On Automata Learning and Conformance Testing

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Acknowledgments

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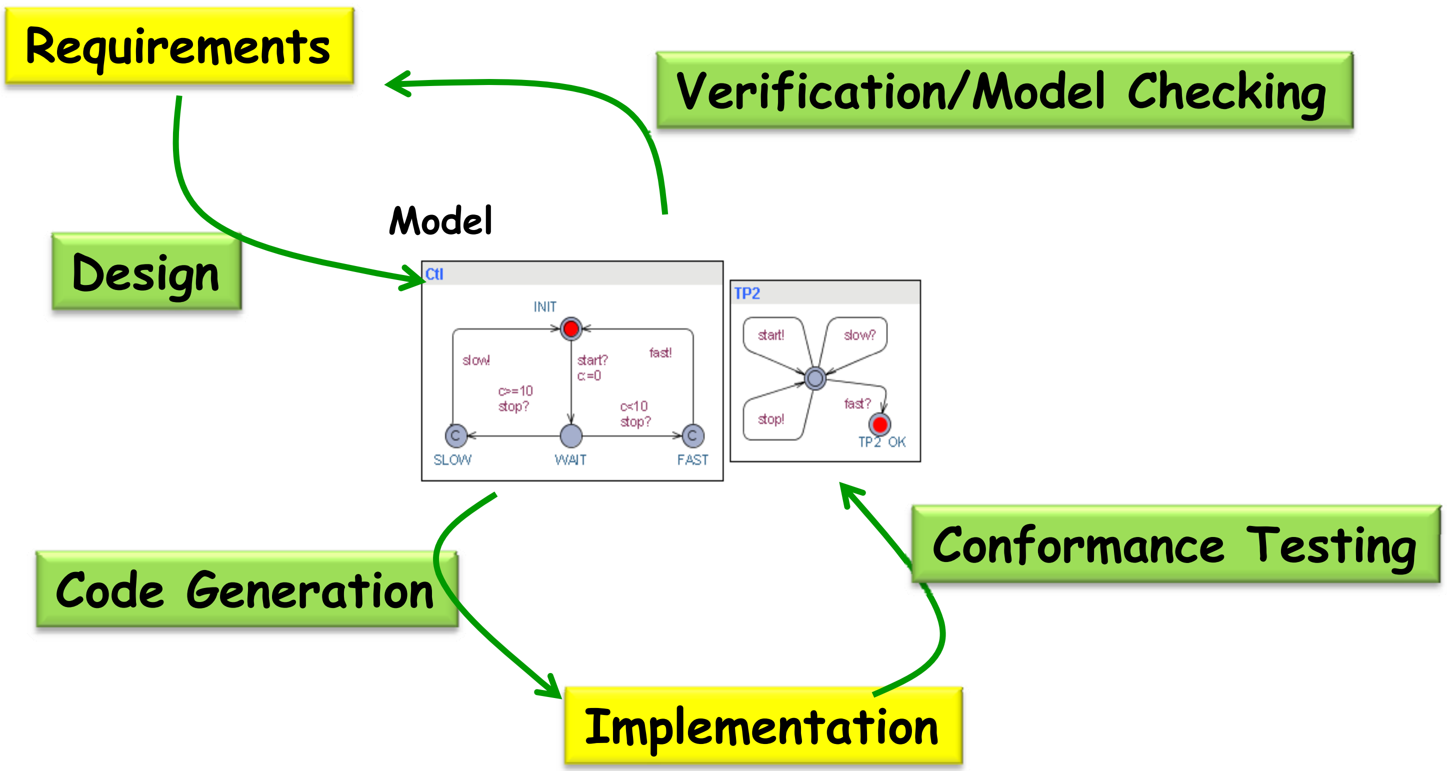
Outline

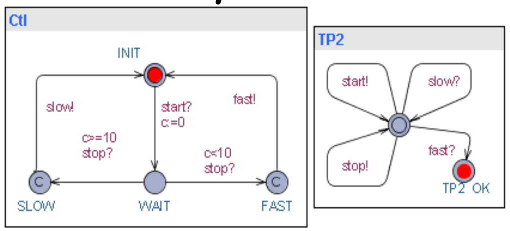
- Motivation
- Automata Learning
- Conformance Testing, Model Checking
- Extensions to richer Automata Models
- Applications in Protocol Model Generation

Modeling in System Development



Model BasedTest Generation

Model:
What the system should do



Test case generator

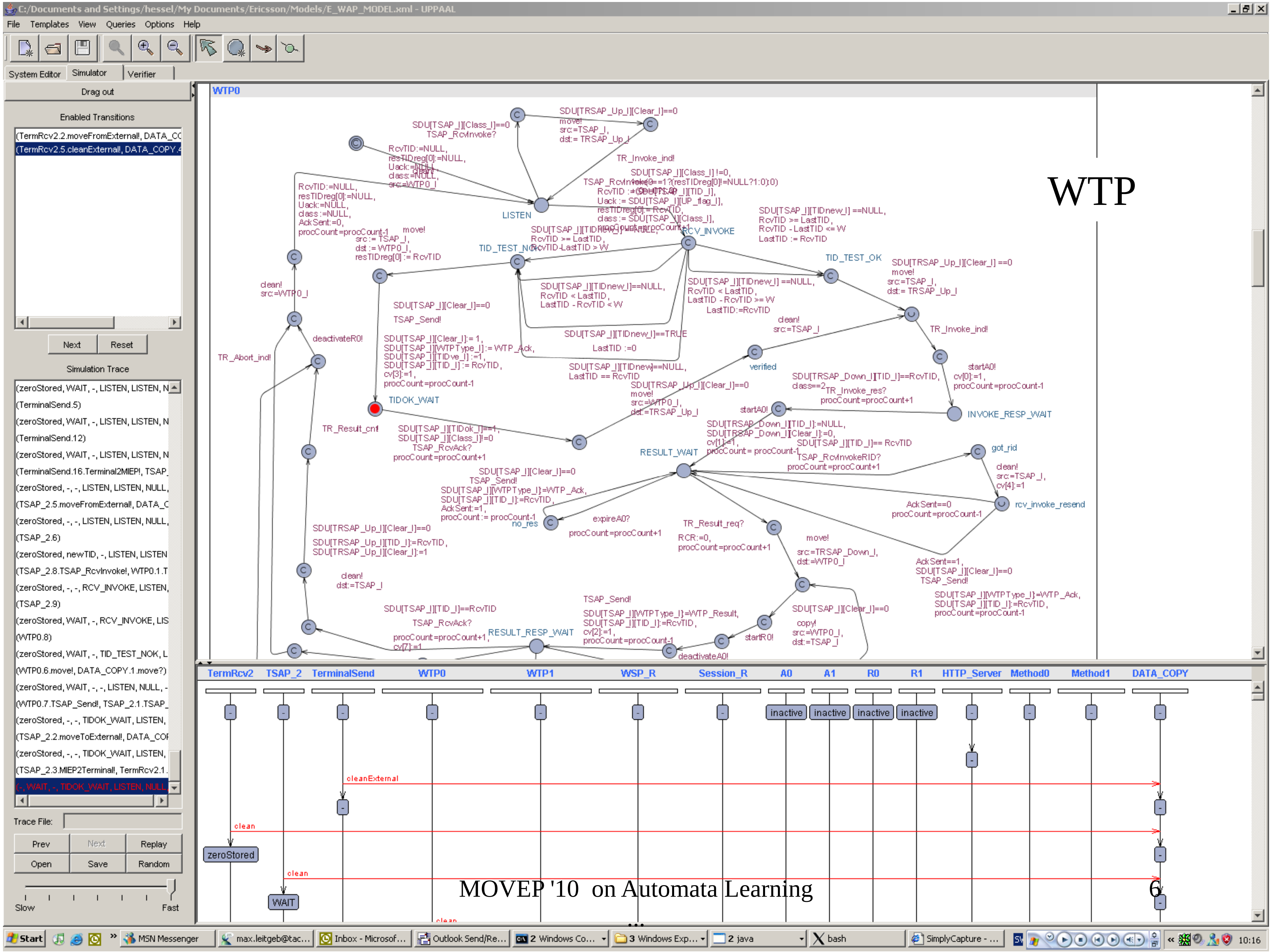
Test Objective:
What should be tested?

Test Suite

Well-Developed Tools:
- TGV, TorX, Gotcha, …
- Conformic Qtronic, …

Implementation Under Test

WTP



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File Templates View Queries Options Help
System Editor
Simulator
Verifier
Drag out
Enabled Transitions
Next
Reset
Simulation Trace
Trace File:
Prev
Next
Replay
Open
Save
Random
Slow
Fast
WTP0
LISTEN
RCV_INVOKE
TID_TEST_NOK
TID_TEST_OK
TIDOK_WAIT
INVOKE_RESP_WAIT
RESULT_WAIT
RESULT_RESP_WAIT
rcv_invoke_resend
TermRcv2
TSAP_2
TerminalSend
WTP0
WTP1
WSP_R
Session_R
A0
A1
R0
R1
HTTP_Server
Method0
Method1
DATA_COPY
inactive
cleanExternal
clean
zeroStored
WAIT

Modeling Gap

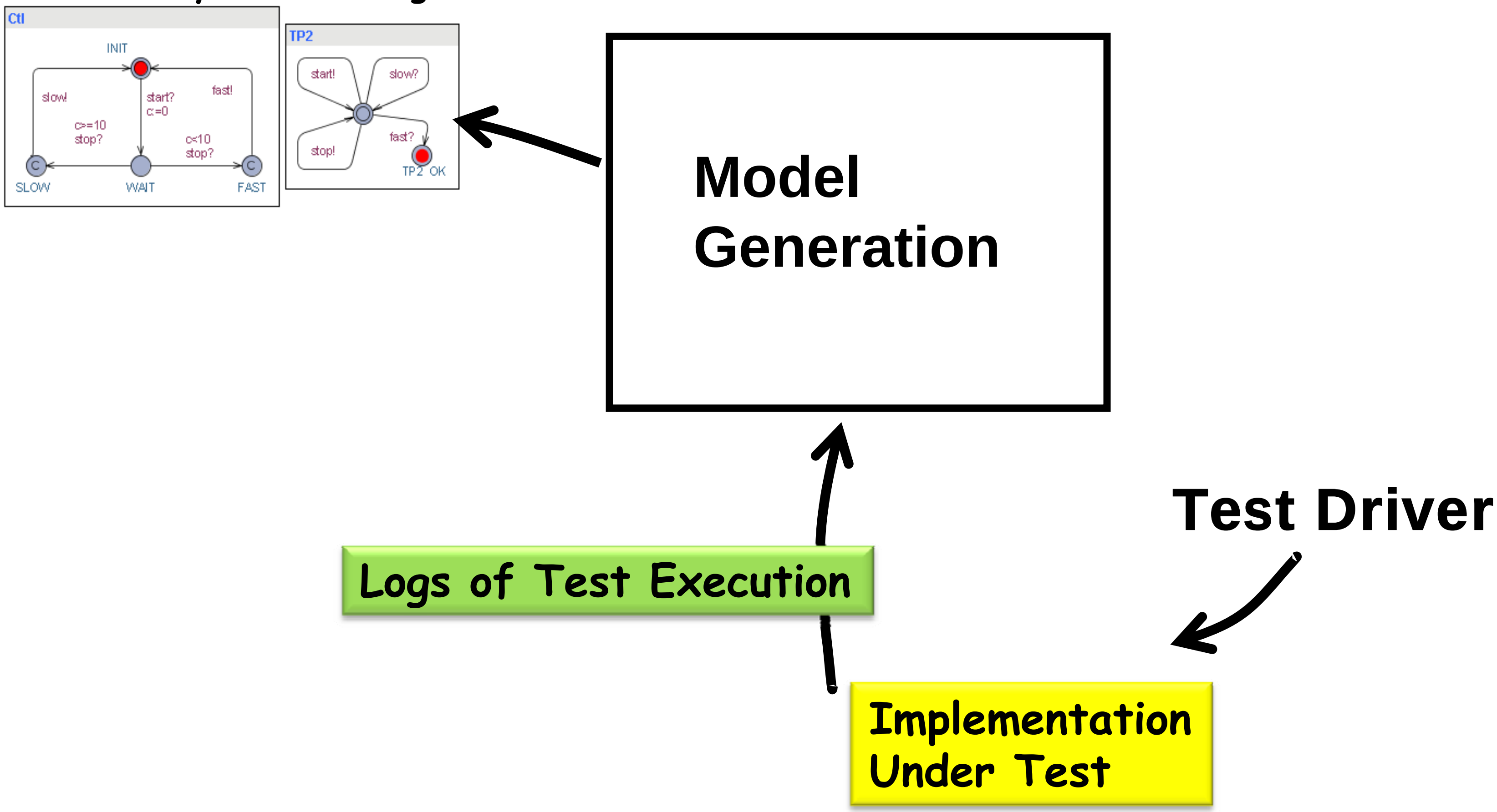
- **Typically, models are not available**

- **Modeling SUT** [system under test] is among **biggest obstacles** in Model Based Testing [A. Hartman]

- What to do if there is no model?
  (the norm in practice)

Supporting Model Generation

Model:
What the system is doing



How to support generation of models?

- Model Behavior of existing implementation
  - By observations gained during extensive testing
- Potential Applications:
  - Regression testing
  - Migrating from manual to model-based testing
  - Modeling environment of SUT, libraries
- Problem: Constructing State Machines from traces/executions/words
  - Has been studied in Automata Learning

Simplest form of Automata Learning

- From sample of words
- find simple(st) state machine that explains them

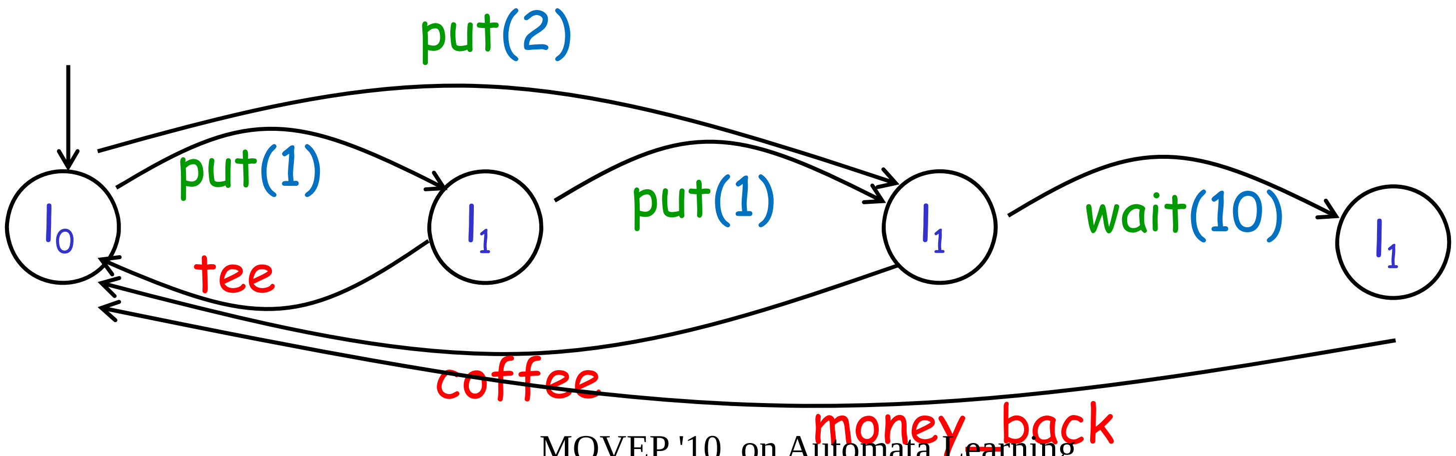
Requirements Capture

- Generate State Machine Specification from set of allowed (and disallowed) scenarios:

put(1) put(1) / coffee
put(1) / tee
put(2) /coffee
put(1) put (1) wait(10) / money_back

Instances:

- Play engine [Harel,Marelly]
- Smyle [Bollig,Katoen,Kern,Leucker]



Compositional Verification [Giannakopoulou,Pasareanu et al]

Complex Model Checking Problem:

$$E \parallel M \models \varphi$$

If

Checking E || M |= φ too complex:

Find abstraction A of E, s.t.:

E refines A

A || M |= φ

E || M |= φ

Building A using Learning

ASSUME:

w || M |= φ

can be checked for single behavior w

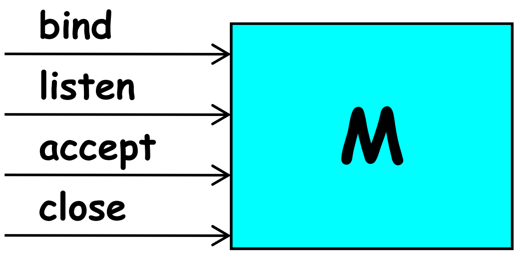
Check w || M |= φ for many w,

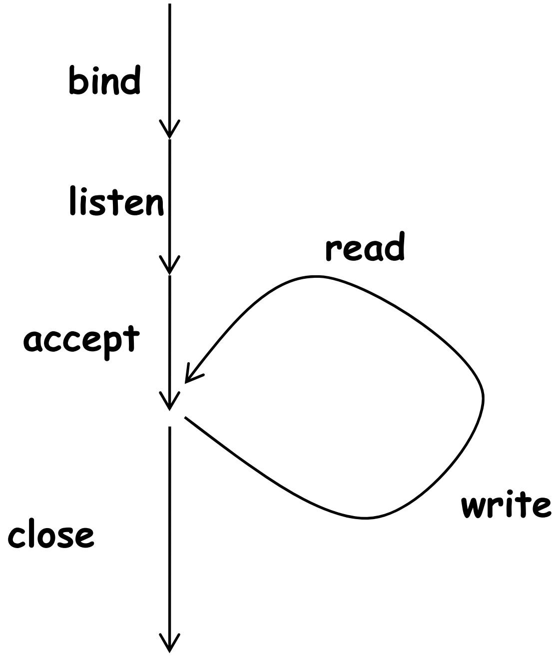
Construct A from these checks

Check whether A satisfies premises

Specification Mining[Ammons,Bodik,Larus]

API:





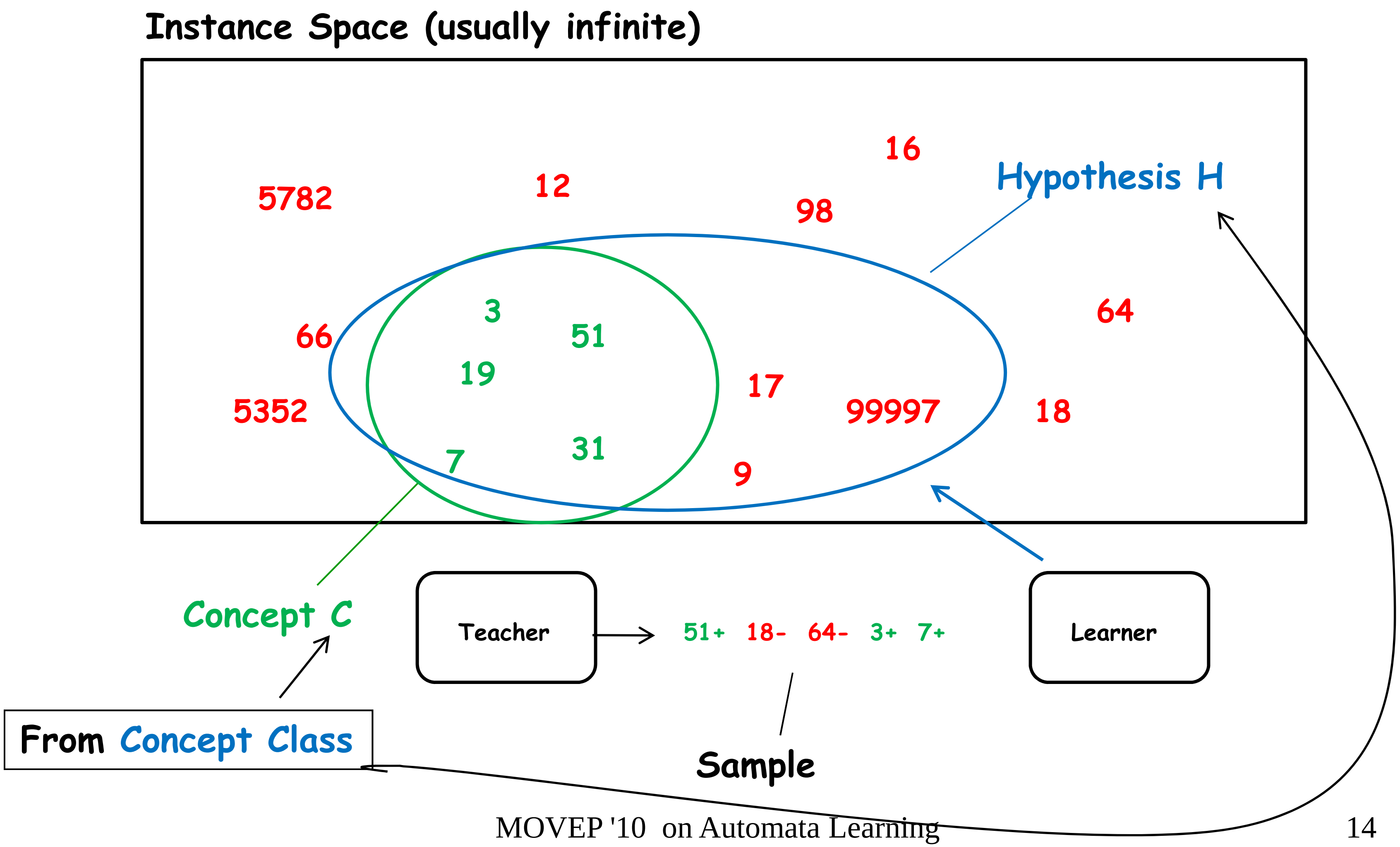
Problem: Find restrictions on how API calls may be ordered

Assume we have well-tested programs that use the API

Analyze executions of such programs.

Form an Automaton that summarize these executions.

Learning



Instance Space (usually infinite)
5782
12
16
98
Hypothesis H
66
3
51
19
64
17
5352
99997
18
7
31
9
Concept C
Teacher
51+ 18- 64- 3+ 7+
Learner
From Concept Class
Sample

Some Terminology

Given an Instance space X

- Concept is a subset of X
- Concept Class is a class of Concepts
- Sample is a (finite) set of labeled examples
  - x+ where $x \in C$
  - x- where $x \notin C$
- Learner produces Hypothesis (in Concept Class) from Sample
- Teacher knows Concept, produces Sample
  - Can also, e.g., answer queries
- Hypothesis H is correct if $H = C$
- Hypothesis H is consistent with sample if
  - if x+ in sample then $x \in H$
  - if x- in sample then $x \notin H$
- Concepts have Representations
  - size of Concept C = size of its Representation

Automata learning

- Assume finite set Σ of symbols
- Instance space: Σ^*
- Concept Class: Regular languages
- Representation of Concept: DFA
- Sample is a (finite) set of labeled words
  - w+ where $w \in L$
  - w- where $w \notin L$

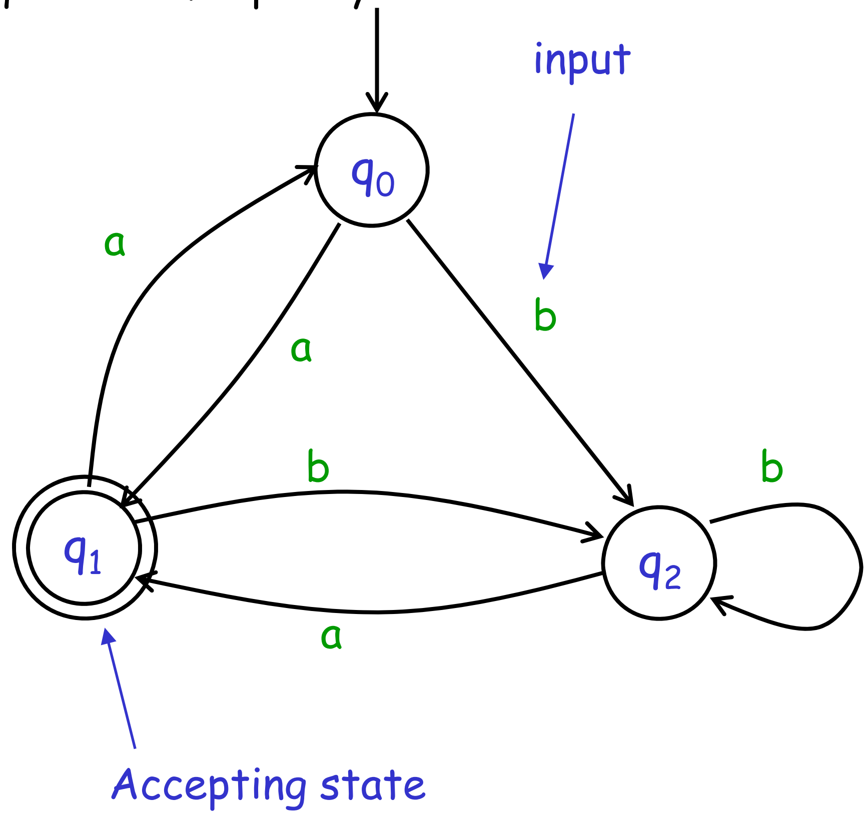
Deterministic Finite Automata (DFA)

Finite State Machines accepting sequences of input symbols

Σ	alphabet of symbols
Q	states
$\delta: Q \times \Sigma \rightarrow Q$	transition function
$F \subseteq Q$	accepting states

Assumptions:

- Deterministic
- Completely specified



Deterministic Finite Automata (DFA)

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Σ symbols

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Myhill-Nerode:

Given language L

For prefix u, define $L_u = \{v \mid uv \in L\}$

Nerode congruence: $u \approx u'$ iff $L_u = L_{u'}$

Unique Minimal DFA accepts regular L

Q : equivalence classes $[u]_\approx$

$\delta([u]_\approx, a) = [ua]_\approx$ transition function

$F : \{[u]_\approx \mid u \in L\}$ accepting states

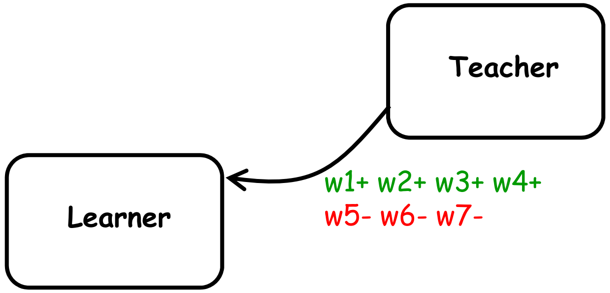
Automata Learning: Frameworks

Construct DFA from sample of accepted and rejected words.

