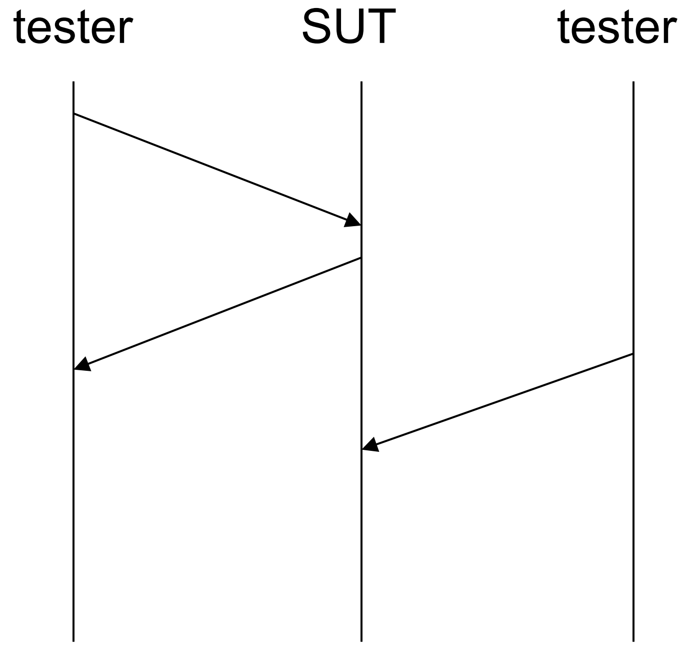
- We can represent this as a two player game problem.
  - The state of the game is a pair of states (specification, implementation).
  - Tester moves: apply input
  - System moves: change state and return output.
- One player (the tester) wants to force the observation of a failure.

Distinguishing FSMs: result

- Similar to a multi-player game problem.
- It is undecidable whether N conforms to M (and so also whether *N* is faulty).
- **Consequence**: there is no general algorithm for generating finite m-complete test suites for distributed testing.