Passive learning: sample given

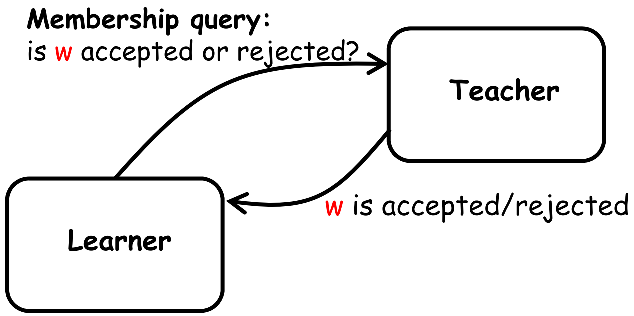
- Only accepted words (positive sample)
- Accepted and rejected words

Observing SUT/test suites



Active learning: Learner chooses words, teacher classifies

Testing SUT



Mealy Machines

Finite State Machines w. input & output

I input symbols

O output symbols

Q states

δ: $Q \times I \rightarrow Q$ transition function

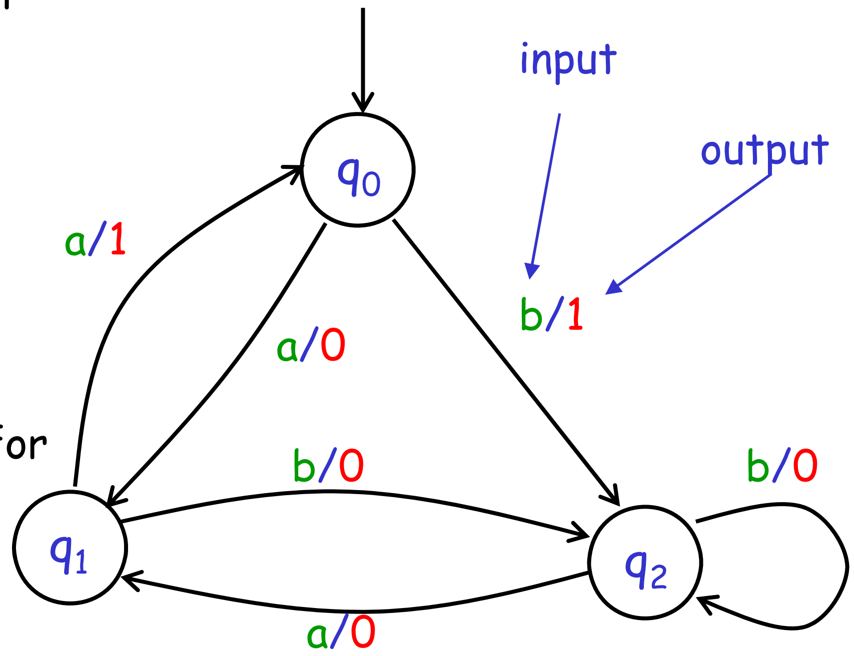
λ: $Q \times I \rightarrow O$ output function

•Often used for protocol modeling, for protocol testing techniques,

Assumptions:

•Deterministic

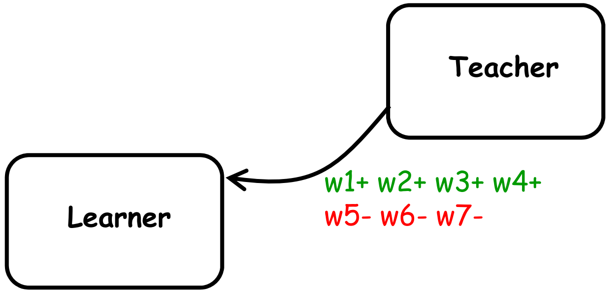
•Completely specified



Passive Learning:

Construct DFA from sample of accepted and rejected words.

- Which DFA?
- The most succinct one!
  - **which conforms to sample,**
  - and has fewest states



- Finding smallest DFA is NP-hard [Gold 78]
- Can be found by constraint solving (Biermann's algorithm)

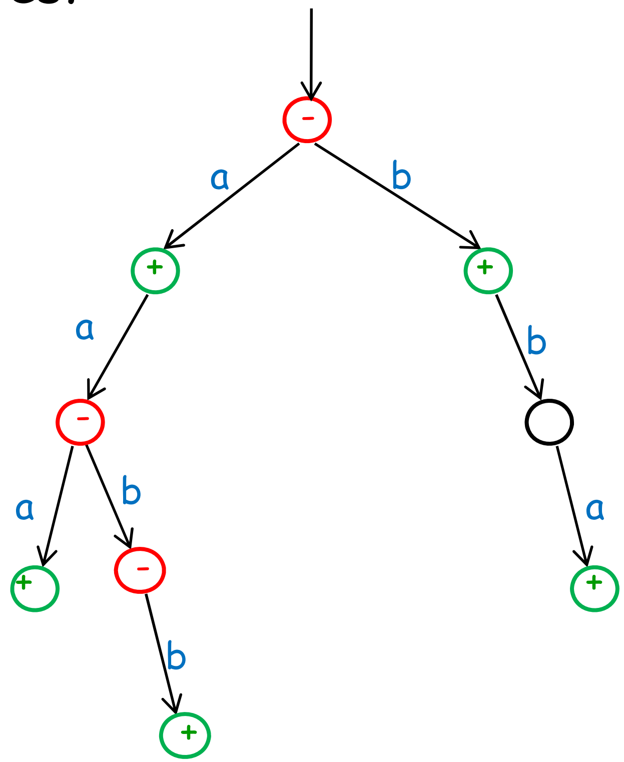
Biermann's Algorithm

Is there a conformant DFA with n states?

Encode this as a CSP problem

- Map each prefix u in tree to some state $q_u \in \{1 .. n\}$
- Subject to constraints:
  - $q_u \neq q_v$ if u accepted, v rejected
  - if ua va are prefixes, then
    $q_u = q_v$ implies $q_{ua} = q_{va}$

Try example for $n = 3$



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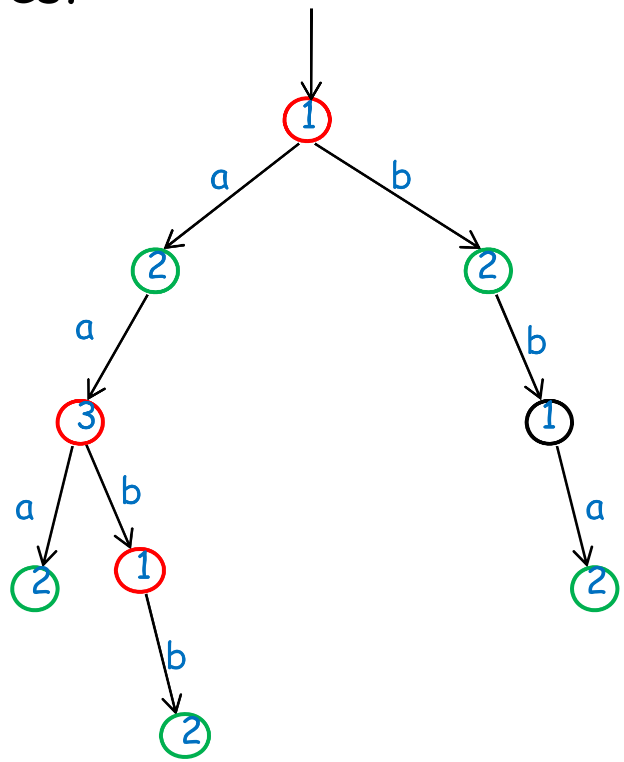

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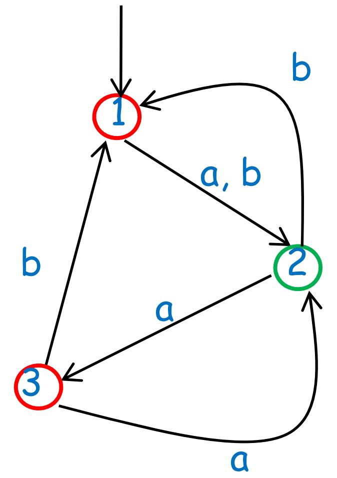


Try example for $n = 3$

Check

Accepted: a b aaa aabb bba

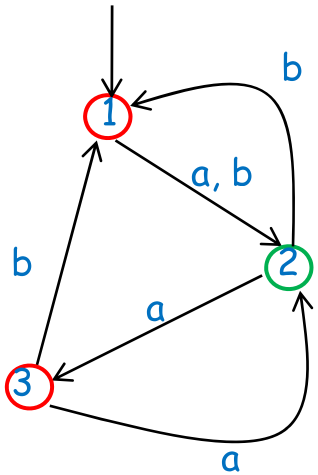
Rejected: λ aa aab

Discussion

- Problem w. Biermanns algorithm: Exponential
- Q: Is there a setting to learn automata polynomially in some way?
- By Gold's result, we cannot hope to learn minimal DFA from arbitrary sample.

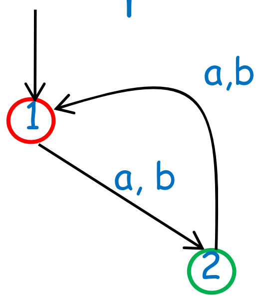
Identification in the Limit

L

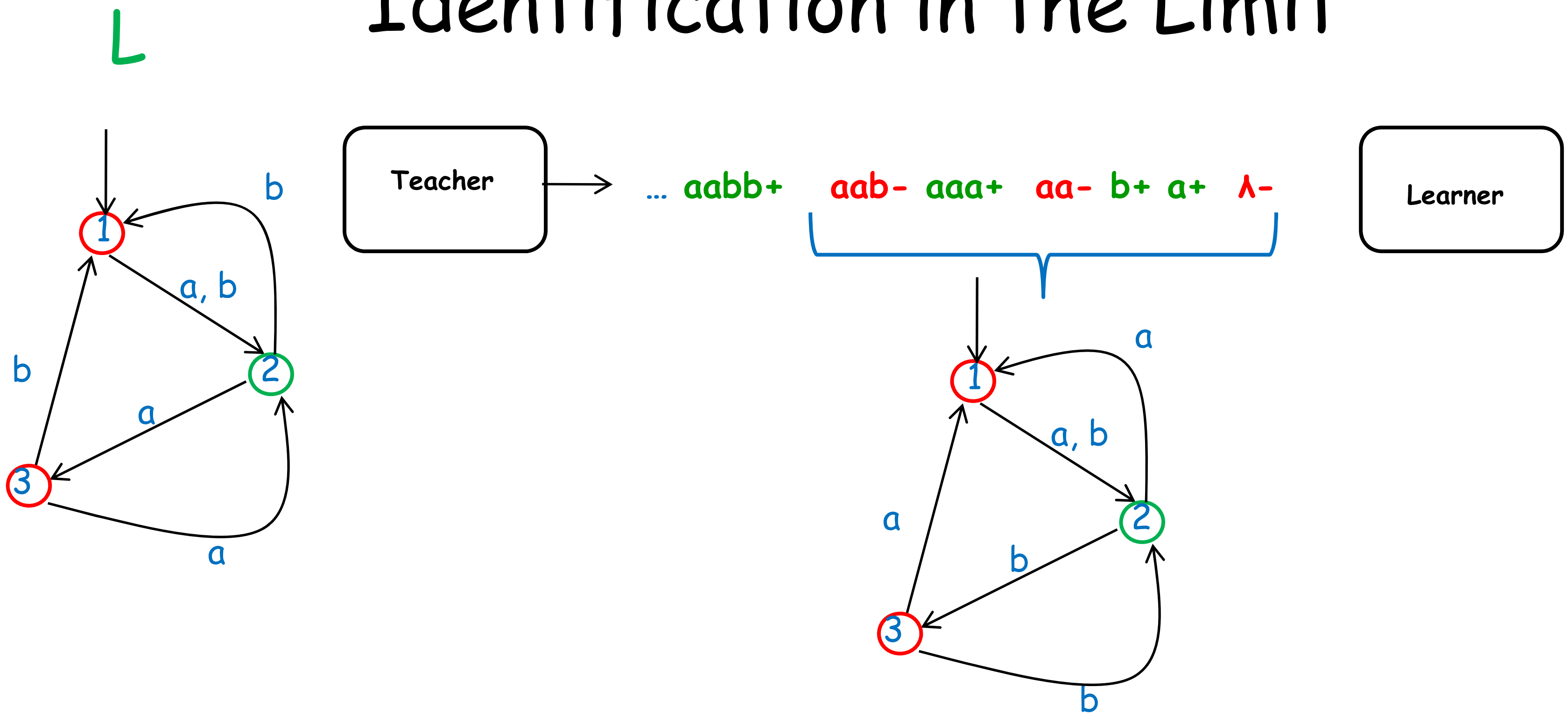


Teacher → … aabb+ aab- aaa+ aa- b+ a+ λ- Learner

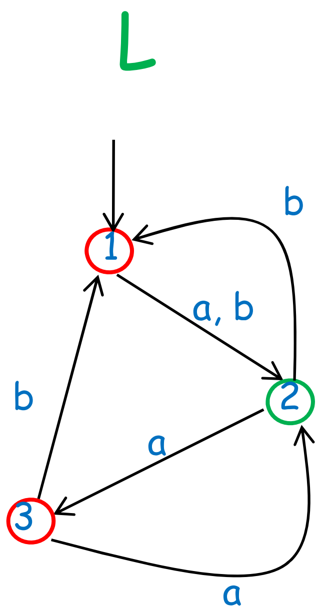
Enumeration of Σ*

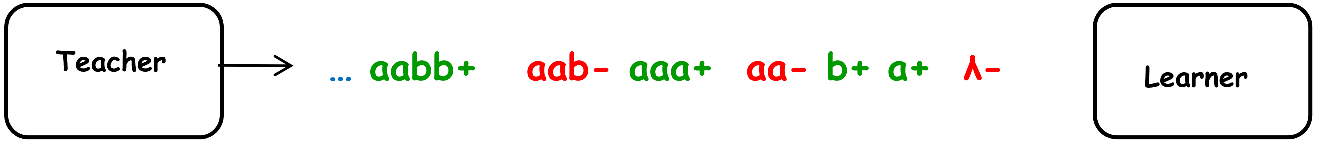


Identification in the Limit



Identification in the Limit





- Assume Teacher incrementally enumerates all words (classified) in Σ^*
- After each word, Learner can use previous words to form hypothesis H

Learner **identifies L in the limit**,

if H converges to correct hypothesis after finitely many words

Still, (exponentially) much data may be needed

Efficient Identification in the Limit

Teacher → … aabb+ aab- aaa+ aa- b+ a+ λ- Learner

Concept Class is **efficiently identifiable in the limit** if
∃polynomials p,q, s.t. for any concept C in concept class

- Learner can produce H in time O(p(|seen sample|))
- Exists sample S of size O(q(|C|)) s.t. Learner produces correct H whenever seen sample contains S

- S called "characteristic sample" for C
- S can depend on Learner

Observations

if Concept class is efficiently identifiable in the limit, then

- Learner needs polynomial time to produce hypothesis
- Concepts characterized by polynomial-size characteristic sets
- With "helpful" Teacher, the Learner needs only polynomially much data to infer *C*
- With "unhelpful" Teacher, the Learner may need a lot of data to infer *C*
- Learner should work well for characteristic sets, should make "reasonable" hypotheses otherwise.

Characteristic Samples

A characteristic sample S for C should uniquely characterize C in the following sense:

Learner should produce hypothesis C from any sample that contains S and is consistent with C

Implies that if

- S is characteristic sample for C and
- S' is characteristic sample for C'

then either

- C is inconsistent with S' or
- C' is inconsistent with S
- (otherwise what to do with $S \cup S'$?)

Characteristic Samples for DFAs

A characteristic sample for L should identify its DFA.
This can be done by

- Demonstrating that there are n states
  - Each state represented by access string u

    u represents $\delta(q_0,u)$
- For each state q and symbol a,

  uniquely identify $\delta(q,a)$

Separating Sequences

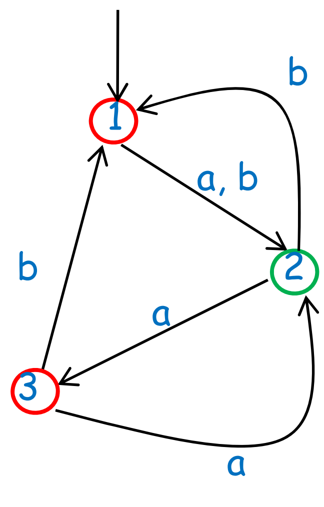
A **separating sequence** for q and q' is a suffix v such that

$\delta(q,v)$ is accepting and $\delta(q',v)$ is rejecting (or vice versa)

1 2 : λ

1 3 : b (not a)

2 3 : λ



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Separating Sequences

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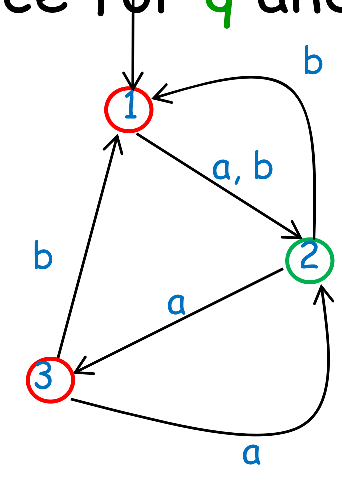
A **separating family of DFA** is a family of sets

$\{ Z_q \mid q \text{ is a state of DFA}\}$

s.t. $Z_q \cap Z_{q'}$ contains separating sequence for q and q'

1 : λ b
2 : λ
3 : λ b



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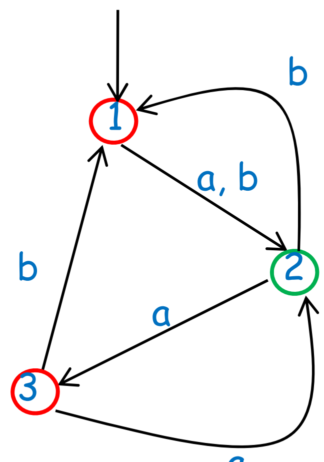
If all Z_q are equal (to W), then W is a **characterizing set**



1	:	λ	b
2	:	λ	
3	:	λ	b

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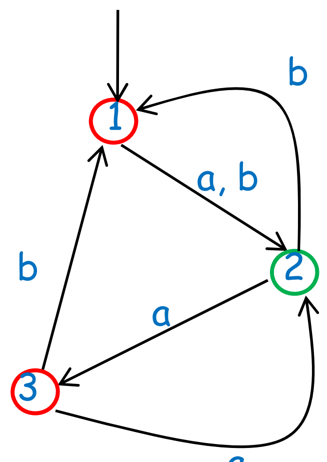
W : λ b



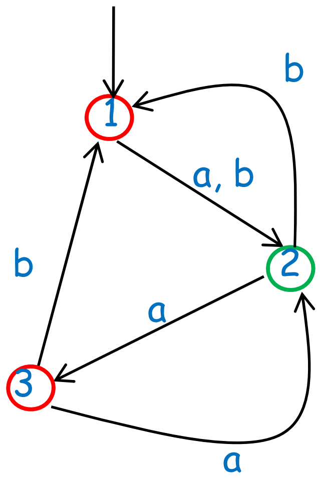
Characteristic Sample

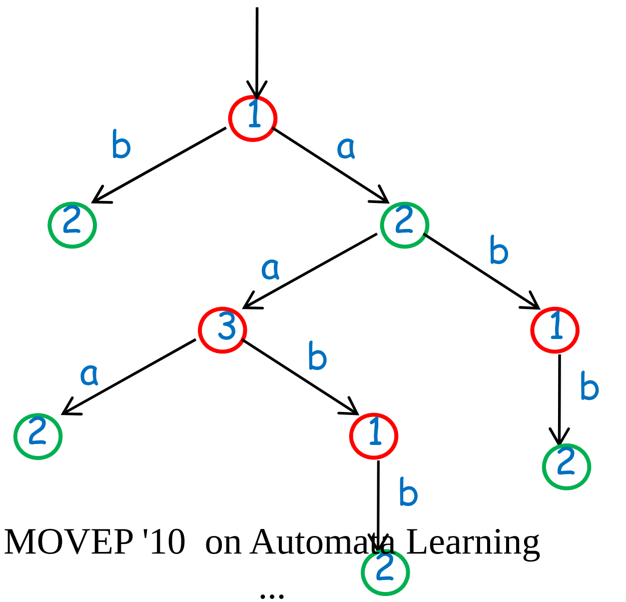
Let Sp(L) be prefixes in minimal spanning tree of DFA(L)

Let K(L) be $\{ ua \mid u \in Sp(L) \quad a \in \Sigma \}$

Let Characteristic Sample be

$$Sp(L) \cup \{ uv \mid u \in Sp(L) \cup K(L) \quad v \in Z_{q_u} \}$$



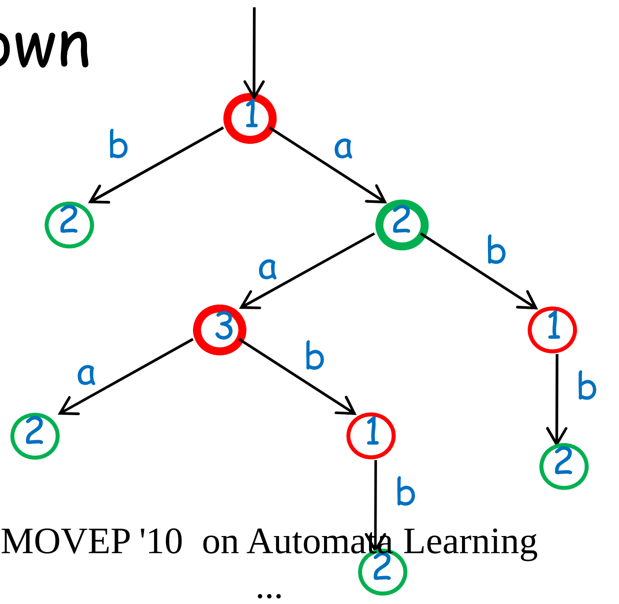


Λ
a
aa
b
ab
aaa
aab
abb
aabb

Why characteristic sample?

When forming DFA from prefix tree:

- The states $\{q_u \mid u \in Sp(L)\}$ cannot be merged
  - since they are separated by suffixes
- Each state in $\{q_u \mid u \in K(L)\}$ can be merged with at most one state in $\{q_u \mid u \in Sp(L)\}$
- Easy to construct minimal DFA from sample
  - if $Sp(L)$ is known

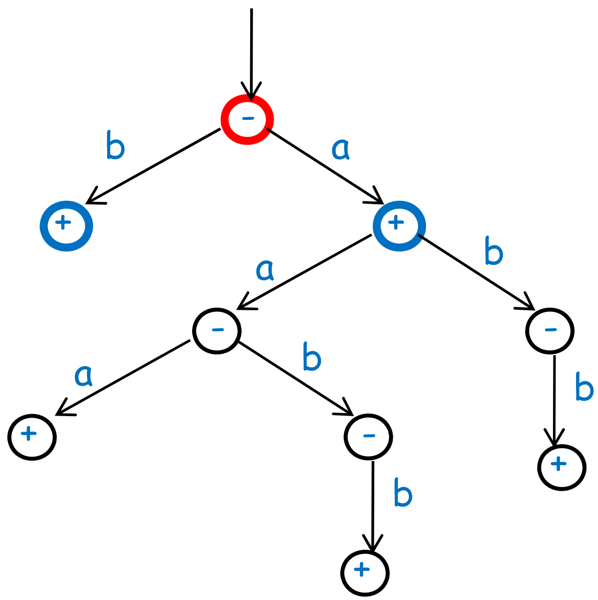


Λ
a
aa
b
ab
aaa
aab
abb
aabb

State Merging Algorithms

- Traverse the prefix tree from root
- For each new state
  - if possible, merge it with some seen state
  - Otherwise, promote it to a new state in the resulting DFA
- Red states are determined to become DFA states
- Blue states (frontier) are the successors of red states, waiting to be candidates for merging with red states.
- Repeatedly
- Merge blue with red if no inconsistency results
- "Unmergeable" blue state becomes red

State Merging: Example



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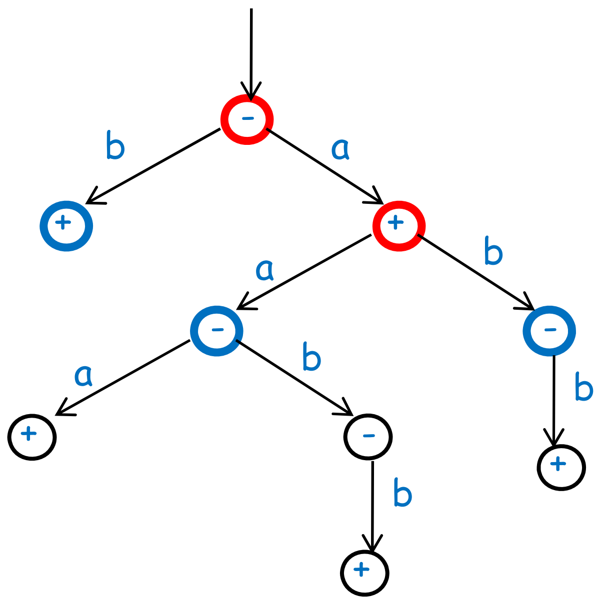

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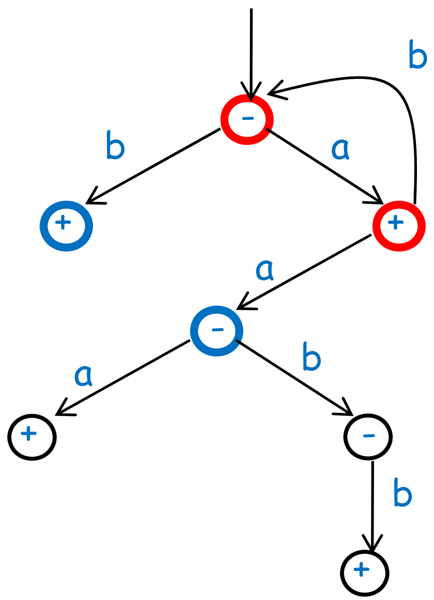

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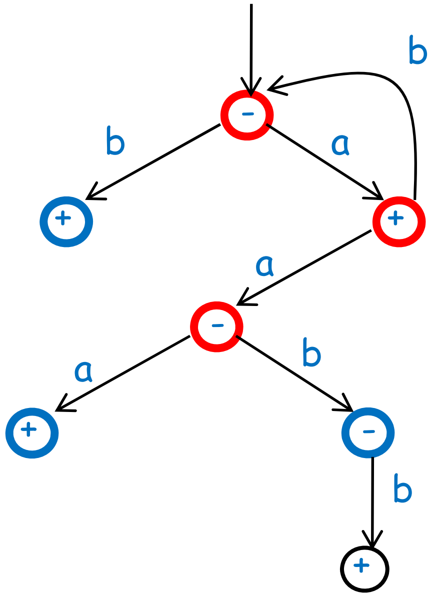

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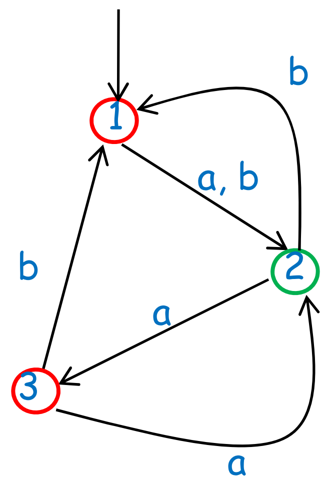
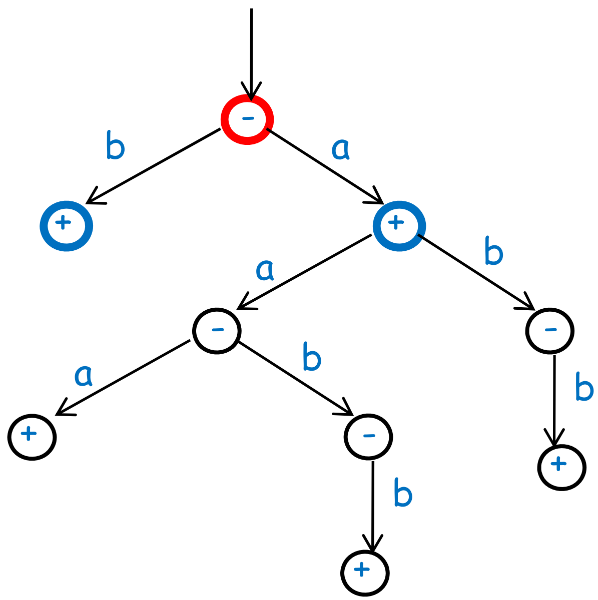


What if we change order?



About State Merging

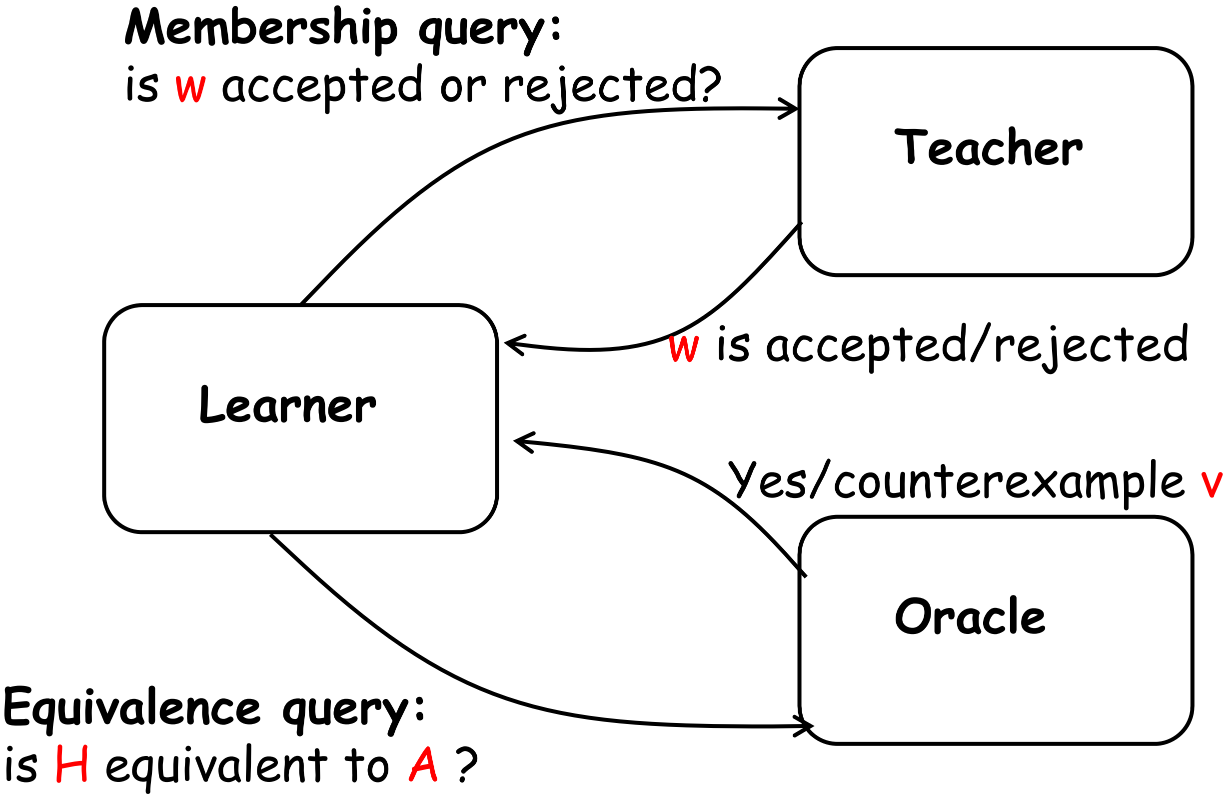
- Order in which blue states are considered matters.
- If considered states stay within $\{q_u \mid u \in K(L)\}$
  a minimal DFA will be constructed
- Otherwise, "suboptimal" merges may result
- Remedy: Teacher and Learner agree on a fixed technique to construct $Sp(L)$
  - e.g., to consider strings in lexicographic order
  - RPNI algorithm. [Oncina, Garcia]
- Otherwise: use heuristics for choosing "best merge",
  - e.g., to select states with "largest" subtrees.

About State Merging

- Time Complexity (in size of sample):
  - At most a quadratic number of candidate merges considered.
  - Each merge takes linear time to check
  - I.e., time complexity is polynomial.

Active Learning

Learner actively constructs the characteristic sample,



Ideas

- Maintain candidates for

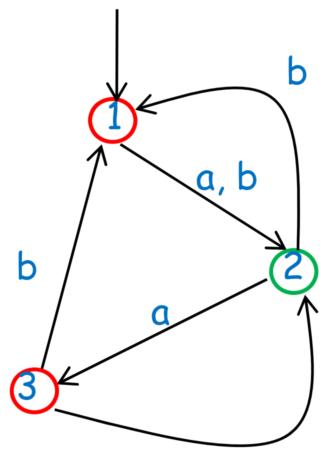
  $Sp(L) \qquad K(L) \qquad W$

  where W is a distinguishing set
- Ask membership queries for

  $$\{ uv \mid u \in Sp(L) \cup K(L) \quad v \in W \}$$

- If u in $K(L)$ is separated from all prefixes in $Sp(L)$ by separating suffix, move u to $Sp(L)$ and extend $K(L)$
- For new u' in $K(L)$ let W be large enough to separate u' from all but (at most) one prefix in $Sp(L)$

L* Algorithm



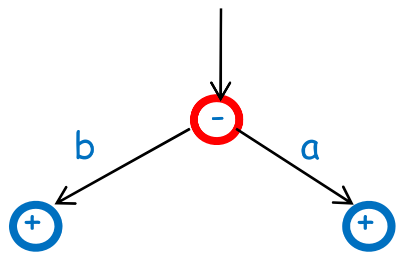
Observation table

W

Sp(L)

K(L)

	λ	
λ	-	
a	+	
b	+	



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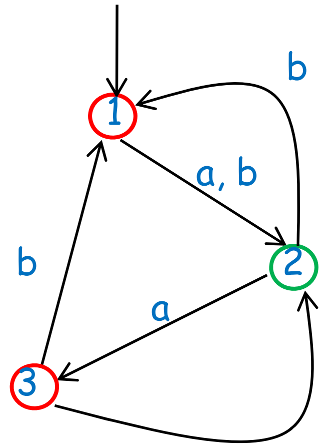
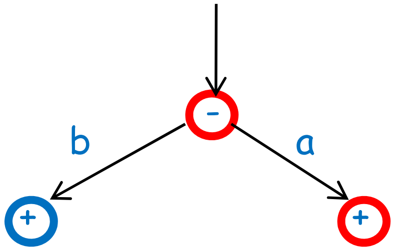


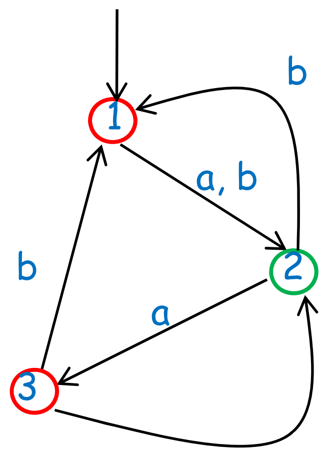
Observation table

W

		λ	
Sp(L)	λ	-	
	a	+	
K(L)			
	b	+	



L* Algorithm



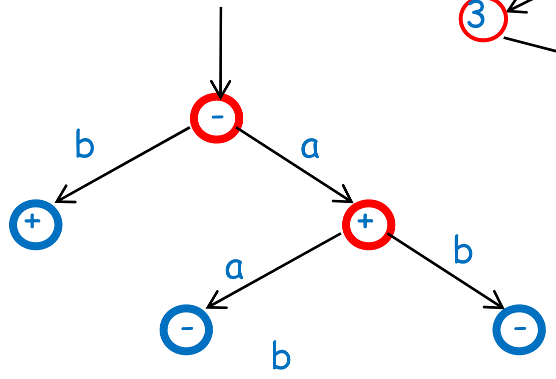
Observation table

W

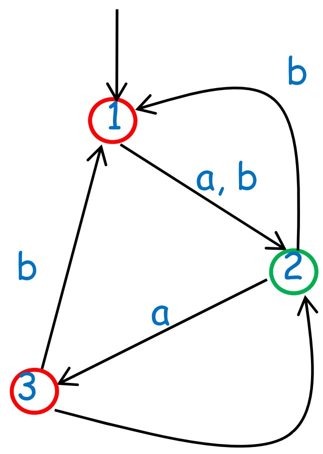
	λ	
λ	-	
a	+	
b	+	
aa	-	
ab	-	

Sp(L)

K(L)



Closed - Form Hypothesis



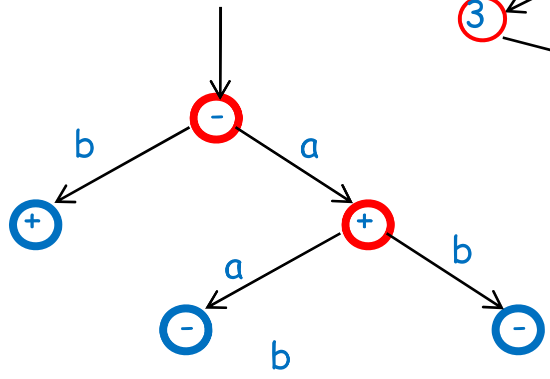
Observation table

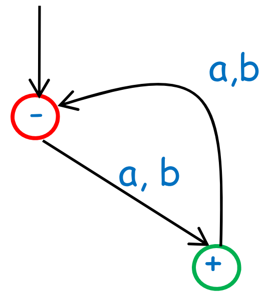
W

	λ	
λ	-	
a	+	
b	+	
aa	-	
ab	-	

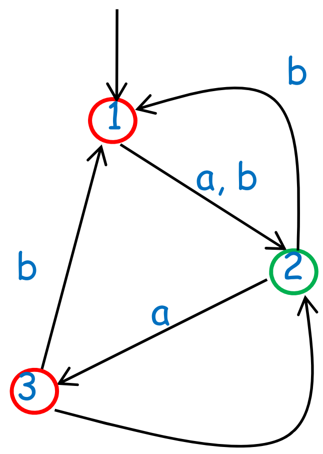
Sp(L): λ, a

K(L): b, aa, ab





Ask Equivalence Query



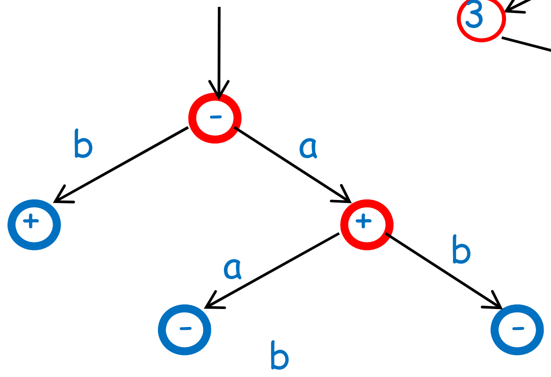
Observation table

W

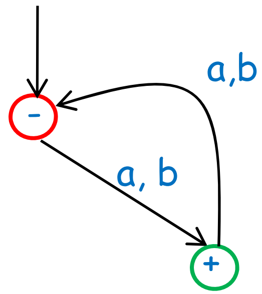
	λ	
λ	-	
a	+	
b	+	
aa	-	
ab	-	

Sp(L)

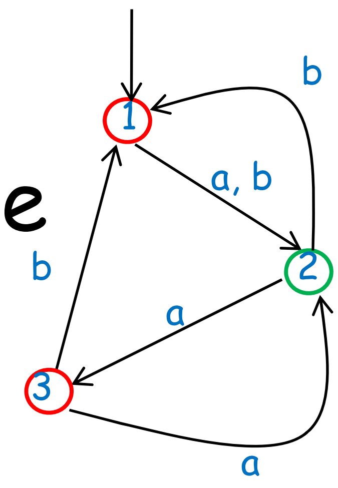
K(L)

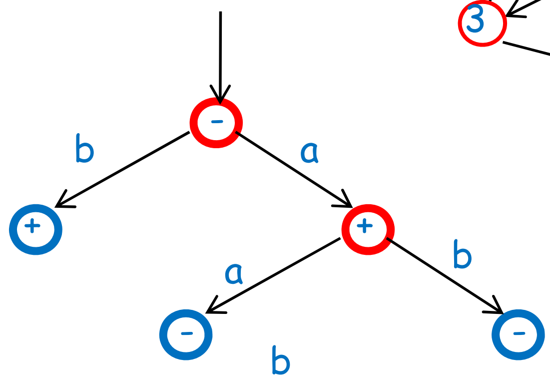


aab-



Decompose counterexample



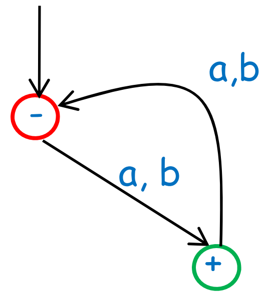


Observation table

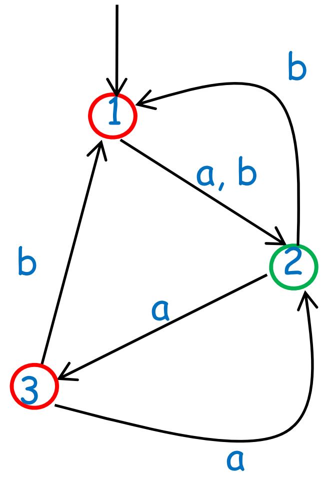
W

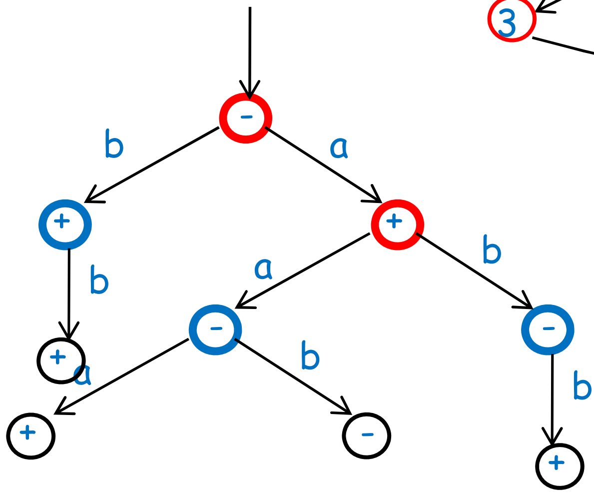
		λ	
Sp(L)	λ	-	
	a	+	
K(L)	b	+	
	aa	-	
	ab	-	

aab-



Add new suffix to W





Observation table

W

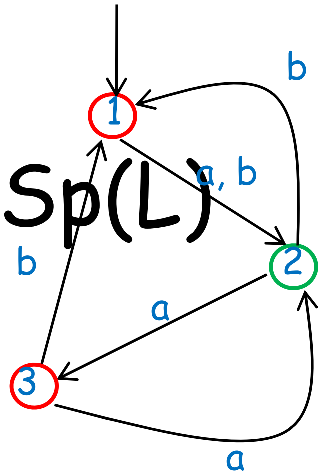
	λ	b
λ	-	+
a	+	-
b	+	-
aa	-	-
ab	-	-

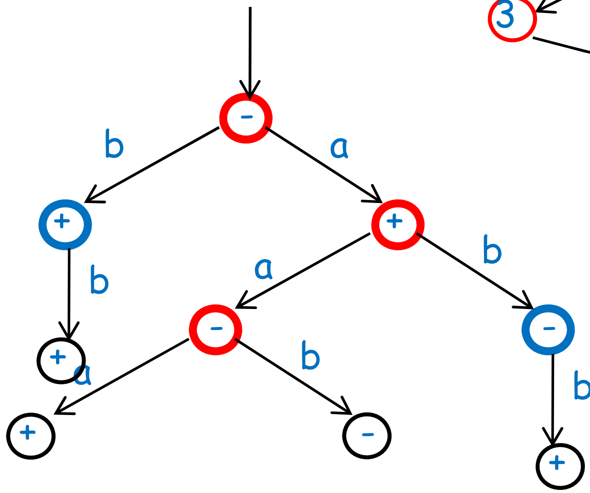
Sp(L)

K(L)

aab-

Not closed- Add new prefix to Sp(L)





Observation table

W

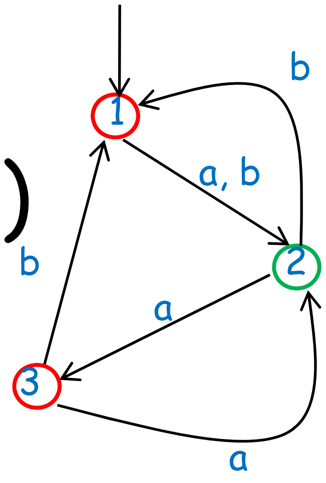
	λ	b
λ	-	+
a	+	-
aa	-	-
b	+	-
ab	-	+

Sp(L)

K(L)

aab-

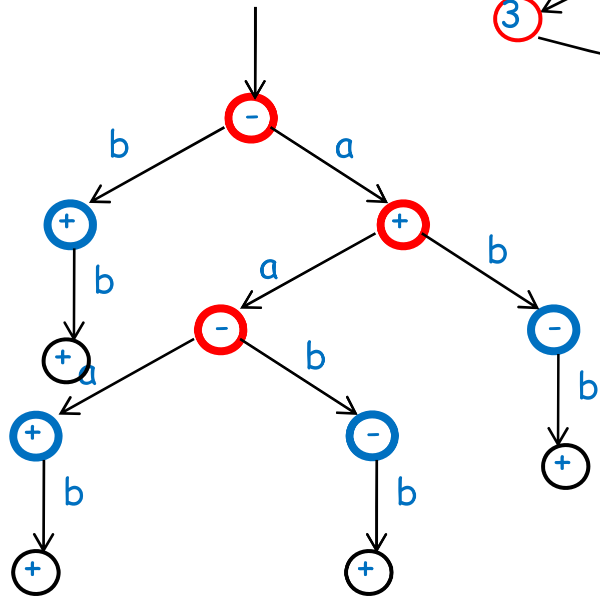
Add new extensions to K(L)



Observation table

W

		λ	b
Sp(L)	λ	-	+
	a	+	-
	aa	-	-
K(L)	b	+	-
	ab	-	+
	aaa	+	-
	aab	-	+



aab-

About L* [Angluin]

- DFA with n states can be learned using
  - $\leq n$ equivalence queries
  - $O(|\Sigma|n^2 + n \log m)$ membership queries
    - m is size of longest counterexample
- Produced hypothesis is always minimal DFA which is consistent with seen membership queries
  - These are a characteristic set for hypothesis
- Equivalence query idealizes (possibly) exponential search for deviations from model
- The setup with Membership and Equivalence queries makes it possible to formulate polymial-complexity algorithm.