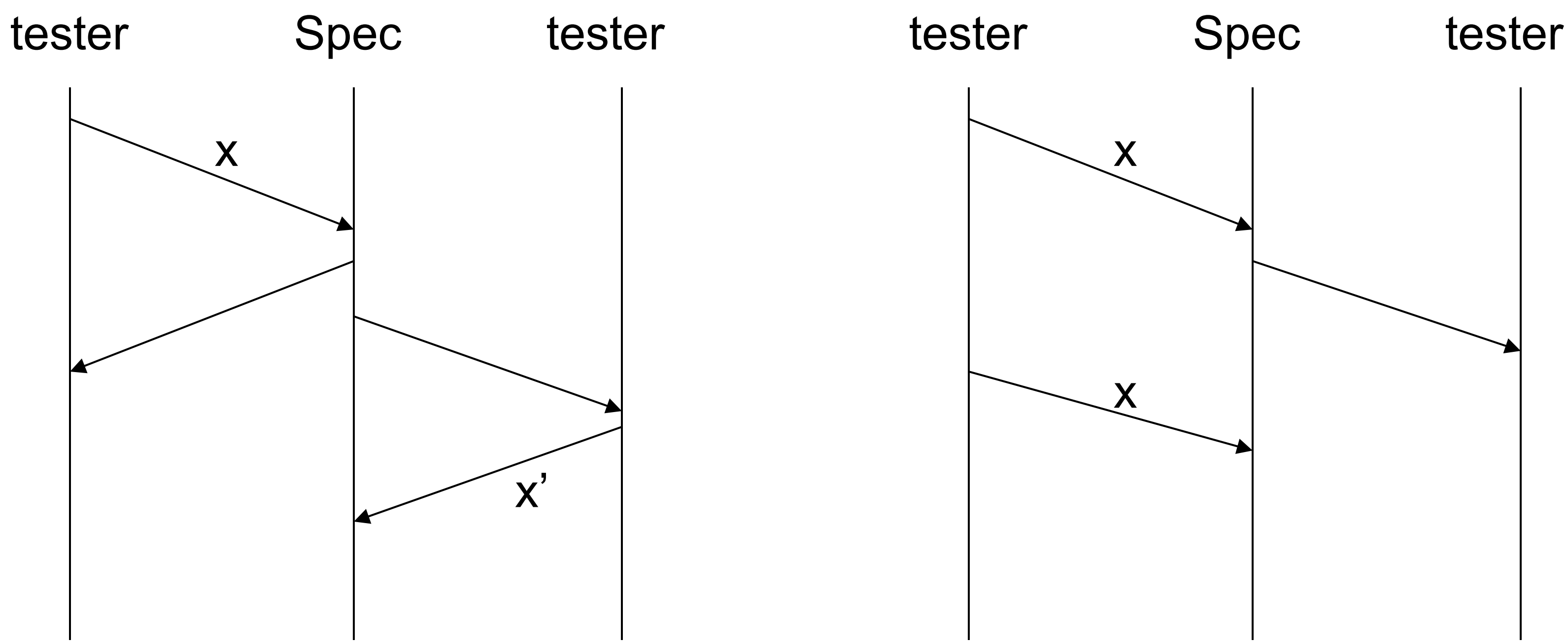
Controllable testing

This is not controllable



Examples of controllability

- Two controllable scenarios



What makes an input sequence controllable?

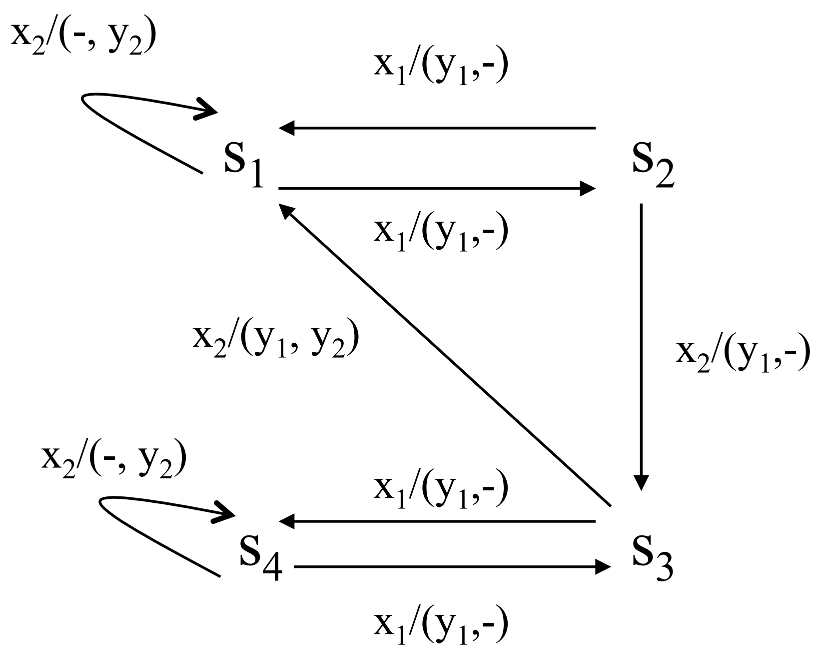
- In controllable testing:
  - We can follow the input of x in state s by input x' if:
    - x and x' are at the same port; or
    - input x' is at a port p that receives output in response to x.
  - The first case relies on the atomicity of input/output pairs.

Distinguishing states s and s'

- If we restrict to controllable testing we need:
  - *(input sequence) x* causes *no controllability problems* from *s* and *s'.*
  - *x* leads to different sequences of interactions, for *s* and *s'*, at *some port*.
- We say that *x locally s-distinguishes s* and *s'*.
- If no input sequence locally distinguishes *s* and *s'* they are *locally s-equivalent*.

Testing is weaker

– We cannot locally s-distinguish s_1 and s_4 but x_1x_2 *can* distinguish them.



Distinguishing two states

- Given port *p* and states s_1 and s_2 of a *k*-port FSM *M* with *n* states:

  - s_1 and s_2 are locally *s*-distinguishable by an input sequence starting at *p* if and only if they are locally *s*-distinguished by some such input sequence of length at most $k(n-1)$.

- This bound is tight.
- The sequences can be found in low-order polynomial time.

Complete testing

- We know that:
  - There is no general algorithm for computing m-complete test suites.
  - There are benefits to using controllable test sequences.
- We might:
  - Try to achieve 'as much as possible' given that testing is controllable.

c(m)-complete test suites

- Given FSM M we say that test suite T is c(m)-complete if:
  - All test sequences in T are controllable.
  - For every FSM N with the same input/output alphabets as M and at most m states:
    - If N and M are locally s-distinguishable then some test sequence in T achieves this.
- i.e. T distinguishes between M and an SUT with at most m states *if this is possible in controllable distributed testing*.