Mealy Machines

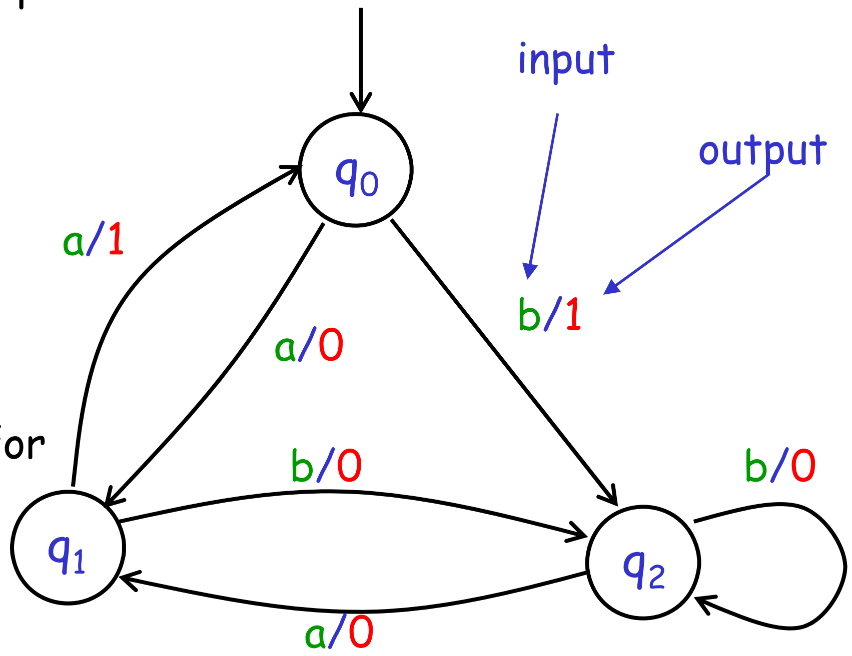
- Finite State Machines w. input & output

I	input symbols
O	output symbols
Q	states
δ: $Q \times I \rightarrow Q$	transition function
λ: $Q \times I \rightarrow O$	output function

- Often used for protocol modeling, for protocol testing techniques,

Assumptions:

- Deterministic
- Completely specified



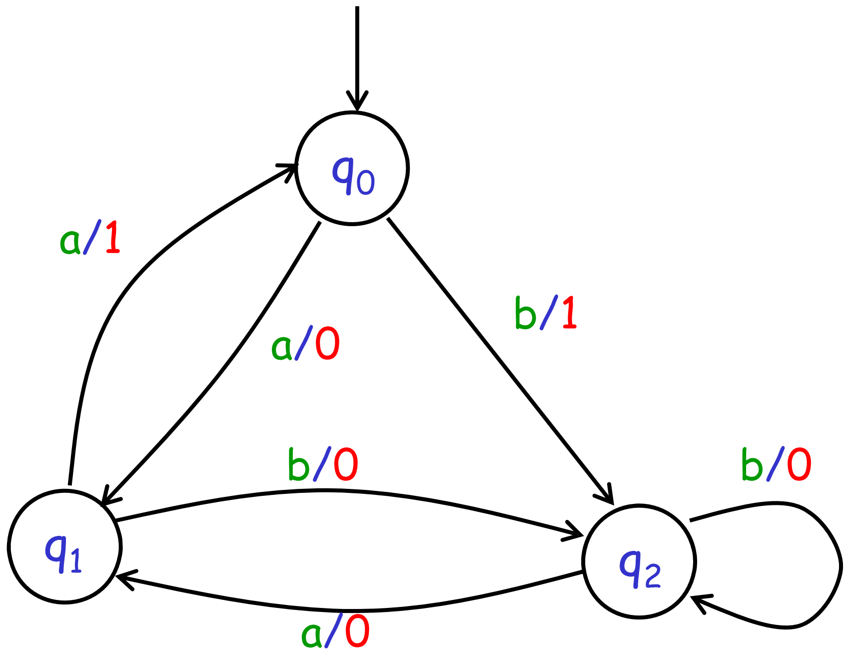
Conformance Testing

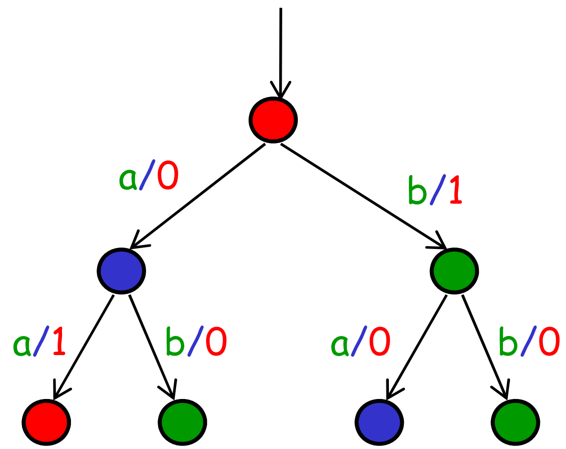
- Given MM A, construct a sample (i.e., a test suite) S such that A is "best fit" to explain S
  - Typically: A is the only MM with $\leq|A|$ states, which is consistent with S

W-method

Let Sp(L) be prefixes in minimal spanning tree of MM

Let K(L) be { ua | u ∈ Sp(L) a ∈ I }



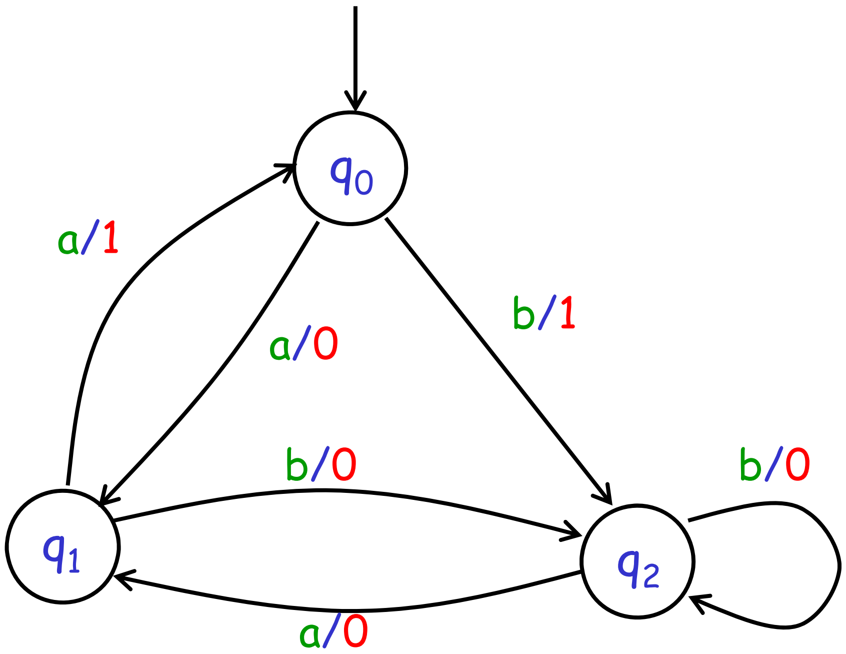


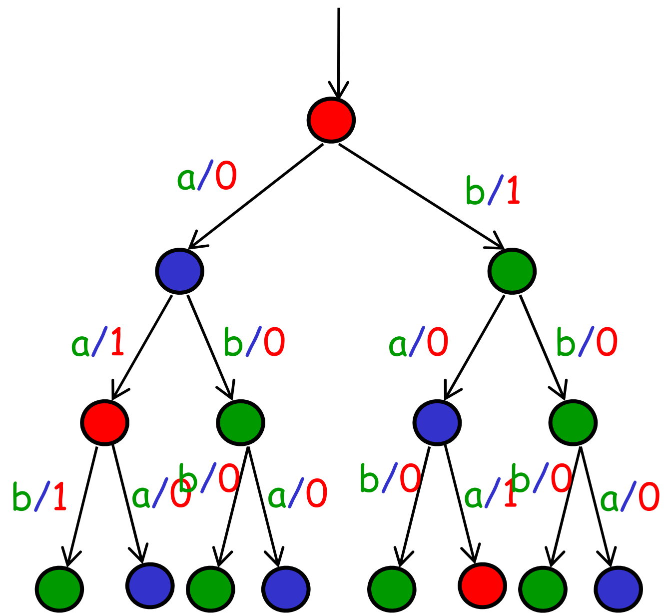
W-method

Let Sp(L) be prefixes in minimal spanning tree of MM

Let K(L) be $\{\ ua \mid u \in Sp(L) \quad a \in I\ \}$

Let Sample be $\{\ uv \mid u \in Sp(L) \cup K(L) \quad v \in W\ \}$
where W is a distinguishing set



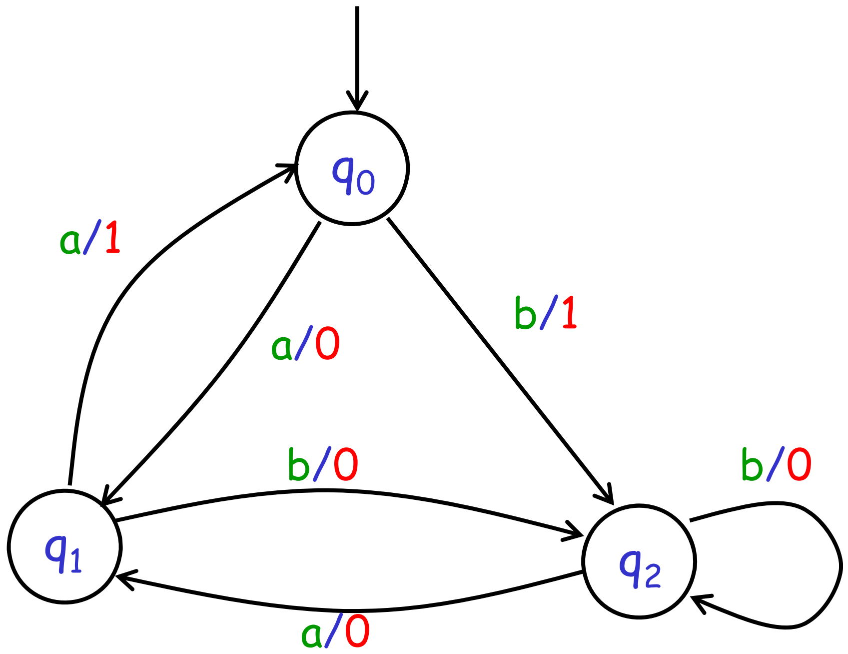


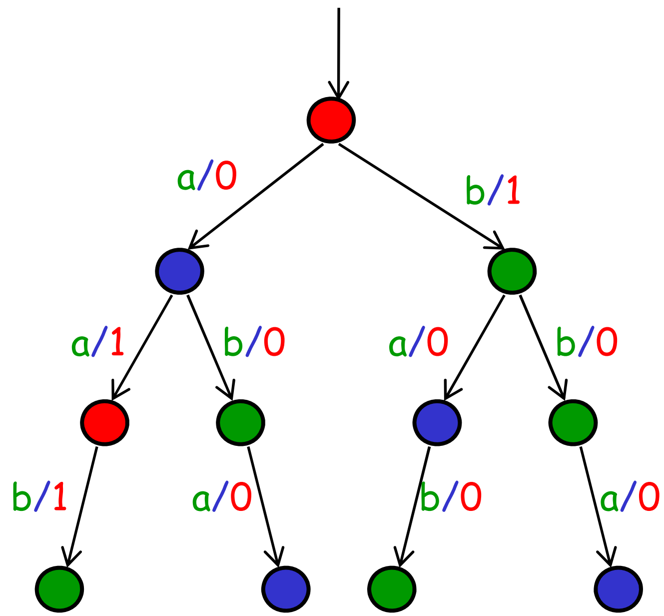
Z-method

Let $Sp(L)$ be prefixes in minimal spanning tree of MM

Let $K(L)$ be $\{ ua \mid u \in Sp(L) \quad a \in I \}$

Let Sample be $\{ uv \mid u \in Sp(L) \cup K(L) \quad v \in Z_{q_u} \}$
where $\{Z_q \mid q \in Sp(L) \}$ is a separating family of MM





Learning vs. Conformance Testing

- Learning: Find Concept *A* which is "best fit" to explain a given sample *S*
- Conformance Testing: Given Concept *A*, construct a sample *S* such that *A* is "best fit" to explain *S*
- For automata learning: A characteristic sample for *A* is also a conformance test suite for *A*

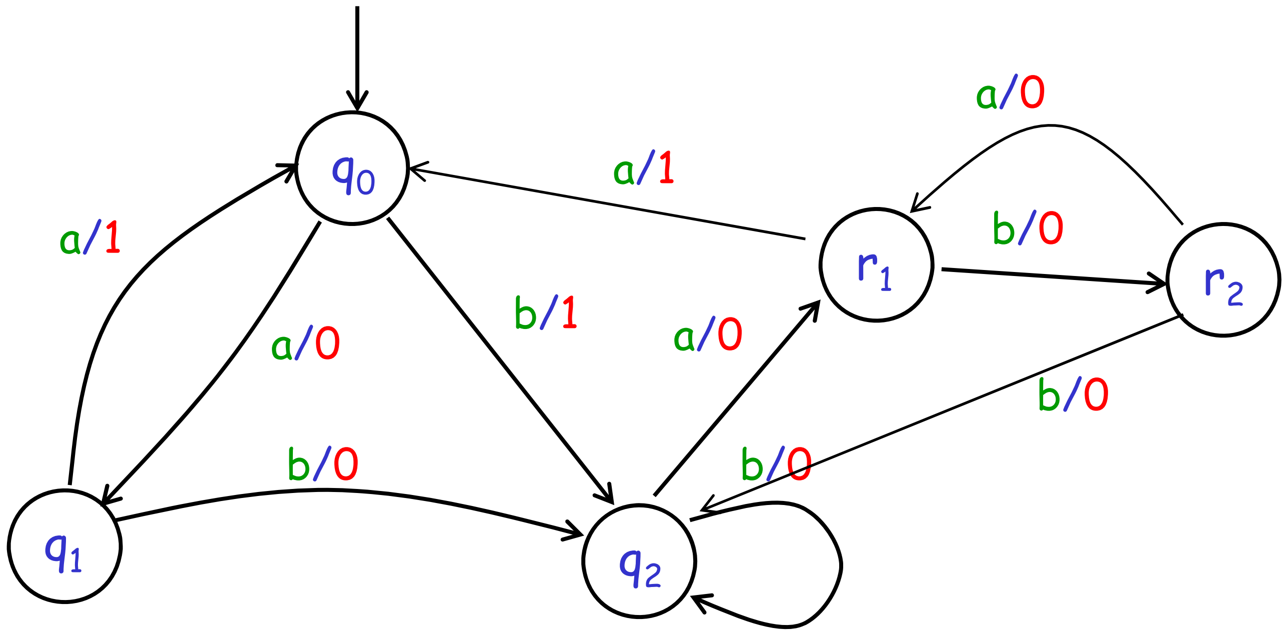
L* vs. W-method

- A sample generated by L* is also a conformance test suite generated by the W-method
- A conformance test suite generated by the W-method is a characteristic sample
- A is the only MM of size $\leq |A|$ which is consistent with S

Q: Can we check whether A is the only automaton of size $\leq |A| + k$ which is consistent with S

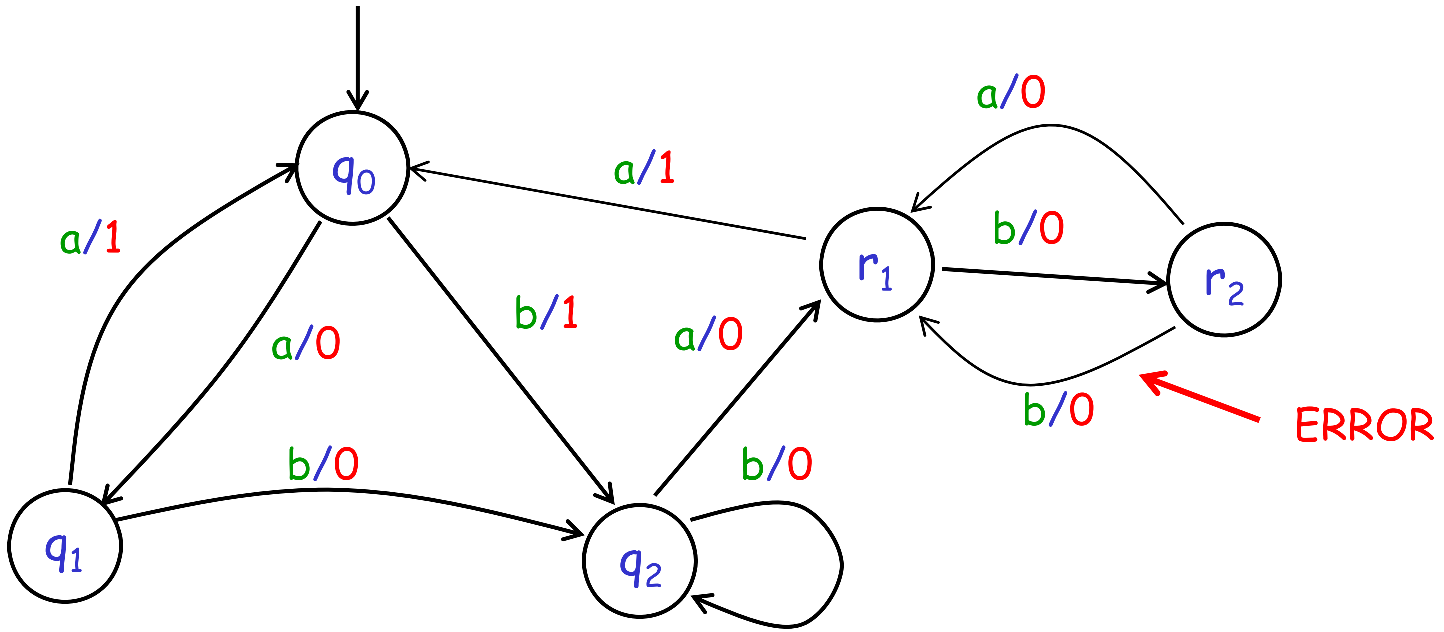
Vasilevski-Chow test suite

- Let k =2
- Test suite should allow non-minimised MM



Vasilevski-Chow test suite

- Let k =2
- Test suite should allow non-minimised MM
- Must cope with anomaly



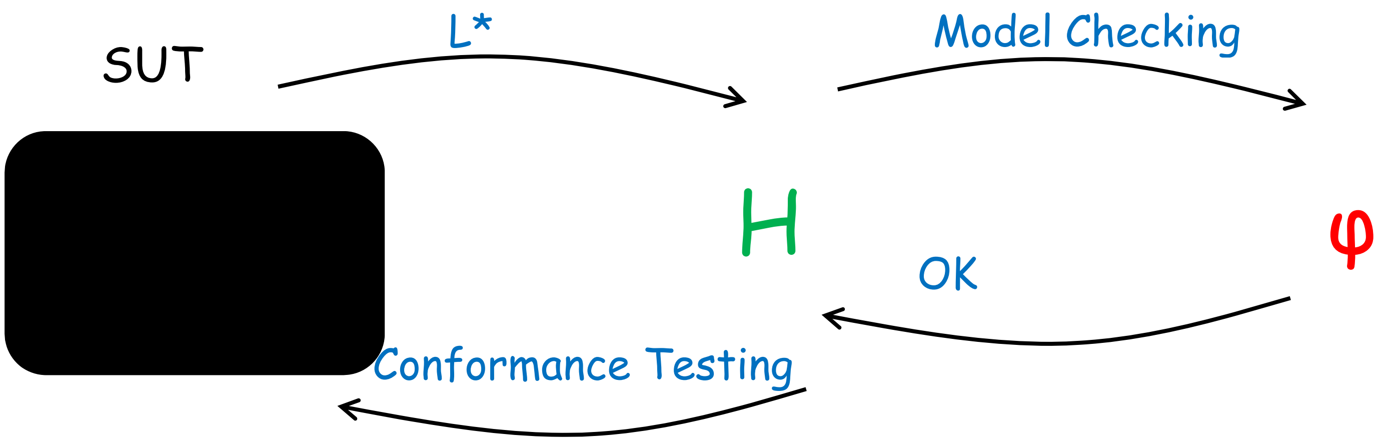
Resulting test suite

- Let W be a characterizing set for A
- VC-test suite has form

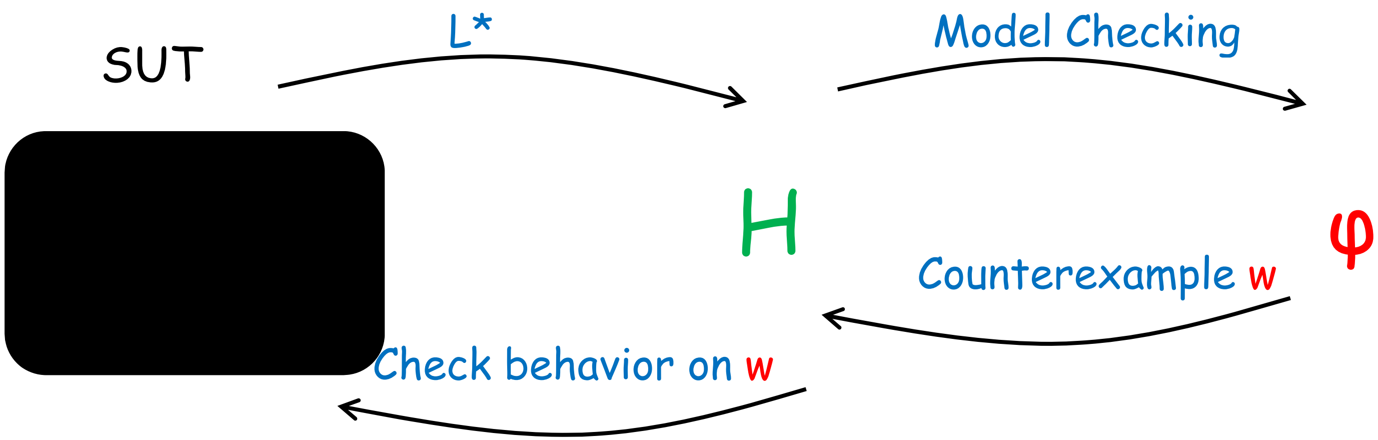
$$S = \{ uxv \mid u \in Sp(L) \cup K(L) \quad x \in I^{\leq k} \quad v \in W \}$$

- A is only MM of size $\leq |A| + k$ which is consistent with S
- Size of sample: $O(|\Sigma|^{k+1}\, n^2)$

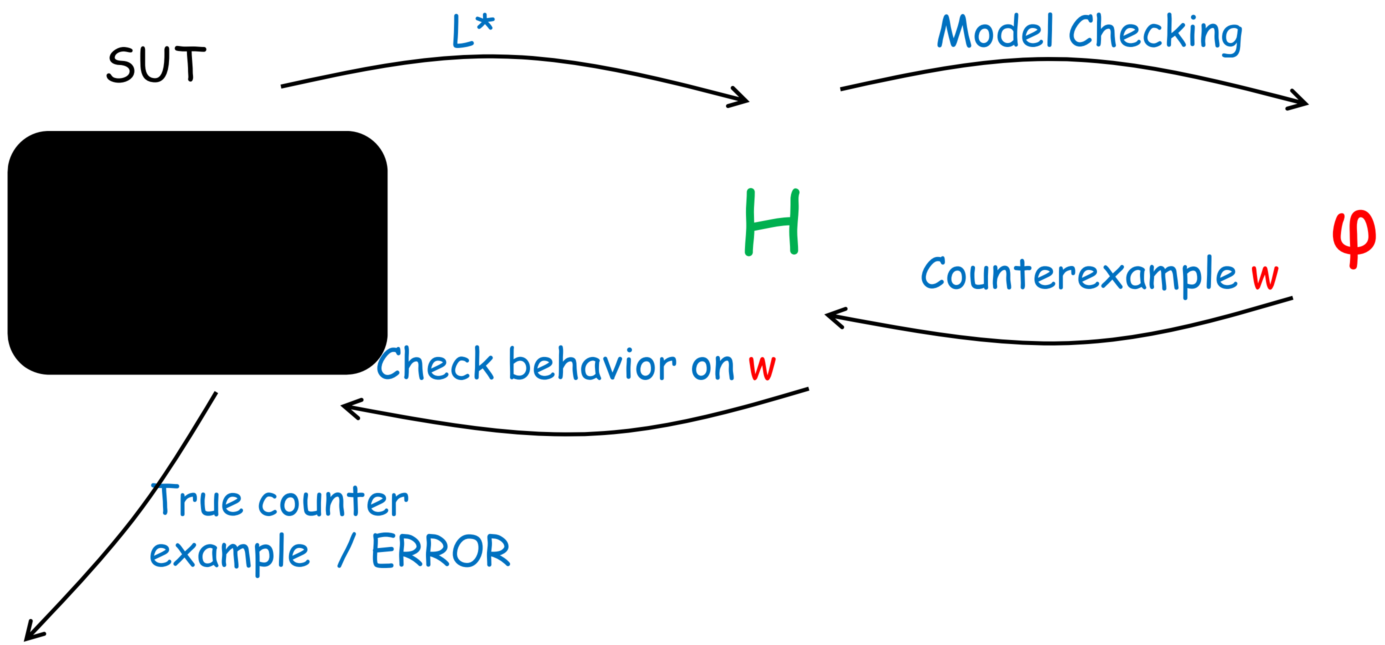
Adaptive Model Checking [Peled Yannakakis 02]



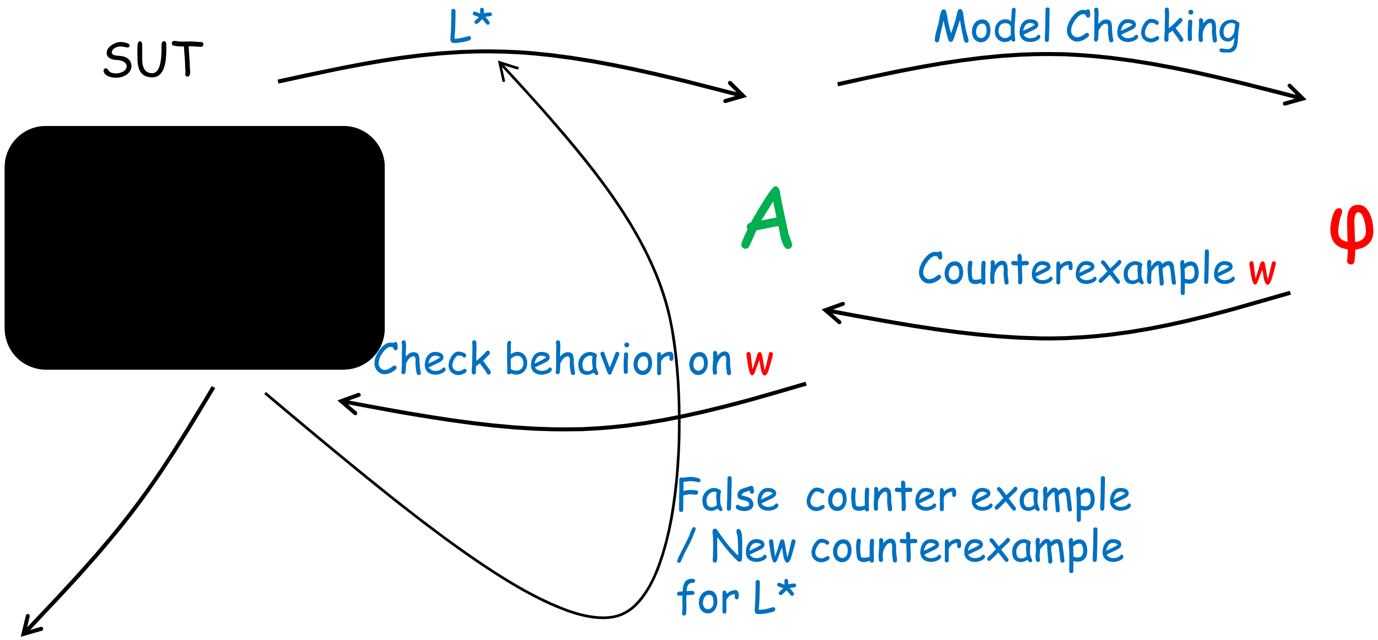
Adaptive Model Checking [Peled Yannakakis 02]



Adaptive Model Checking [Peled Yannakakis 02]



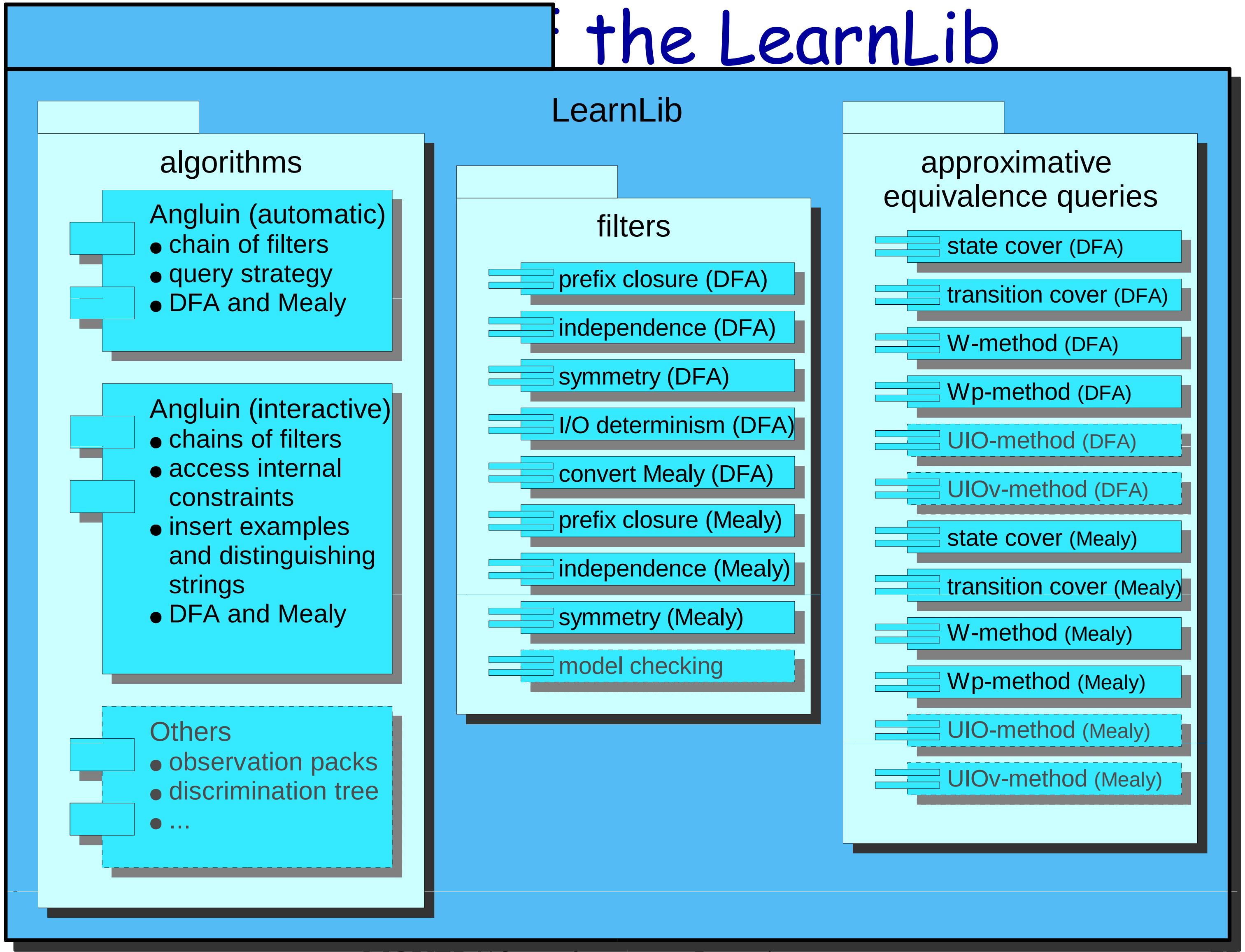
Adaptive Model Checking [Peled Yannakakis 02]



LearnLib: a Tool for Inferring Models

- Developed at Dortmund Univ. [Steffen, Raffelt, Howar, Merten]
- Central Idea: use domain-specific knowledge to reduce the number of queries:
  - Prefix-closure
  - Independence between symbols (e.g., in parallel components)
  - Symmetries
- These properties correspond to “filters” between observation table and SUT

the LearnLib



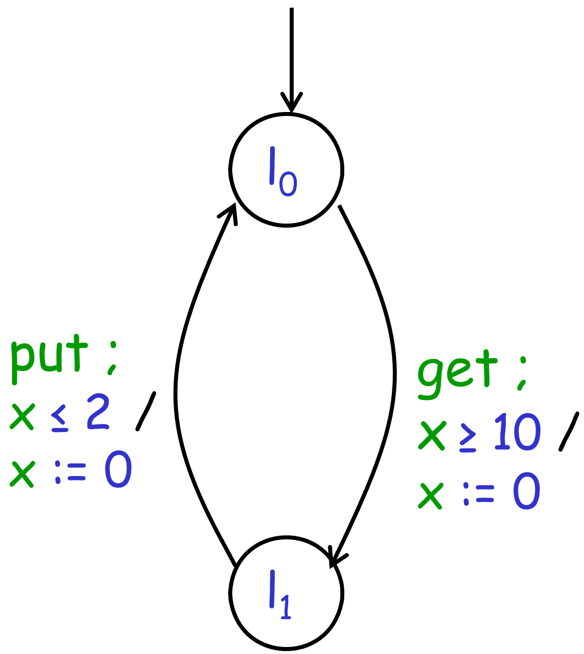
...

Whata about Extensions of Automata?

- Input and output symbols parameterized by data values.
- State variables remember parameters in received input
- Types of parameters could be, .e.,g
  - Identifiers of connections, sessions, users
  - Sequence numbers
  - Time values

Timed Automata

- Based on standard automata
- Clocks give upper and lower bounds on distance in time between occurrences of symbols.
- Temporal properties of Timed Automata (reachability, LTL, …) can be model-checked
- Implemented in tools (UPPAAL, IF/Kronos)



Timed words:

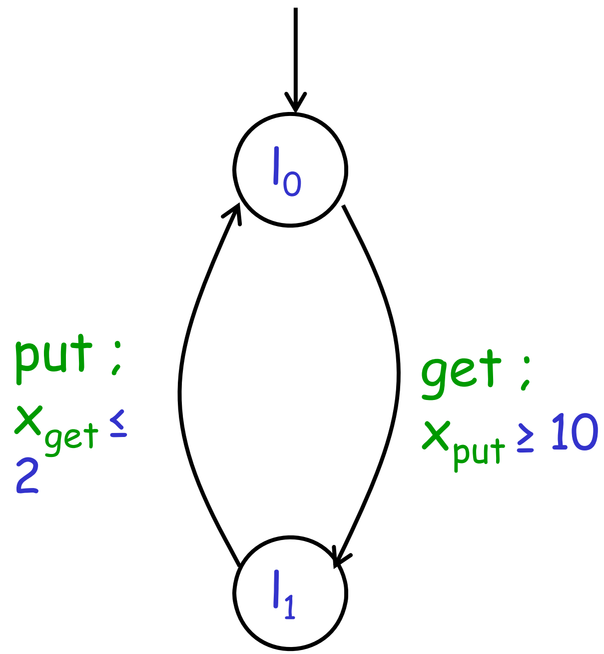
(get, 14.4) (put, 16.4) (get, 29.34) (put, 30.3) …

Event-Recording Automata

- Timed Automata can not be determinized in general
- Event-Recording Automata (ERA): One clock for each symbol, which is reset on that symbol.
- ERA can be determinized

Assumption:

Inference algorithm can precisely control and record timing of symbols.



Timed words:

(get, 14.4) (put, 16.4) (get, 29.34) (put, 30.3) ...

Clocked words:

(get, [14.4,14.4]) (put, [2.0,14.4]) (get, [14.94,12.94]) (get, [0.96,13.9]) ...

Event-Recording Automata

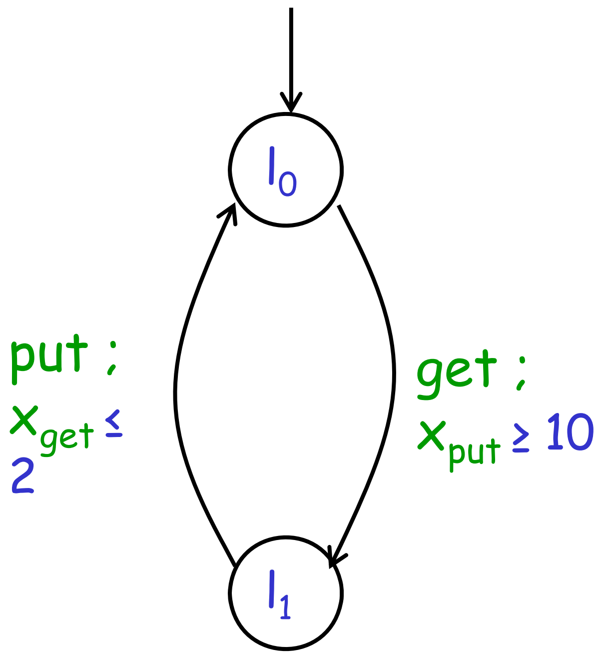
Σ (symbols) {put, get}

L (locations) $\{l_0, l_1\}$

l_0 (initial location)

E (edges) $\subseteq$ L x Σ x Guards x L

F (accepting locations) $\subseteq$ L



Event-Recording Automata

Σ (symbols) {put, get}

L (locations) $\{l_0, l_1\}$

l_0 (initial location)

E (edges) $\subseteq$ $L \times \Sigma \times \text{Guards} \times L$

Conjunctions of interval constraints

F (accepting locations) $\subseteq L$

Semantics

Q (states) $L \times R^{\geq 0} \times R^{\geq 0}$

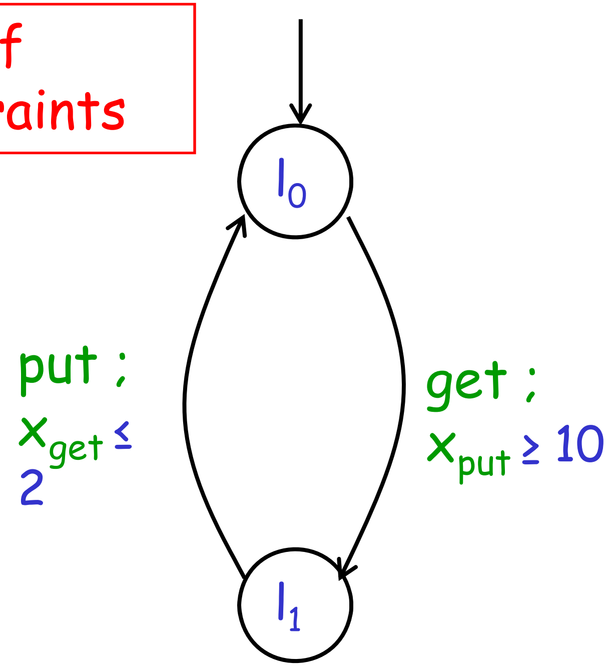
q_0 (initial state) $(l_0, [0,0])$

I $\Sigma \times R^{\geq 0} \times R^{\geq 0}$

δ: $Q \times I \rightarrow Q$

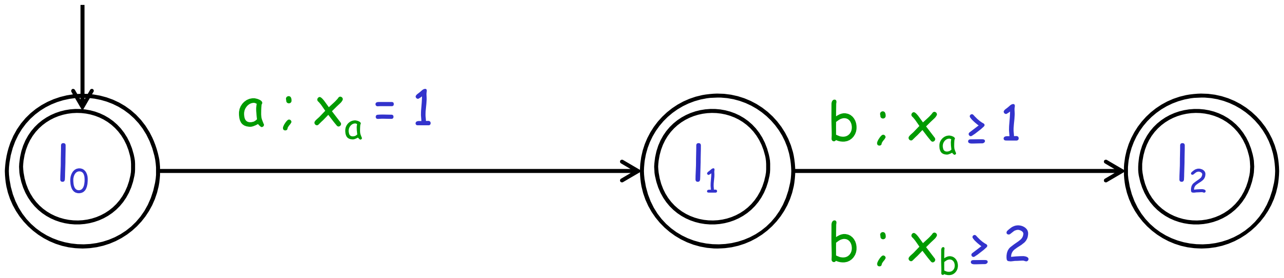
$\delta(\langle l_0, [0,0] \rangle, \langle \text{get}, [14.4, 14.4] \rangle) = \langle l_1, [0, 14.4] \rangle$

$\delta(\langle l_1, [0, 14.4] \rangle, \langle \text{put}, [2.0, 14.4] \rangle) = \langle l_0, [2.0, 0] \rangle$



Non-Unique Representation

- Deterministic ERAs do not have unique representations



Learning DERAs by Quotienting [Grinchtein , Leucker, al.]

- **Find equivalence relation $\approx$ on symbols and states, s.t.**
  - **$\approx$ respects accepting/non-accepting states**
  - $q \approx q'$ $a \approx a'$ **implies** $\delta(q,a) \approx \delta(q',a')$
- **Learn the Quotient DFA**

  $\Sigma / \approx$ $\quad Q / \approx$ $\quad \delta^{\approx}$ ($\delta([q]_{\approx},[a]_{\approx}) = [\delta(q,a)]_{\approx}$) $\quad F / \approx$

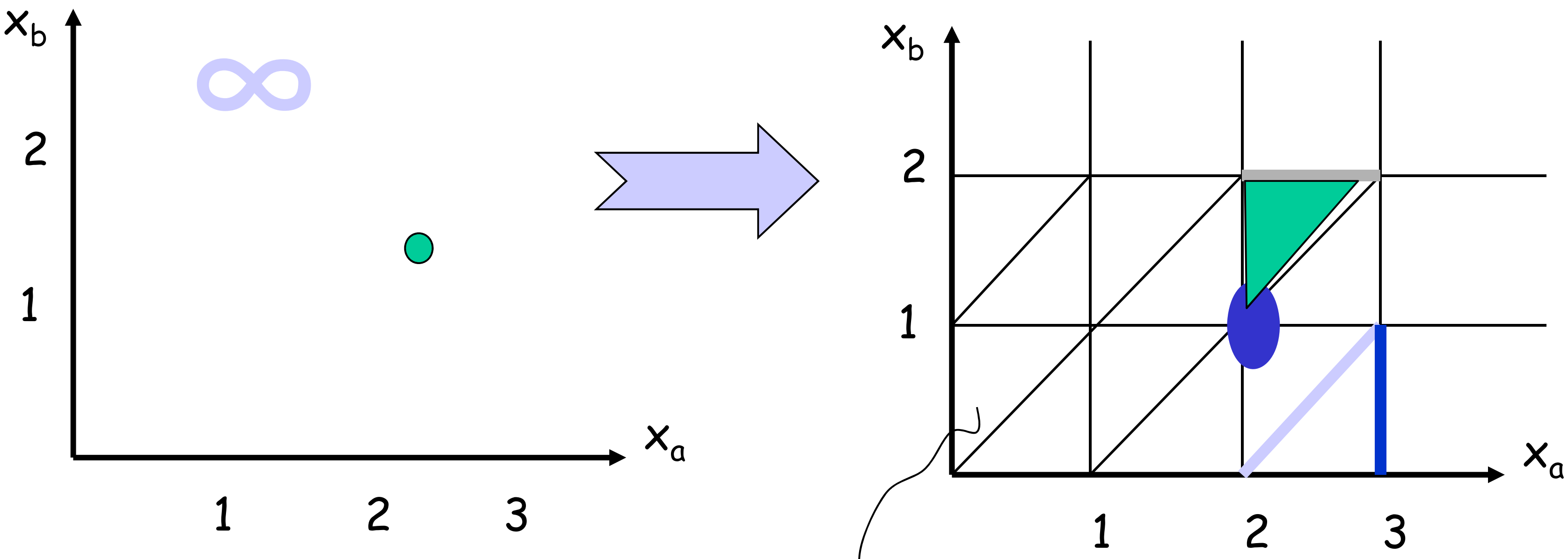
For DERAs

- **Equivalence on states based on region equivalence**
- **Assume largest constant K_a in constraints on x_a**
- $\langle l , [x_a, x_b]\rangle \approx \langle l , [y_a, y_b]\rangle$ **iff**
  - $x_a > K_a$ **and** $y_a > K_a$ **or**
    integer parts of x_a **and** y_a **same** **and** x_a **is integer iff** y_a **is integer**
  - **same for** x_b **and** y_b
  - **If** $x_a \leq K_a$ **and** $x_b \leq K_b$ **then** $x_a \leq x_b$ **iff** $y_a \leq y_b$
- $\langle a , [x_a, x_b]\rangle \approx \langle a , [y_a, y_b]\rangle$ **iff for all** $k \leq K_a$
  - $x_a \leq k$ **iff** $y_a \leq k$ **and** $x_a \geq k$ **iff** $y_a \geq k$

Regions: From infinite to finite

Concrete State
(l, [2.2, 1.5])

Symbolic state (region)
(l, ◥)



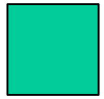
An equivalence class (i.e. a *region*)
... There are only *finite* many such!!

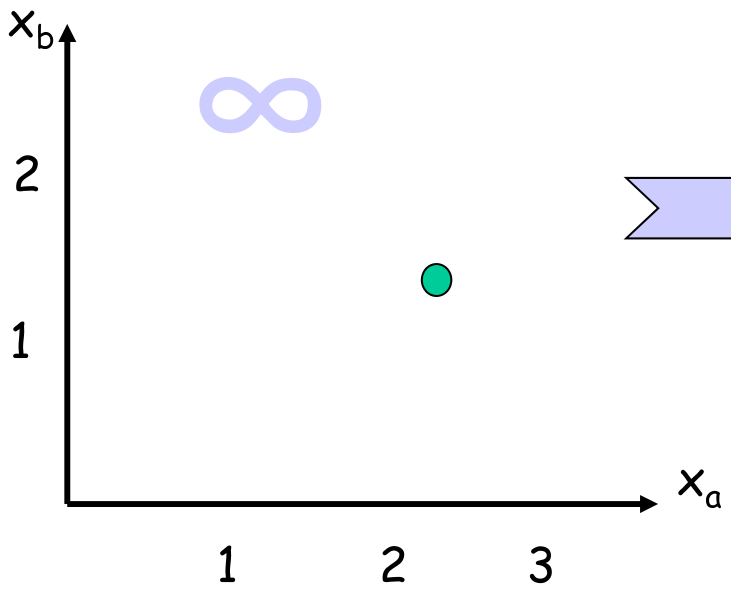
Abstraction of symbols

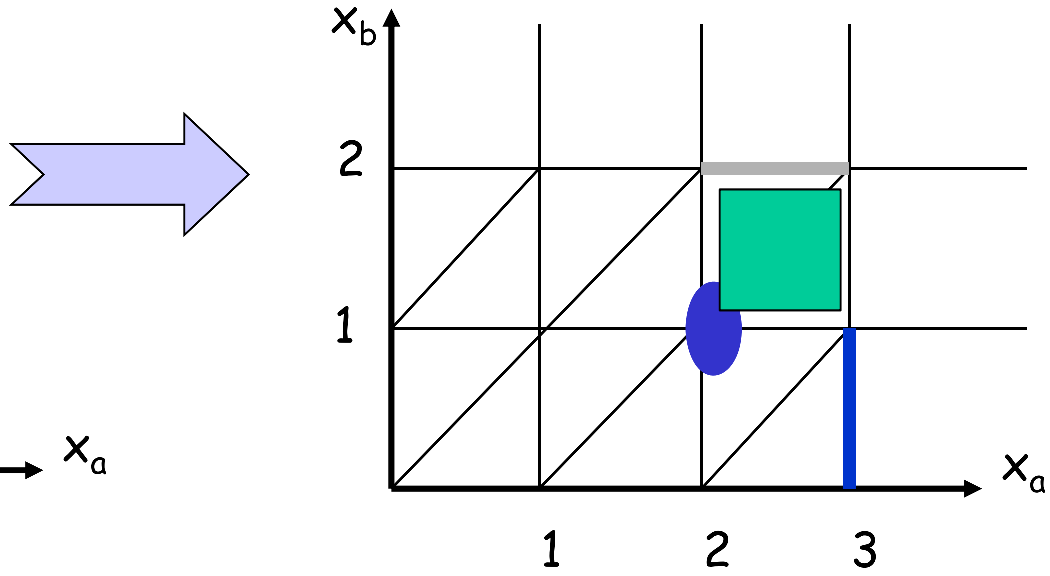
Concrete Symbol

(a, [2.2, 1.5])

Abstract symbol

(a, )

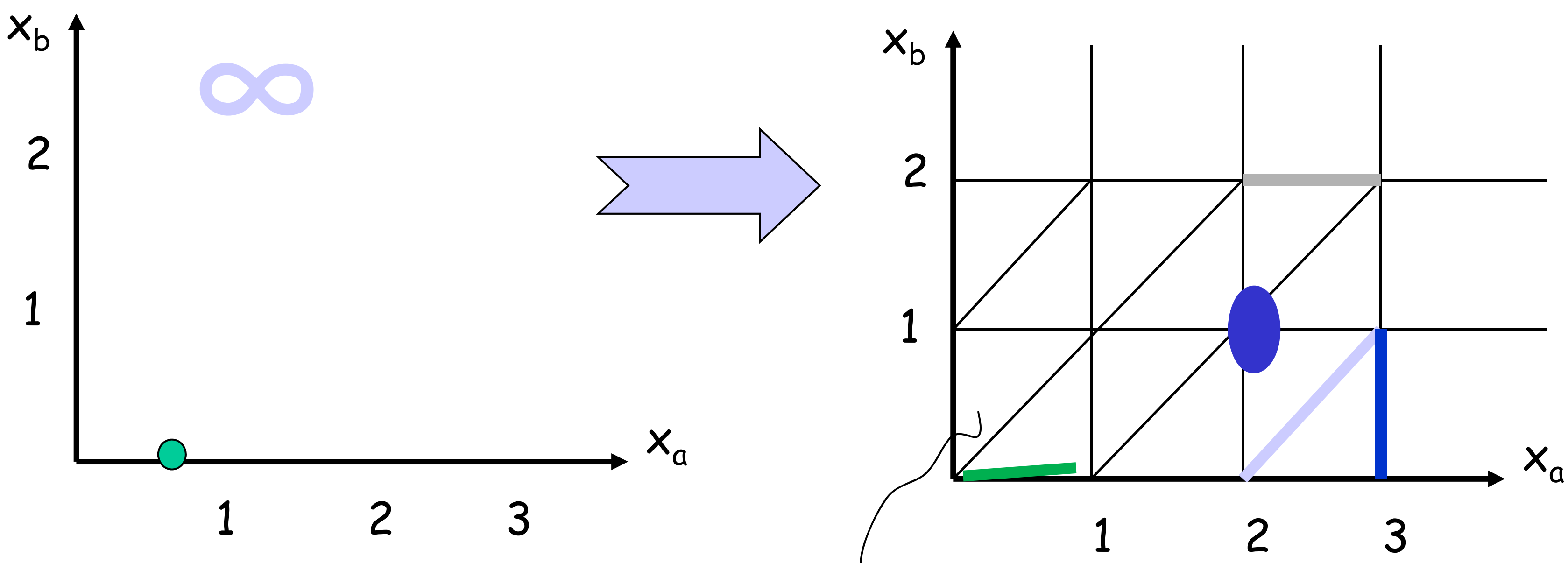




We need only initial regions

Concrete State
(l, [0.7, 0])