Generating c(m)-complete test suites

Restricting attention to controllable test sequences

- We would like to represent the set of controllable test sequences.

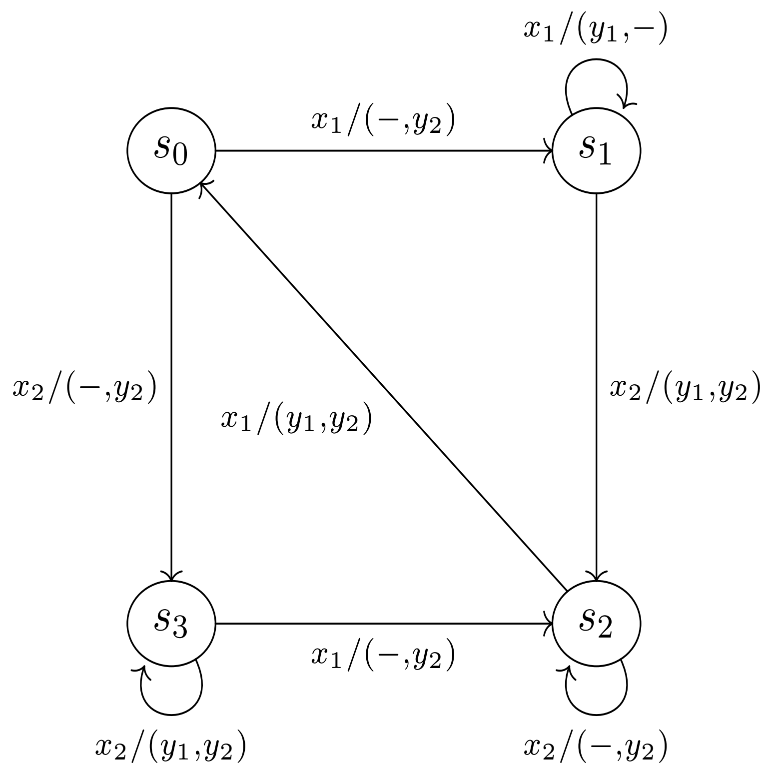
- We will use a partial FSM to do this.