Symbolic state (region)
(l,)

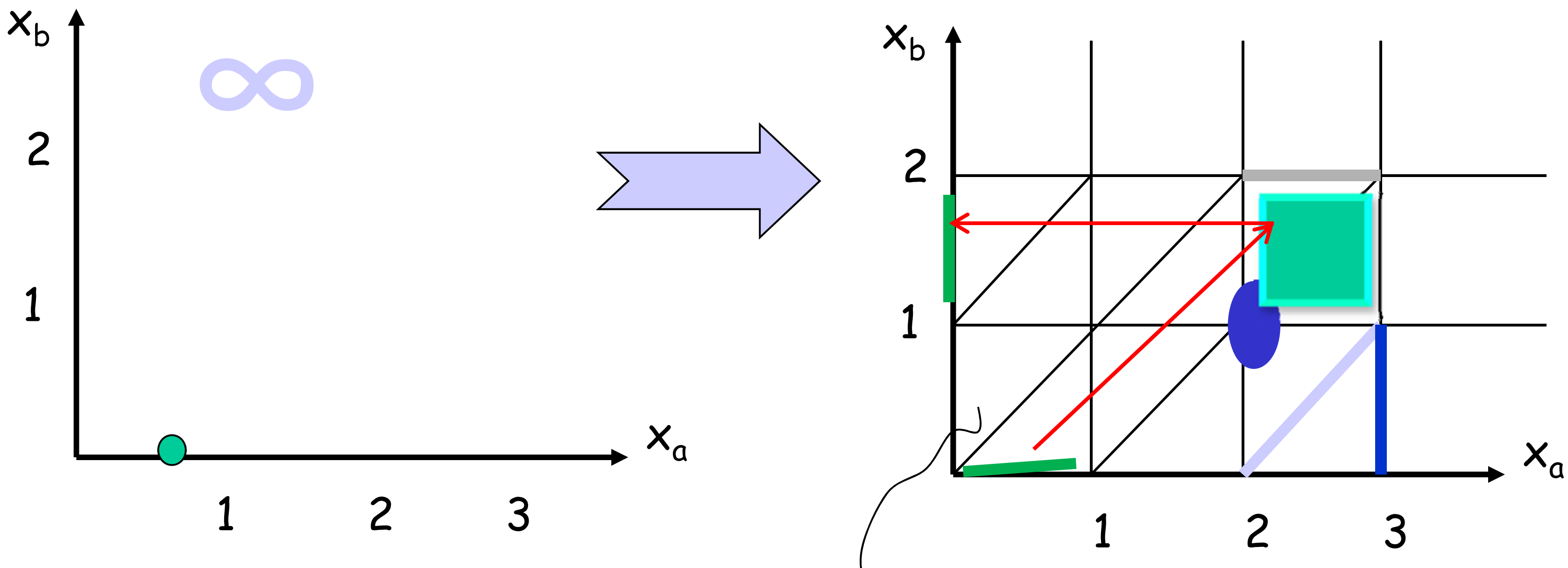


An equivalence class (i.e. a *region*)
… There are only *finite* many such!!

Regions preserved by transitions

Concrete State
(l, [0.7, 0])

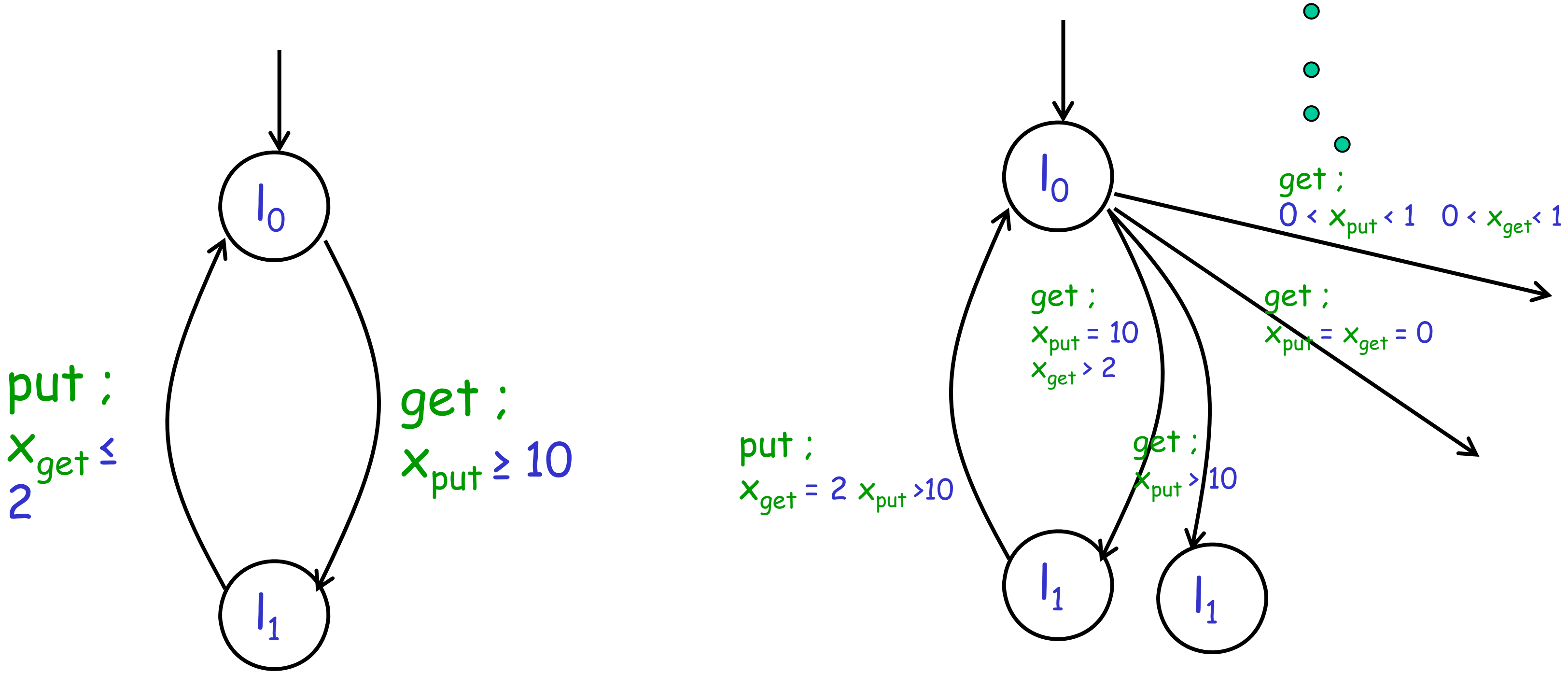
Symbolic state (region)
(l,)



An equivalence class (i.e. a *region*)
… There are only *finite* many such!!

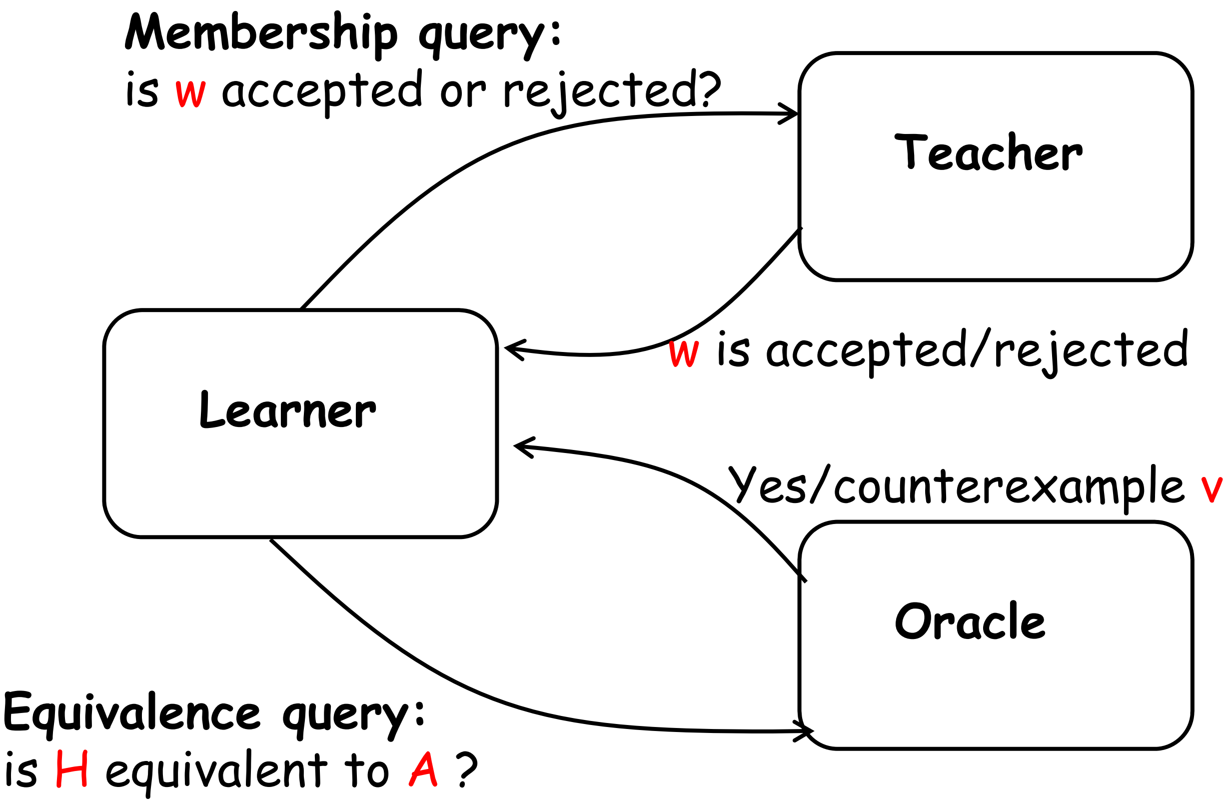
Simple DERAs

- DERA with "small guards"



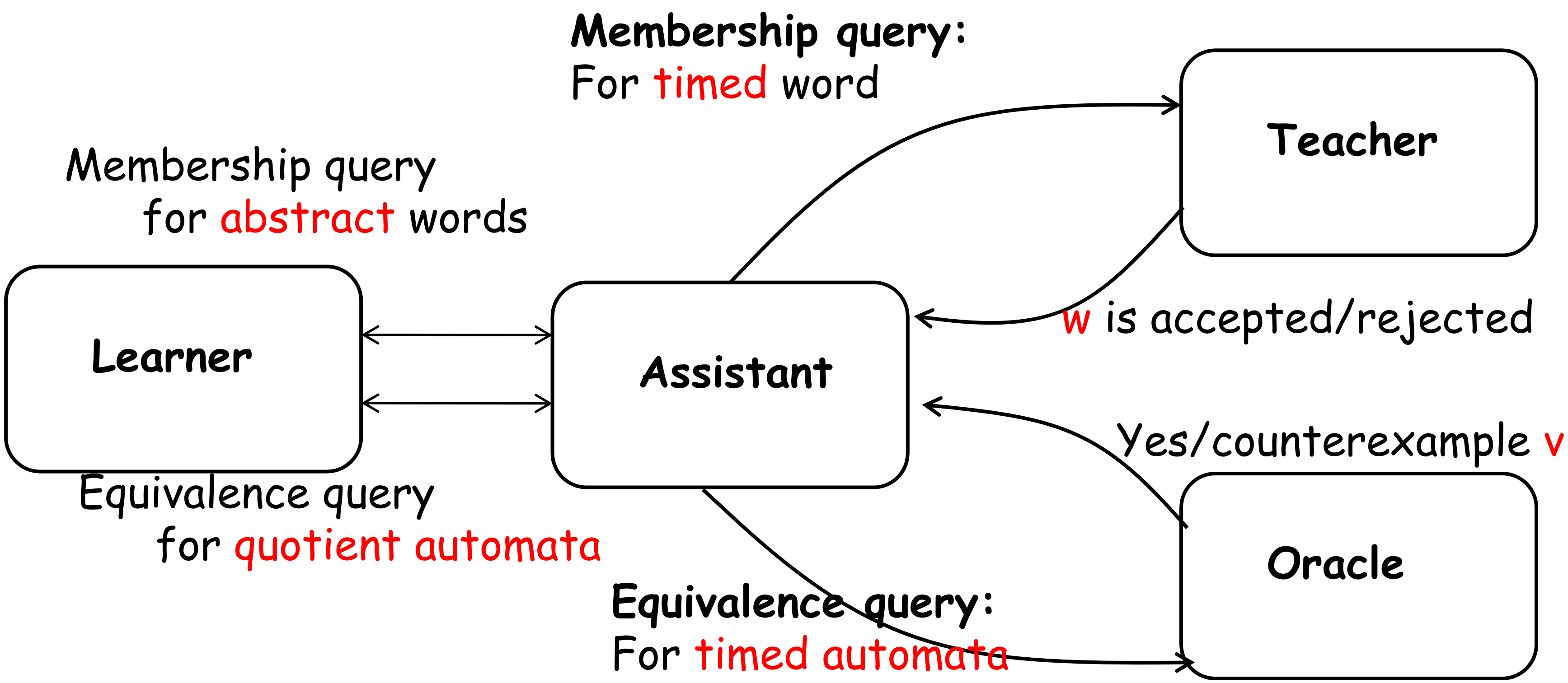
Modifying Setup

The following setup does not work



Adding Assistant

Learner actively constructs the characteristic sample,



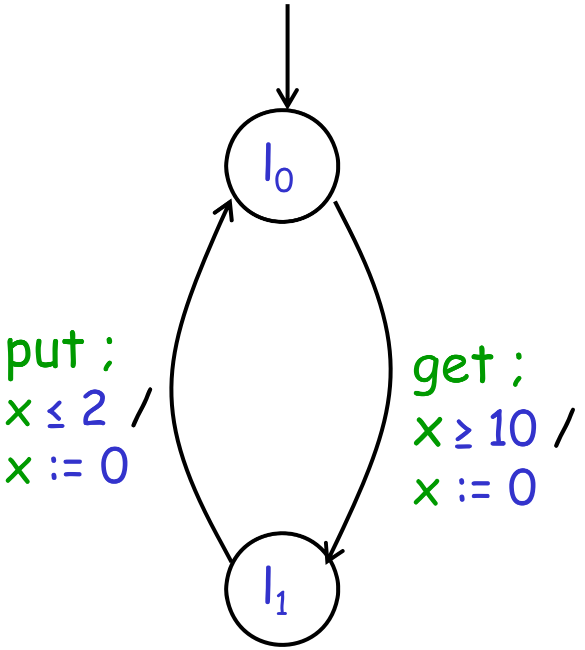
Query Complexity

- **Size of Region graph is roughly**
  $O(|L| \, K^{|\Sigma|})$
- **Number of Membership Queries is about cubic in this number**

Single-Clock Automata [Verwer et al. 09]

Consider Deterministic Timed Automata with one clock

- **Still, no unique minimal representation**
- **But, there is a variant of Nerode Congruence**
  - ***if we know where resets occur***



Timed word:

(get, 14.4) (put, 16.4) (get, 29.34) (put, 30.3) …

Clocked word:

(get, 14.4) (put, 2.0) (get, 12.96)

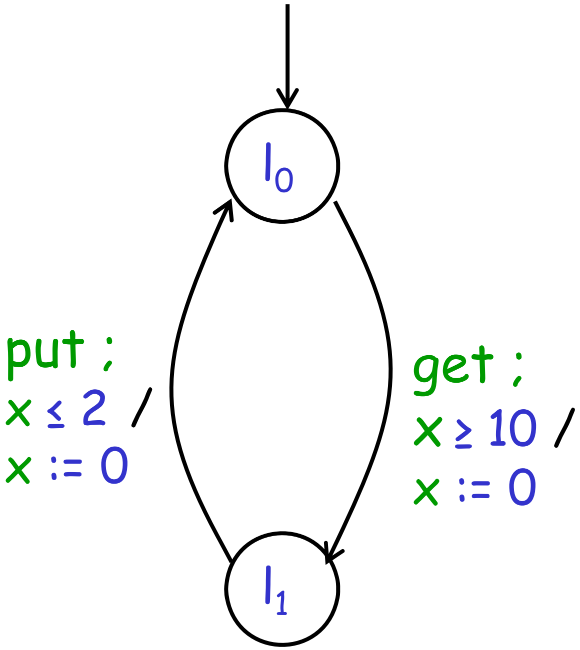
(get, 14.4) reset (put, 2.0) reset (get, 12.96) reset
Is equivalent to
(get, 12.4) reset
but not to
(get, 12.4)

Single-Clock Automata [Verwer et al. 09]

The timed language can be formed from a finite number of Congruence classes

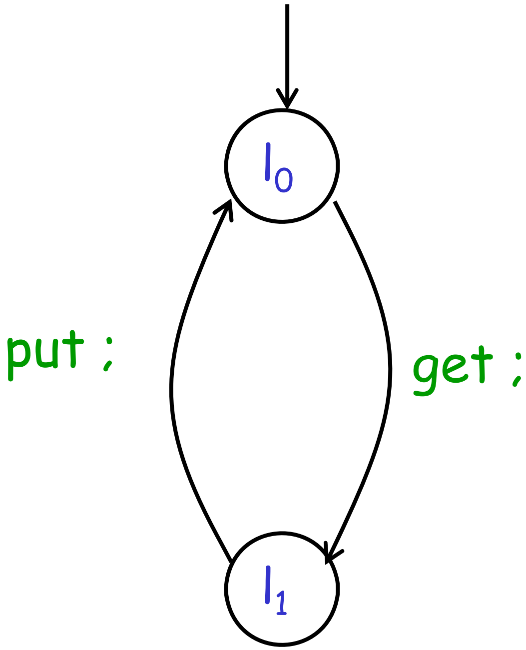
Only, it must be determined when to reset?

Define canonical form by prioritizing conflicts



Refining Guards [Verwer et al. 09]

- **Guards can be refined by counterexamples**



Guards refined from counterexamples

- get @0 put @2 accepted
- get @3 put @7 rejected

Determine the reason for difference by investigating other traces

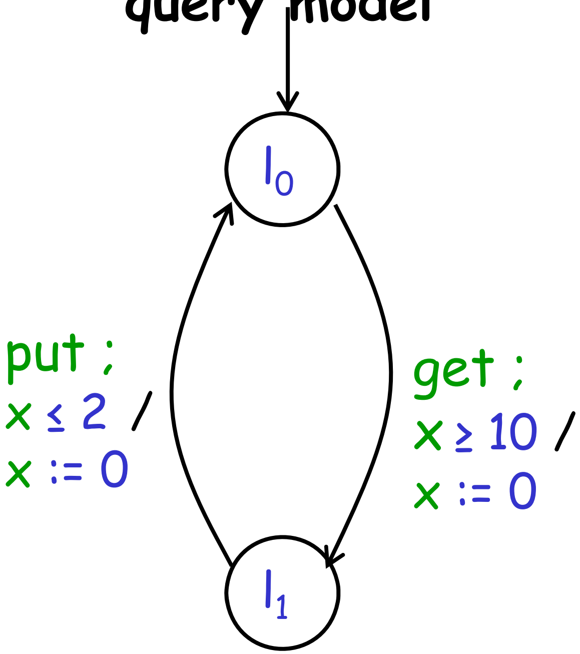
- (binary) search procedure
- Finds "explaining pair", e.g.,
  - get @2.2 put @4.2 accepted
  - get @2.2 put @4.7 rejected
- Suggests reset at get and guard $x \leq 2$ on put transition

Single-Clock Automata [Verwer et al. 09]

Have "reasonable" canonical forms

Exist characteristic samples which are polynomial in size of canonical form (does not depend on largest constant)

Learning can be polynomial in (Membership,Equivalence)-query model



Version for multiple clocks [Grinchtein,Jonsson]

Higher complexity

...

Applications to Realistic Procotols

SIP Protocol [Aarts,Jonsson, Uijen]

From RFC 3261:

- SIP is an application-layer control protocol that can
  - establish, modify, and terminate multimedia sessions (conferences) such as Internet telephony calls.
  - invite participants to already existing sessions, such as multicast conferences.

Structure of SIP packets

Method(From;To; Contact; CallId; CSeq; Via), where

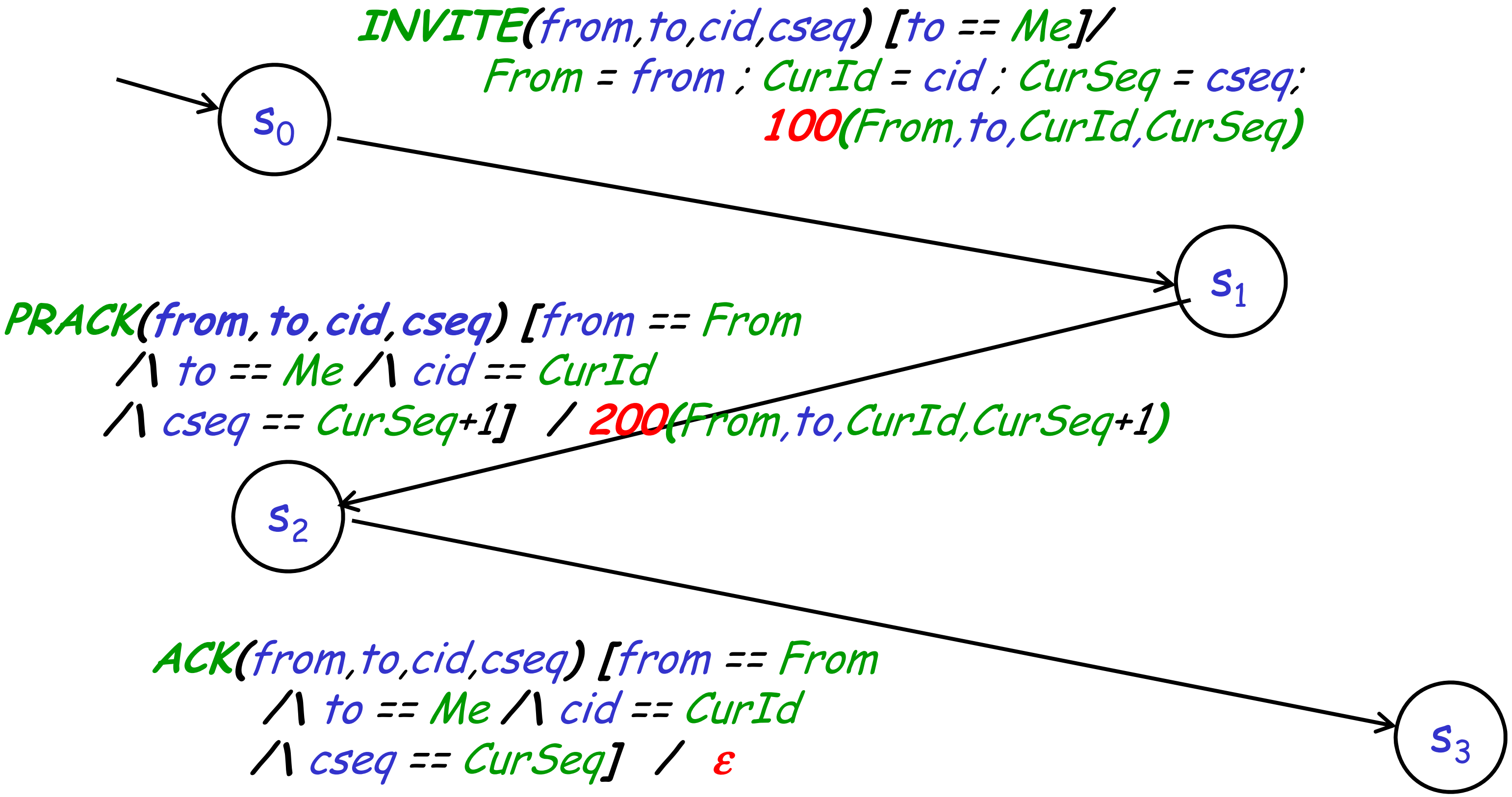
- Method: type of request, either INVITE, PRACK, or ACK.
- From and To: addresses of the originator and receiver
- CallId: unique session identier.
- Cseq: sequence number that orders transactions in a session.

IGNORE THE BELOW

- Contact: address where the Client wants to receive input
- Via: transport path for the transaction.

part of SIP Server

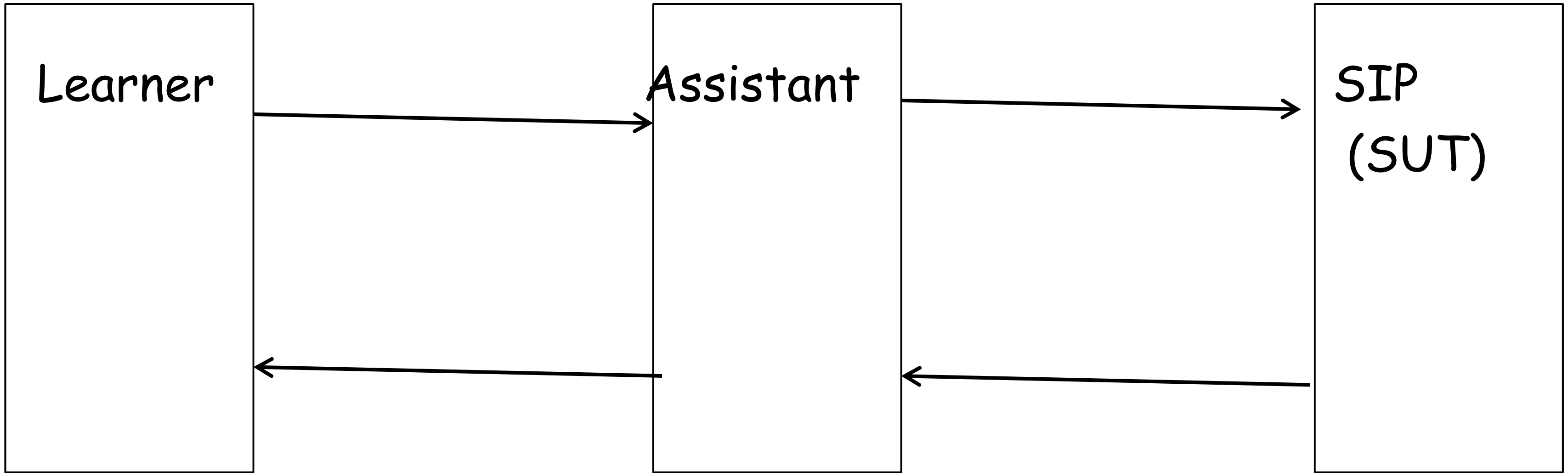
Variables: *From, CurId, CurSeq*
Constants: *Me*



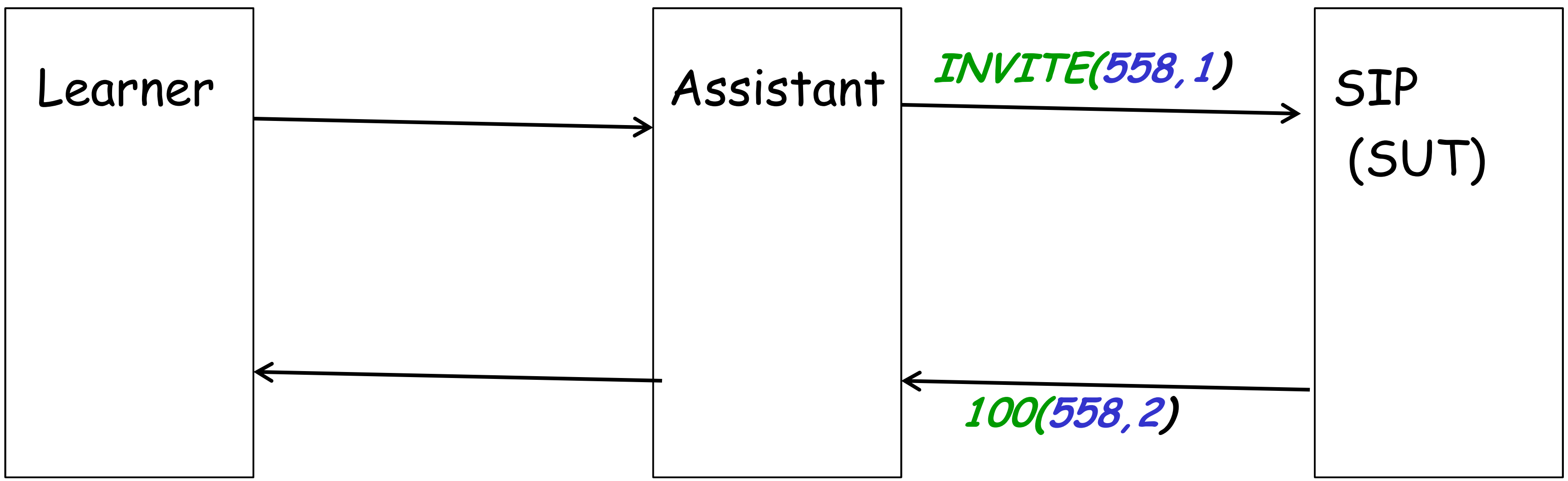
Finding an Abstraction

- **Abstraction of Concrete Message** *PRACK(558,1)*
  depends on internal state of SUT
  previous history
- **Assistant must maintain relevant parts of history:**
  e.g., local copies of *CurId, CurSeq*

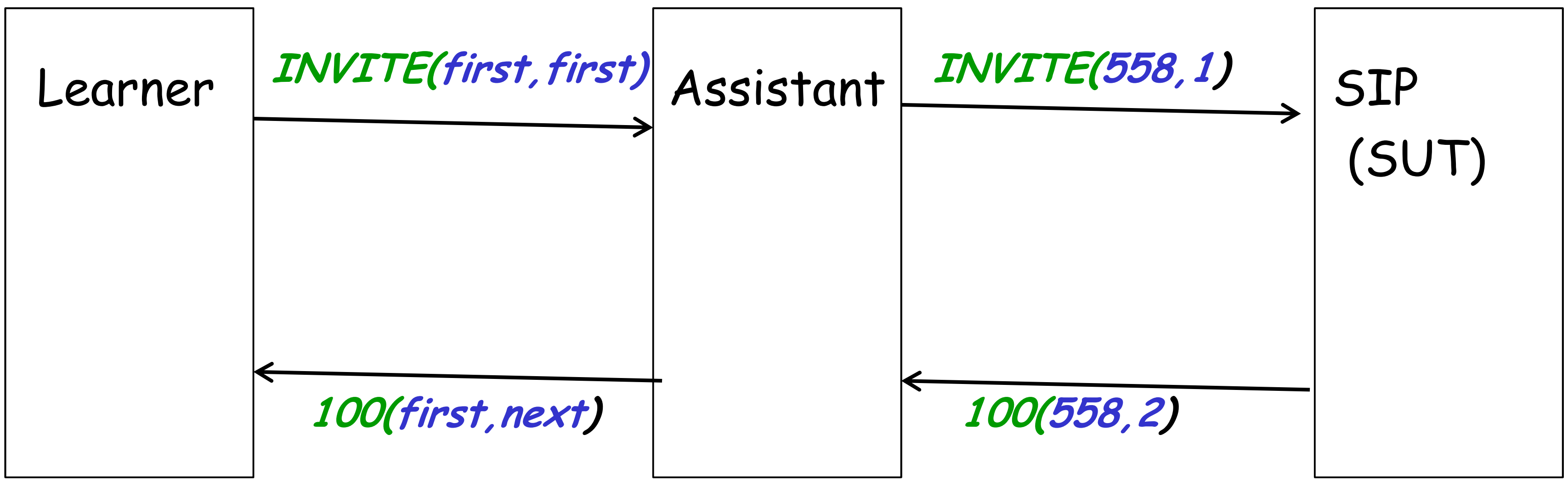
Adapting to Automata Learning



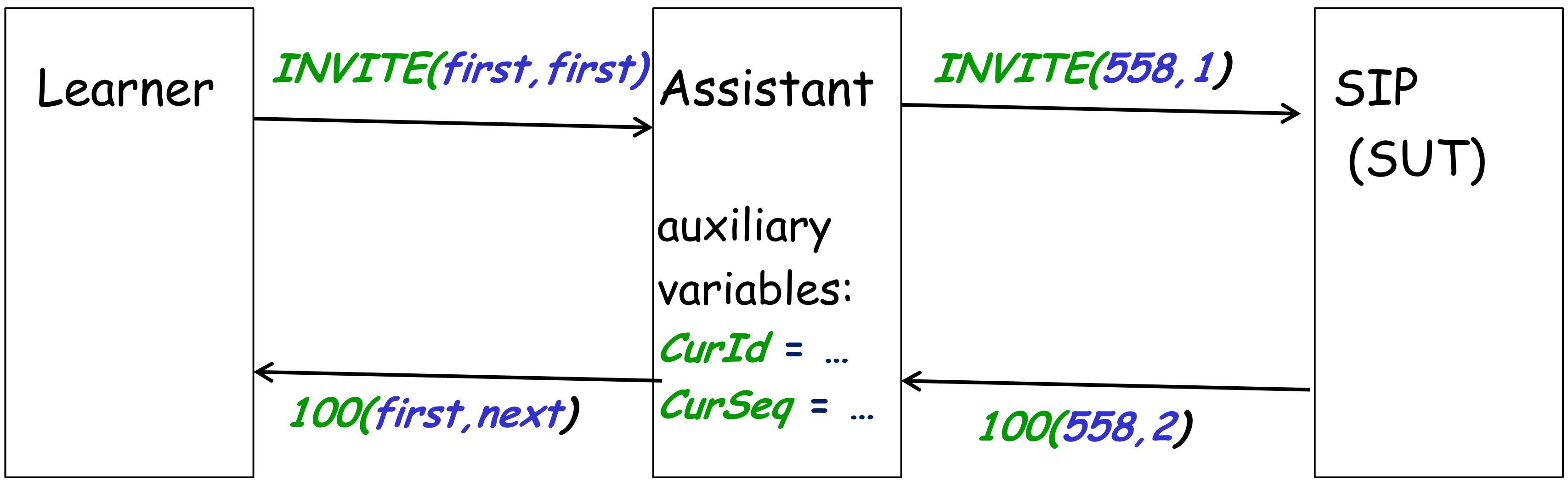
Adapting to Automata Learning



Adapting to Automata Learning



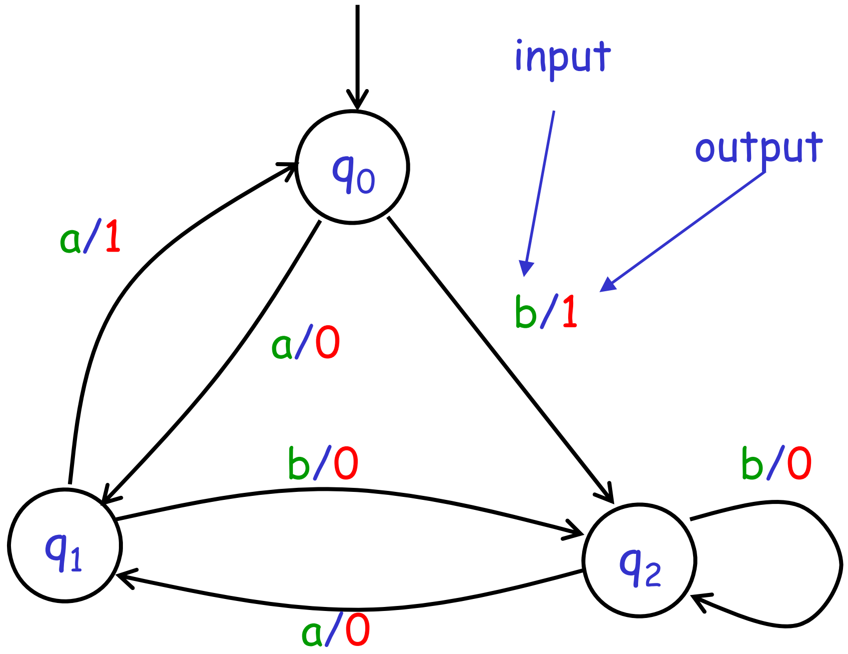
Adapting to Automata Learning



Abstraction: Formal definition

Possibly Infinite State Mealy Machine

I	input symbols
O	output symbols
Q	states
q_0	initial state
$\delta: Q \times I \rightarrow Q$	transition function
$\lambda: Q \times I \rightarrow O$	output function



Abstraction: Formal definition

Possibly Infinite State Mealy Machine		Abstraction	
I	input symbols	I^A	abstract input symbols
O	output symbols	O^A	abstract output symbols
Q	states	R	states
q_0	initial state	r_0	initial state
$\delta: Q \times I \rightarrow Q$	transition function	$\delta^R: R \times (I \cup O) \rightarrow R$	update
$\lambda: Q \times I \rightarrow O$	output function	$\alpha_I: R \times I \rightarrow I^A$	input abstraction
		$\alpha_O: R \times O \rightarrow O^A$	output abstraction

Abstraction: Formal definition

Possibly Infinite State Mealy Machine		Abstraction	
I , O	symbols	I^A , O^A	abstract symbols
Q , q_0	states , initial state	R , r_0	states , initial state
$\delta: Q \times I \to Q$	transition function	$\delta^R: R \times (I \cup O) \to R$	update
$\lambda: Q \times I \to O$	output function	$\alpha_I: R \times I \to I^A$	input abstraction
		$\alpha_O: R \times O \to O^A$	output abstraction

Abstraction: Formal definition

Possibly Infinite State Mealy Machine

I , O	symbols
Q , q_0	states , initial state
δ: $Q \times I \rightarrow Q$	transition function
λ: $Q \times I \rightarrow O$	output function

Abstraction

I^A , O^A	abstract symbols
R , r_0	states , initial state
δ^R: $R \times (I \cup O) \rightarrow R$	update
α_I: $R \times I \rightarrow I^A$	input abstraction
α_O: $R \times O \rightarrow O^A$	output abstraction

Abstracted Mealy Machine

I^A , O^A abstract symbols

$Q \times R$, $\langle q_0, r_0 \rangle$ states , initial state

δ^A: $Q \times R \times I^A \rightarrow Q \times R$ transition function:

$$\delta^A(\langle q,r \rangle , a^A) = \{ \langle \delta (q , a), \delta^R(r , a) \rangle \mid \alpha_I (r , a) = a^A \}$$

λ^A: $Q \times R \times I^A \rightarrow O^A$ output function:

$$\lambda^A(\langle q,r \rangle , a^A) = \{ \alpha_O (\delta^R(r , a) , \lambda (q , a)) \mid \alpha_I (r , a) = a^A \}$$

In general Nondeterministic

Abstraction: Formal definition

Abstracted Mealy Machine

I^A , O^A abstract symbols

$Q \times R$, $\langle q_0, r_0 \rangle$ states , initial state

$\delta^A: Q \times R \times I^A \rightarrow Q \times R$ transition function:

$\delta^A(\langle q,r \rangle , a^A) = \{ \langle \delta(q, a), \delta^R(r, a) \rangle \mid \alpha_I(r, a) = a^A \}$

$\lambda^A: Q \times R \times I^A \rightarrow O^A$ output function:

$\lambda^A(\langle q,r \rangle , a^A) = \{ \alpha_O(\delta^R(r, a), \lambda(q, a)) \mid \alpha_I(r, a) = a^A \}$

Exists equivalence $\approx$ on $Q \times R$ s.t.

- $\langle q,r \rangle \approx \langle q',r' \rangle$ and $\alpha_I(r,a) = \alpha_I(r',a')$ implies
  - $\langle \delta(q, a), \delta^R(r, a) \rangle \approx \langle \delta(q', a'), \delta^R(r', a') \rangle$
  - $\alpha_O(\delta^R(r, a), \lambda(q, a)) = \alpha_O(\delta^R(r', a'), \lambda(q', a'))$

Modified Criterion

Exists equivalence $\approx$ on $Q \times R$ s.t.

- $\langle q,r\rangle \approx \langle q',r'\rangle$ and $\alpha_I(r,a) = \alpha_I(r',a')$ implies
  - $\langle \delta(q,a), \delta^R(r,a)\rangle \approx \langle \delta(q',a'), \delta^R(r',a')\rangle$
  - $\alpha_O(\delta^R(r,a), \lambda(q,a)) = \alpha_O(\delta^R(r',a'), \lambda(q',a'))$

Can happen, e.g., if Q can be written $L \times R$, and

- if $\delta(\langle l,r\rangle, a) = \langle l',r'\rangle$ then
  - $r' = \delta^R(r,a)$
  - l' depends only on $\alpha_I(r,a)$
- if $\lambda(\langle l,r\rangle, a) = b$ then
  - $\alpha_O(\delta^R(r,a), b)$ depends only on $\alpha_I(r,a)$

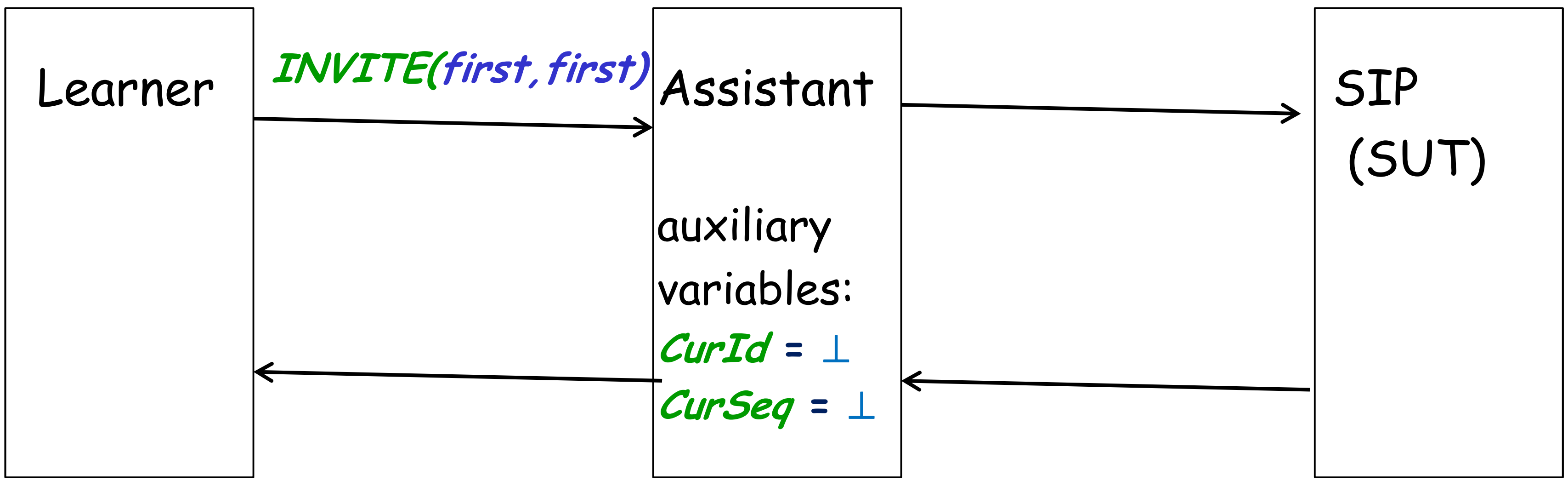
Mapping parameters of input messages

	first	next	last
cid	CurId = ⊥ and **Method = INVITE** or cid = CurId		<otherwise>
cseq	CurSeq = ⊥ and **Method = INVITE** or cseq = CurSeq	cseq = CurSeq+1	<otherwise>