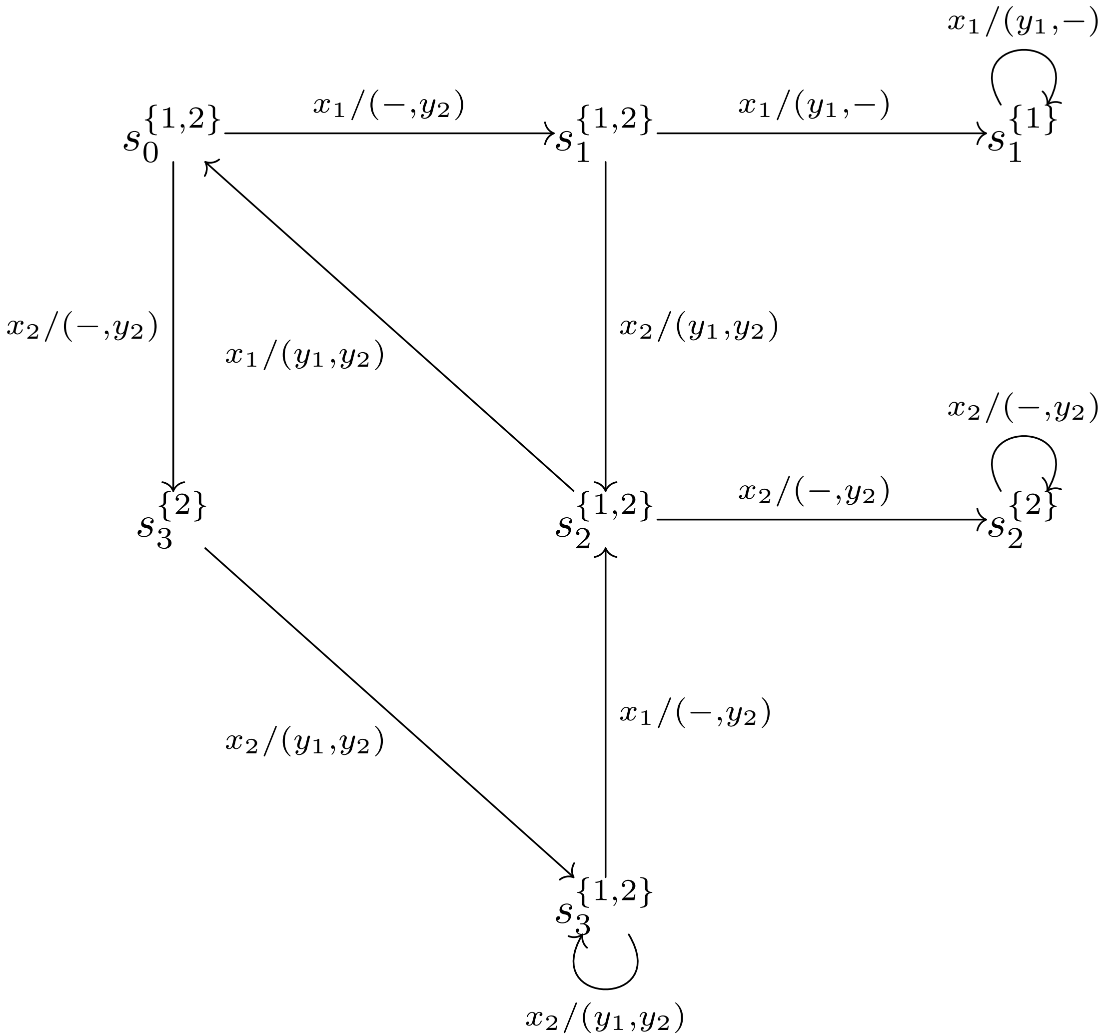
Copies of states

- Let us suppose that:
  - t is the transition (s',s,x/y).
  - P is the set of ports involved (p is in P if x is at p and/or y contains output at p).
- We will represent the situation 'after t' by state: s^P
- The state s^P denotes the situation in which:
  - The FSM is in state s and can receive input at any port in P in controllable testing.

Transitions leaving a ‘new state’

- Let us suppose that:
  - t is the transition (s,s’,x/y).
- We will include a copy of t from every state of the form s^P such that:
  - Input x is at a port in P.
- We also include an initial state (initial state of M, input at any port).
- The combination defines the FSM M_{min}


$x_1/(y_1,-)$
$x_1/(-,y_2)$
s_0
s_1
$x_2/(-,y_2)$
$x_1/(y_1,y_2)$
$x_2/(y_1,y_2)$
s_3
s_2
$x_1/(-,y_2)$
$x_2/(y_1,y_2)$
$x_2/(-,y_2)$


$x_1/(y_1,-)$
$s_0^{\{1,2\}}$
$x_1/(-,y_2)$
$s_1^{\{1,2\}}$
$x_1/(y_1,-)$
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$x_1/(y_1,y_2)$
$x_2/(y_1,y_2)$
$x_2/(-,y_2)$
$s_3^{\{2\}}$
$s_2^{\{1,2\}}$
$x_2/(-,y_2)$
$s_2^{\{2\}}$
$x_1/(-,y_2)$
$x_2/(y_1,y_2)$
$s_3^{\{1,2\}}$
$x_2/(y_1,y_2)$

Results

- A path in M with label σ is controllable if and only if M_{min} has a path with label σ.
- So: M_{min} captures ‘controllable testing’

Canonical FSMs

- Given FSM M, we can find:
  - Minimal M_{min} that is locally *s*-equivalent to M.
  - Maximal (nondeterministic) M_{max} that is locally s-equivalent to M (adding ‘chaos state’ to complete M_{min}).
- We can find them efficiently.

Relevance of max and min machines

- Machine M_{min} captures all of the traces that FSM N *has to implement* to conform to M (under s-equivalence).
- Machine M_{max} contains all of the traces that an SUT *can have* without being distinguishable from M in controllable testing:
  - We can examine M_{max} to determine whether it is acceptable to restrict attention to controllable test cases.

Reaching states

- State s of M is reachable in controllable testing if and only if:
  - There is some P such that s^P is reachable in M_{min}
- Decidable in polynomial time.