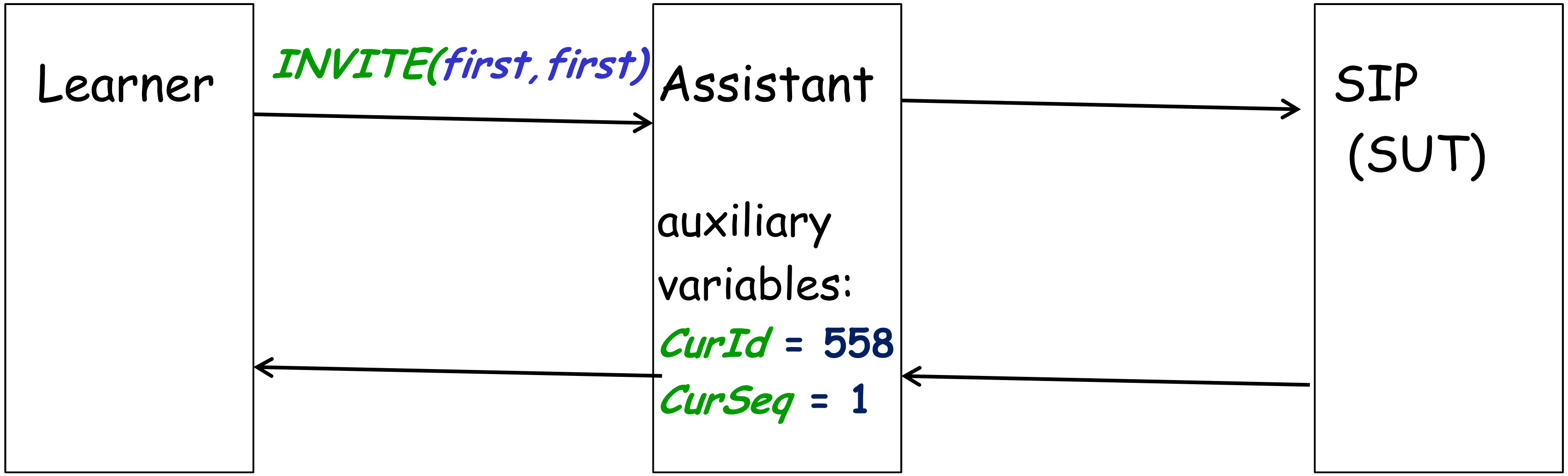
Maintaining auxiliary variables

	first	last	next
CurId	:= cid	<unchanged>	
CurId	:= cseq	<unchanged>	<unchanged>

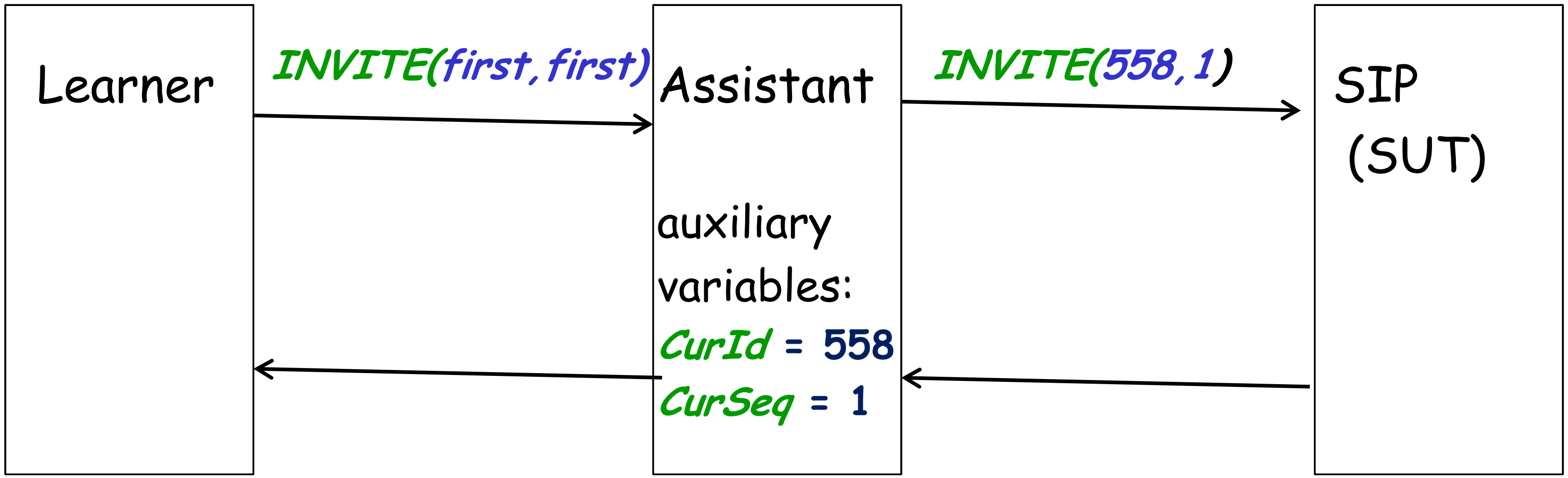
Inference by Abstraction



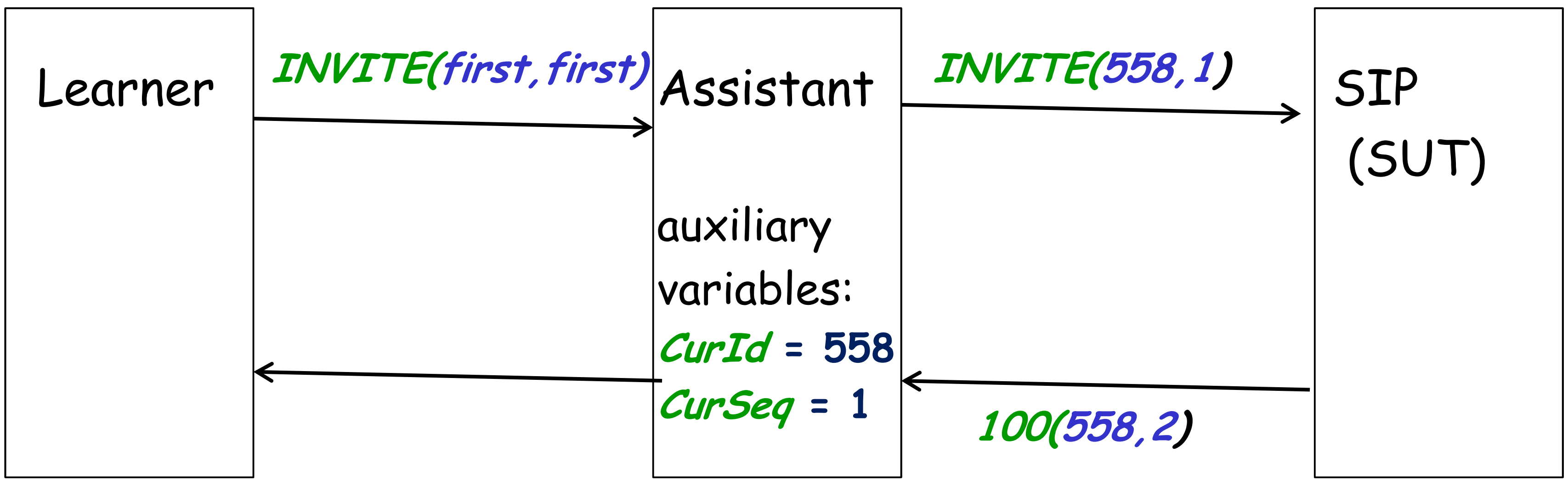
Inference by Abstraction



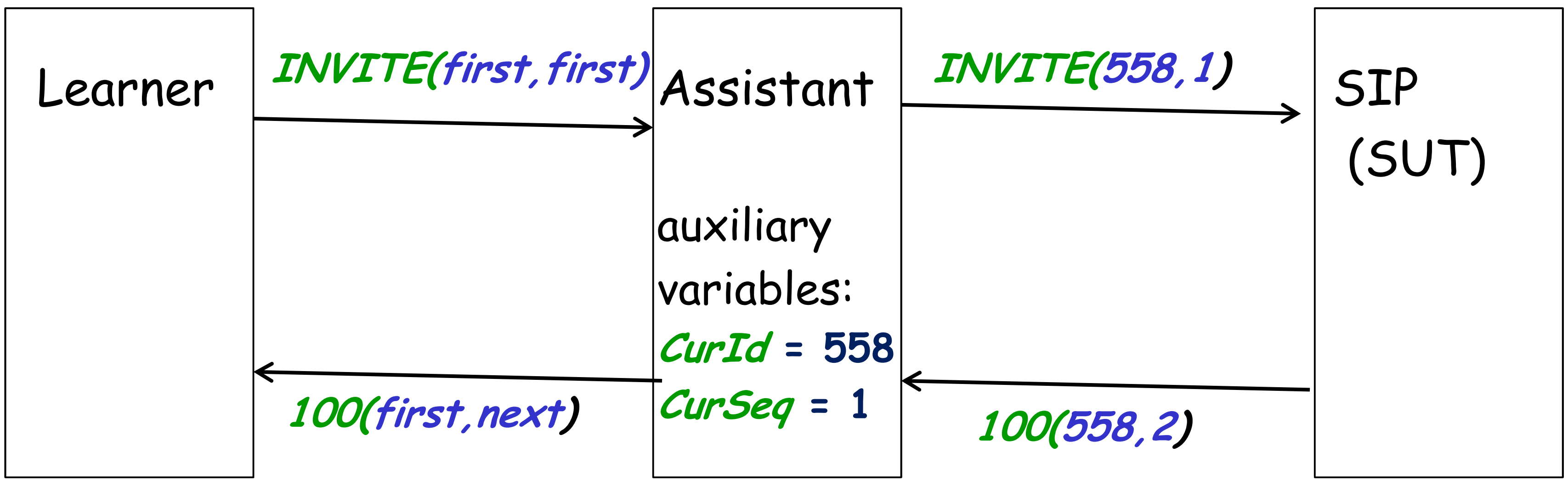
Inference by Abstraction



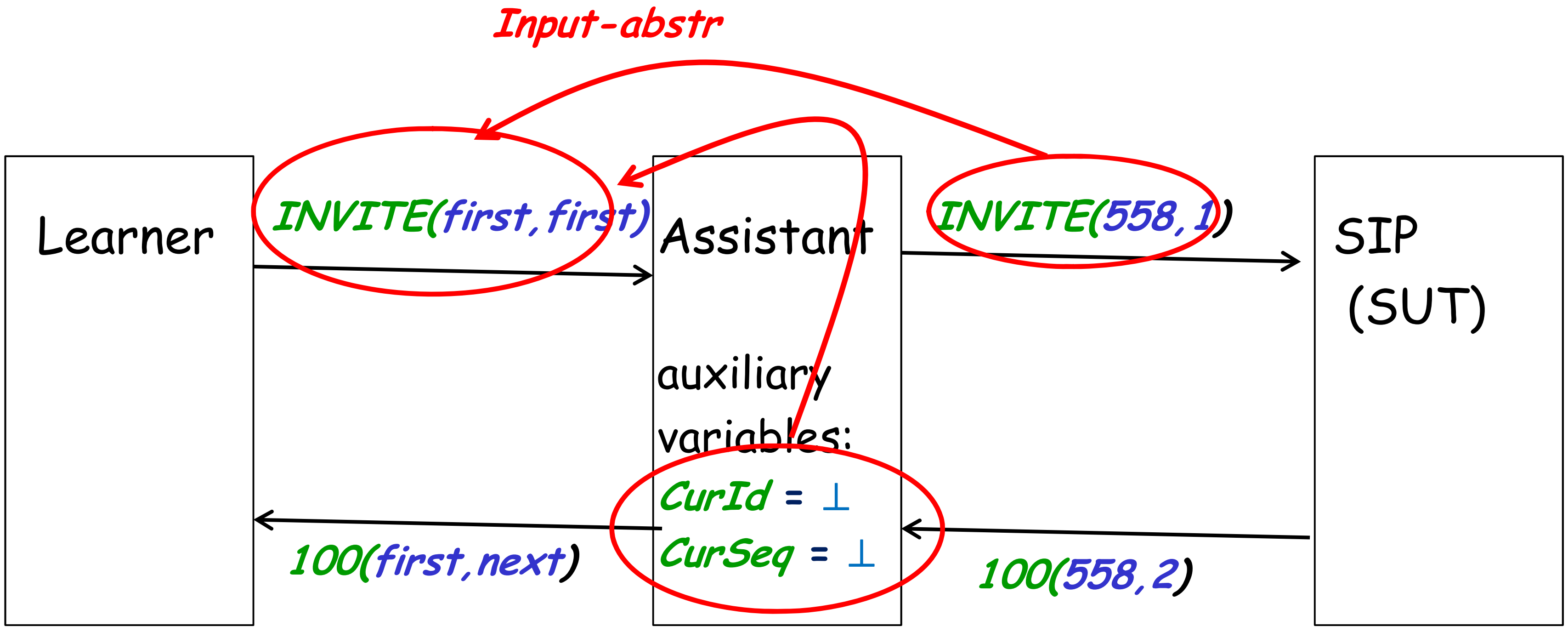
Inference by Abstraction



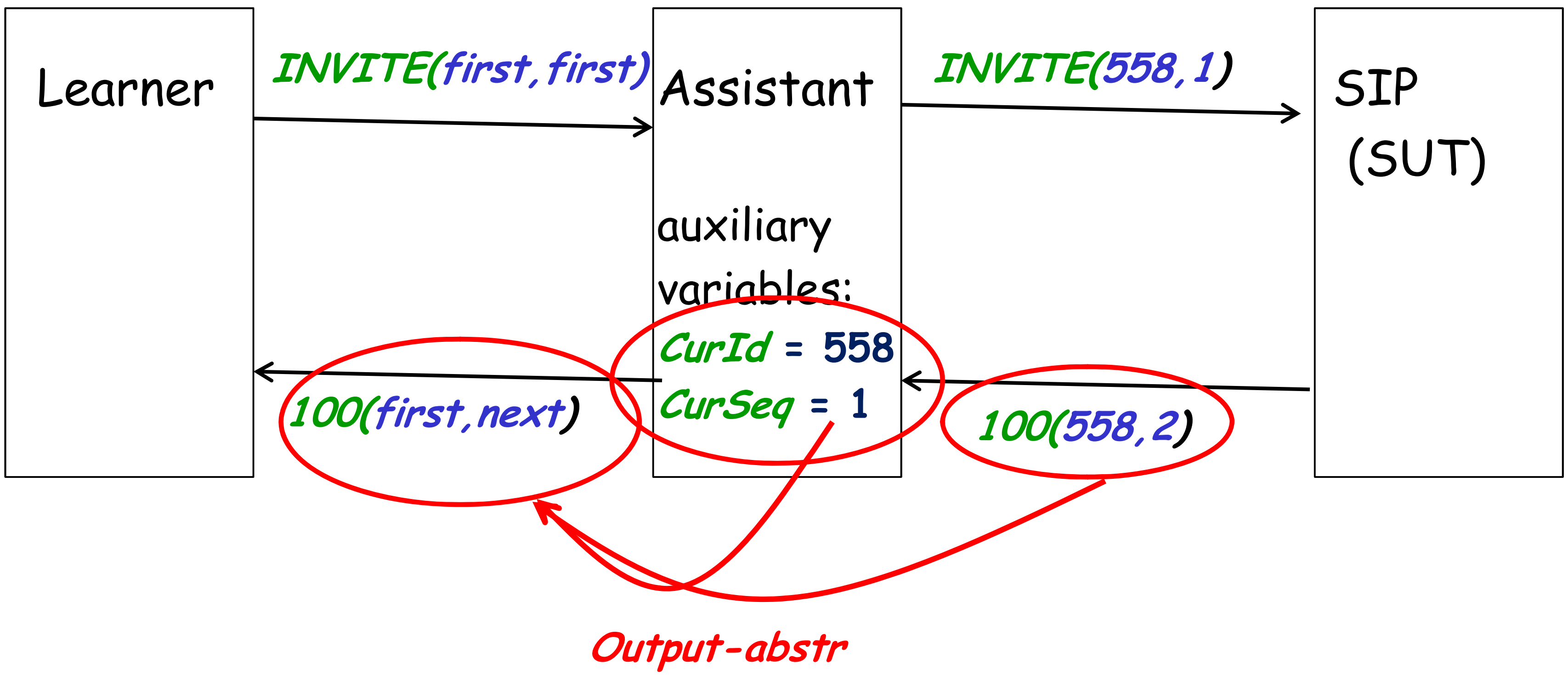
Inference by Abstraction



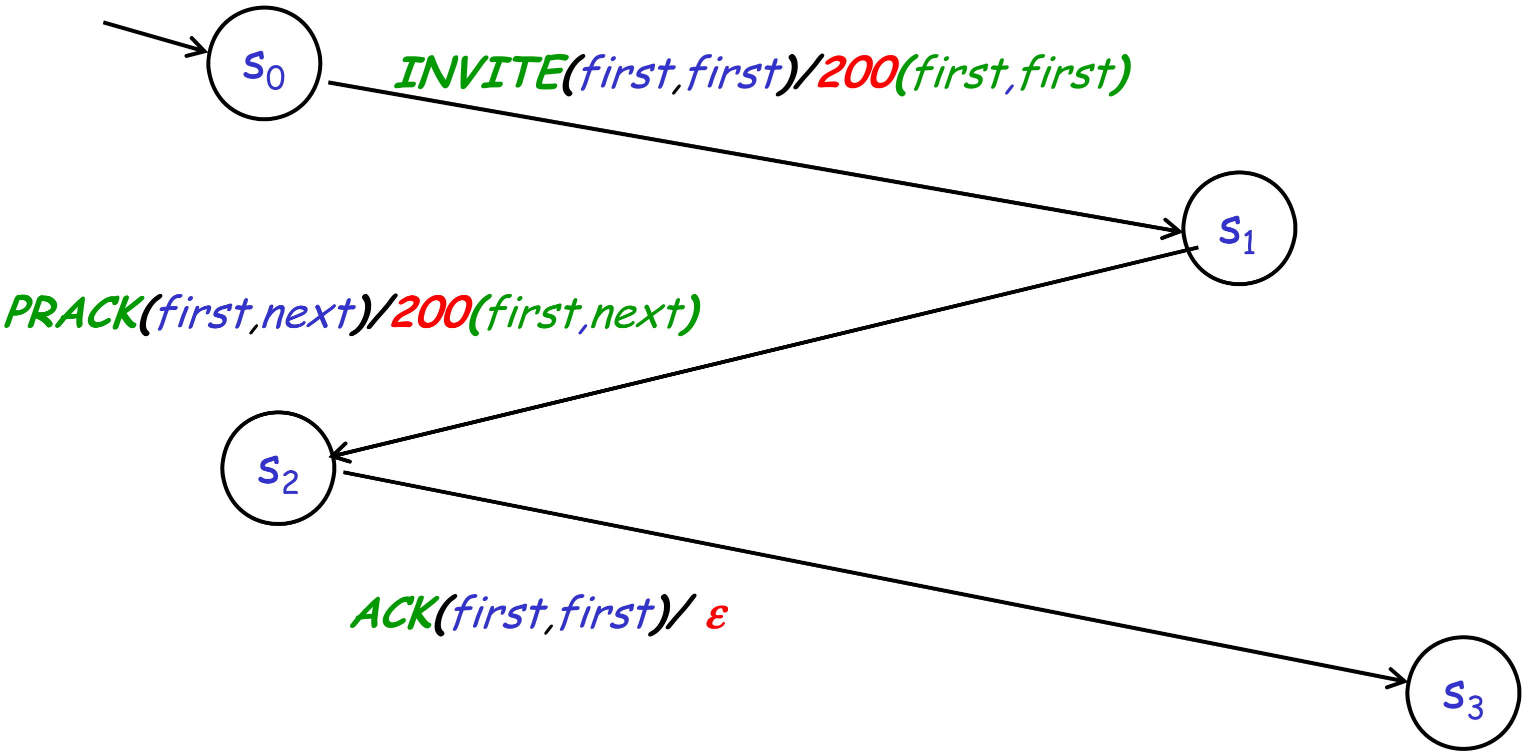
Abstraction Mappings



Abstraction Mappings

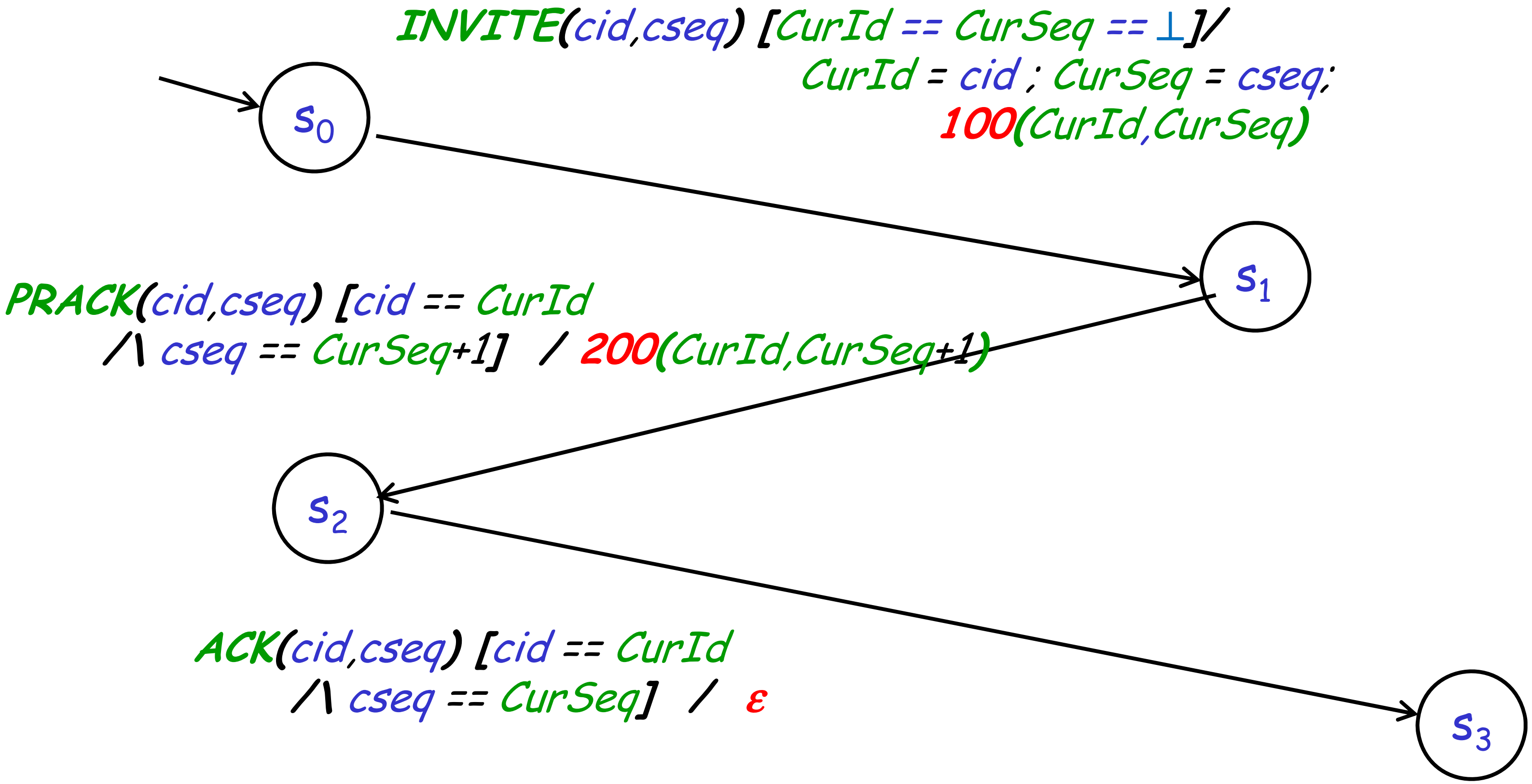


Model inferred by Learner (part)



What the SUT must have done:

Variables: *CurId*, *CurSeq*



Experiments

- Learner: the LearnLib tool (developed at TU Dortmund)
  - Efficient implementation of L*
  - Several equivalence oracles, e.g., controllable-size random test suite.
- SUT: ns-2 protocol simulator
  - Provides implementations of many standard protocols
  - Rather convenient C++ interface (no packet analyzer necessary)
- Assistant
  - Bridges asynchronous interface of LearnLib w. synchronous interface of ns-2
  - Implements instantiation of input symbols, and abstraction of output symbols

Learning SIP in ns-2

- Inference: about 1 thousand membership queries
  one equivalence query
- Model w. 10 locations and 70 transitions
- ns-2 implementation does not check incoming cseq parameter, just returns it.

Resulting Model

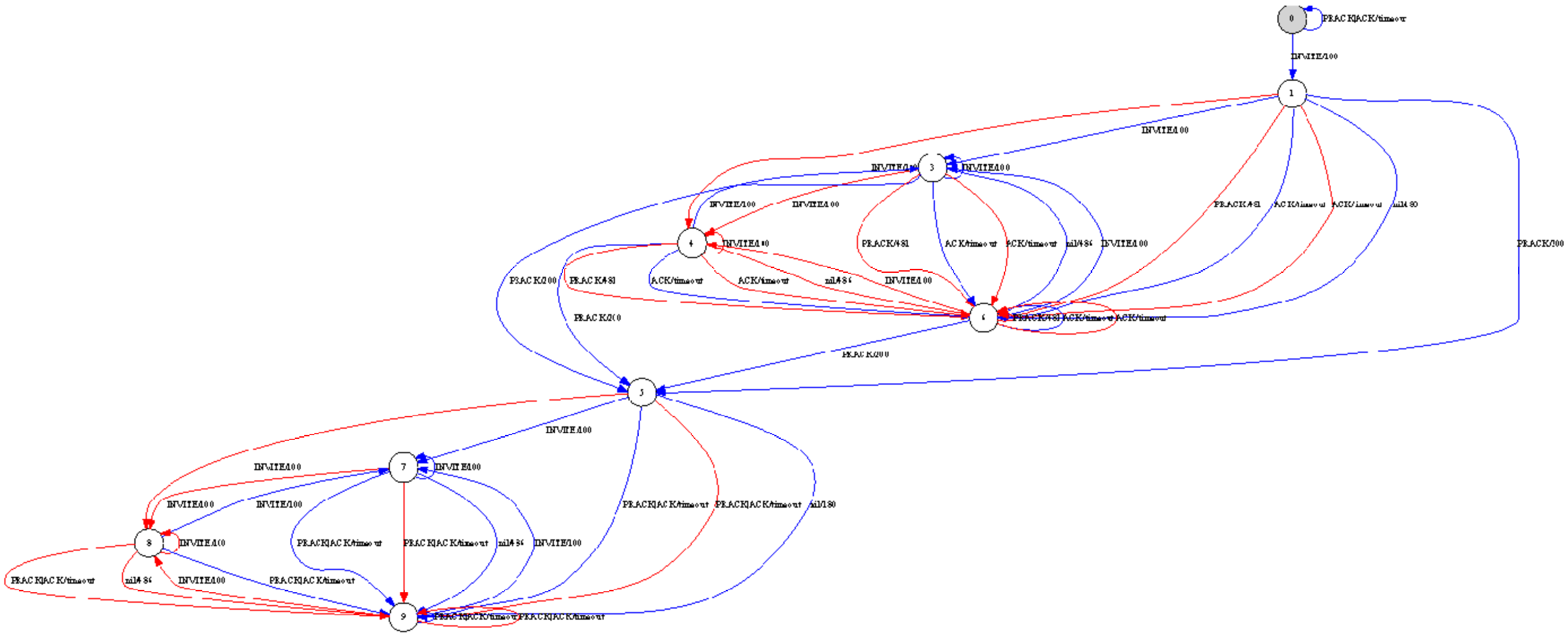


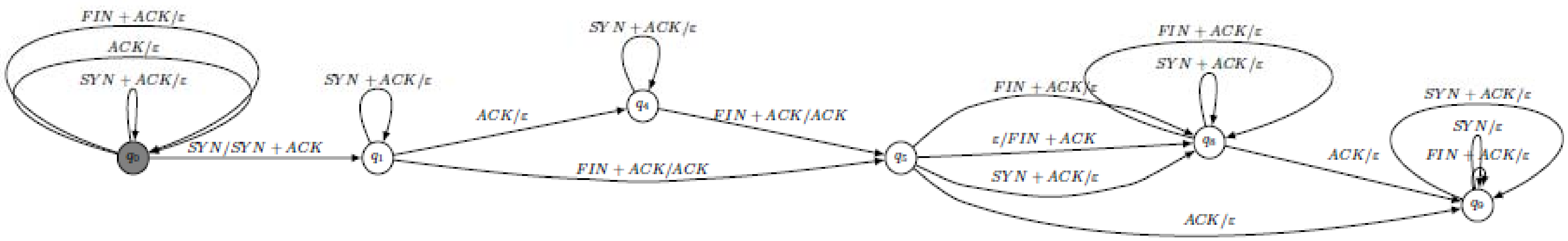
Fig. 3. Full SIP model

Transport Control Protocol (TCP)

- Only connection establishment and termination
- SUT is ns-2 implementation of TCP
- Consider 2 sequence number parameters
- Similar type of abstraction

TCP

- Model of behavior of TCP in ns-2
- Only transitions with “accepted” values of input parameters are shown.
- Values of parameters not displayed



Conclusions

- Basic Principles of Automata Learning for Finite-State systems understood
- Learning and Conformance Testing:
  - Two sides of the same coin.
- Learning for extended automata models largely unexplored

Some Future work

- Techniques for handling common forms of data
- Dynamically refining abstractions
- Learning nondeterministic models
- Learning timed models in practice
- Learning under assumptions on module usage
- Efficient search for counterexamples
- Efficient construction of test harnesses
- Some references can be found at

http://leo.cs.tu-dortmund.de:8100/