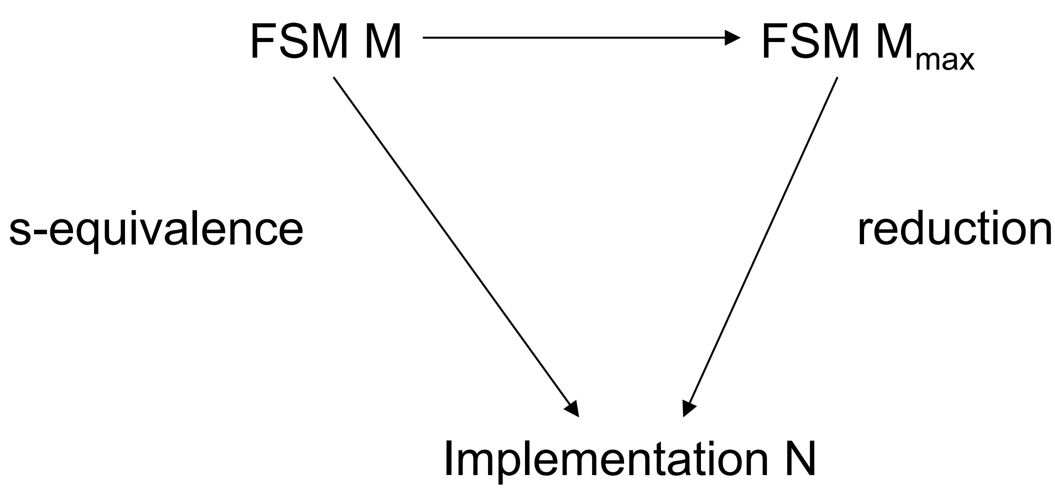
Distinguishing states

- We have that s_1^P and $s_2^{P'}$ are distinguishable in controllable testing if and only if:
  - There is a port $p \in P \cap P'$ and input sequence x starting at p such that x s-distinguishes s_1 and s_2.
- Decidable in polynomial time.

Comparing FSMs

- FSM N is locally s-equivalent to FSM M if and only if N_{min} is equivalent to M_{min}.
- FSM N is locally s-equivalent to FSM M if and only if N is a reduction of M_{max}.
- Both decidable in polynomial time.

Refinement and Testing



Generating a c(m)-complete test suite

- It is now straightforward:
  - We generate an m-complete test suite from partial FSM M_{min}.
    - or
  - We generate an m-complete test suite from nondeterministic FSM M_{max}.
- There are standard algorithms that can be adapted (e.g. using state counting).

Efficiency issue

- Many test generation methods use:
  - Sets of pairwise distinguishable states.

- Size of test suite depends on how large these are.

Graphs and cliques

- Given an undirected graph $G=(V,E)$ we can generate an FSM M as follows:
  - Each vertex v_i in V is represented by a corresponding state s_i of M.
  - We can distinguish states s_i and s_j if and only if there is an edge between v_i and v_j.
- Consequence:
  - Finding a maximal set of pairwise distinguishable states of M is equivalent to finding a maximal clique of G.

Consequence

- The problem of finding largest sets of pairwise distinguishable states is NP-hard.

- There are potential efficiency issues.
- Note:
  - This result also holds for single-port testing from a nondeterministic FSM or a partial FSM.

Some papers (FSMs)

- B. Sarikara and G. Von Bochmann, Synthesis and Specification Issues in Protocol Testing, *IEEE Transactions on Communications*, 3**2** 4, pp. 389-395: 1984.
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- R. M. Hierons: Verifying and Comparing Finite State Machines for Systems that have Distributed Interfaces, *IEEE Transactions on Computers*, **62** 8, pp. 1673-1683, 2013.
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- R. M. Hierons: Generating Complete Controllable Test Suites for Distributed Testing*, IEEE Transactions on Software Engineering*, **41** 3, pp. 279-293 , 2015.
- R. M. Hierons and Uraz C. Turker: Distinguishing Sequences for Distributed Testing: Adaptive Distinguishing Sequences, *The Computer Journal* (to appear).

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Conclusions

- If a system has distributed interfaces/ports then we have different implementation relations.
- This can affect testing and also development.
- We have new notions of correctness and corresponding test generation algorithms.

- Restricting attention to controllable test sequences brings practical benefits.

Questions?