Learning of Automata Models Extended with Data

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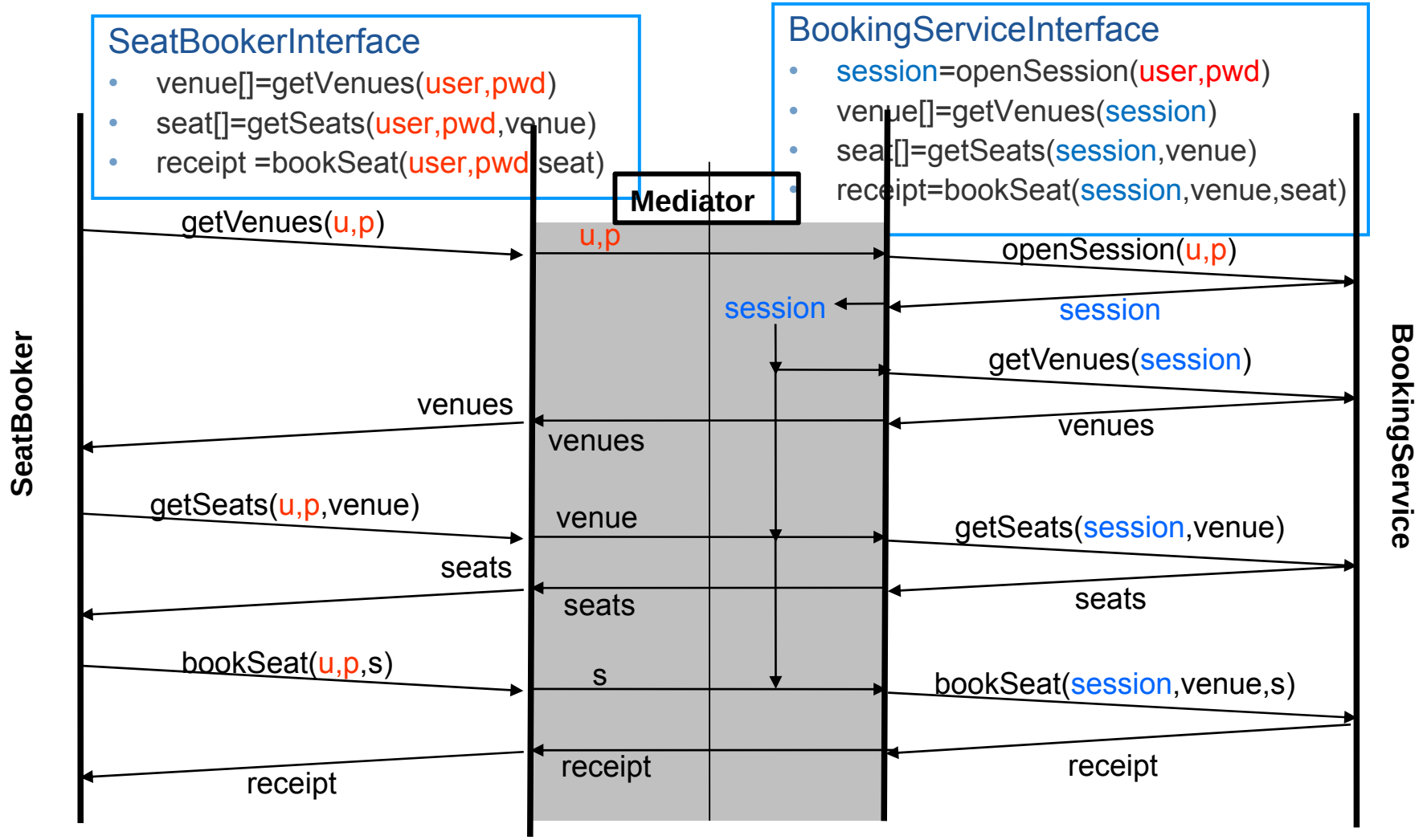
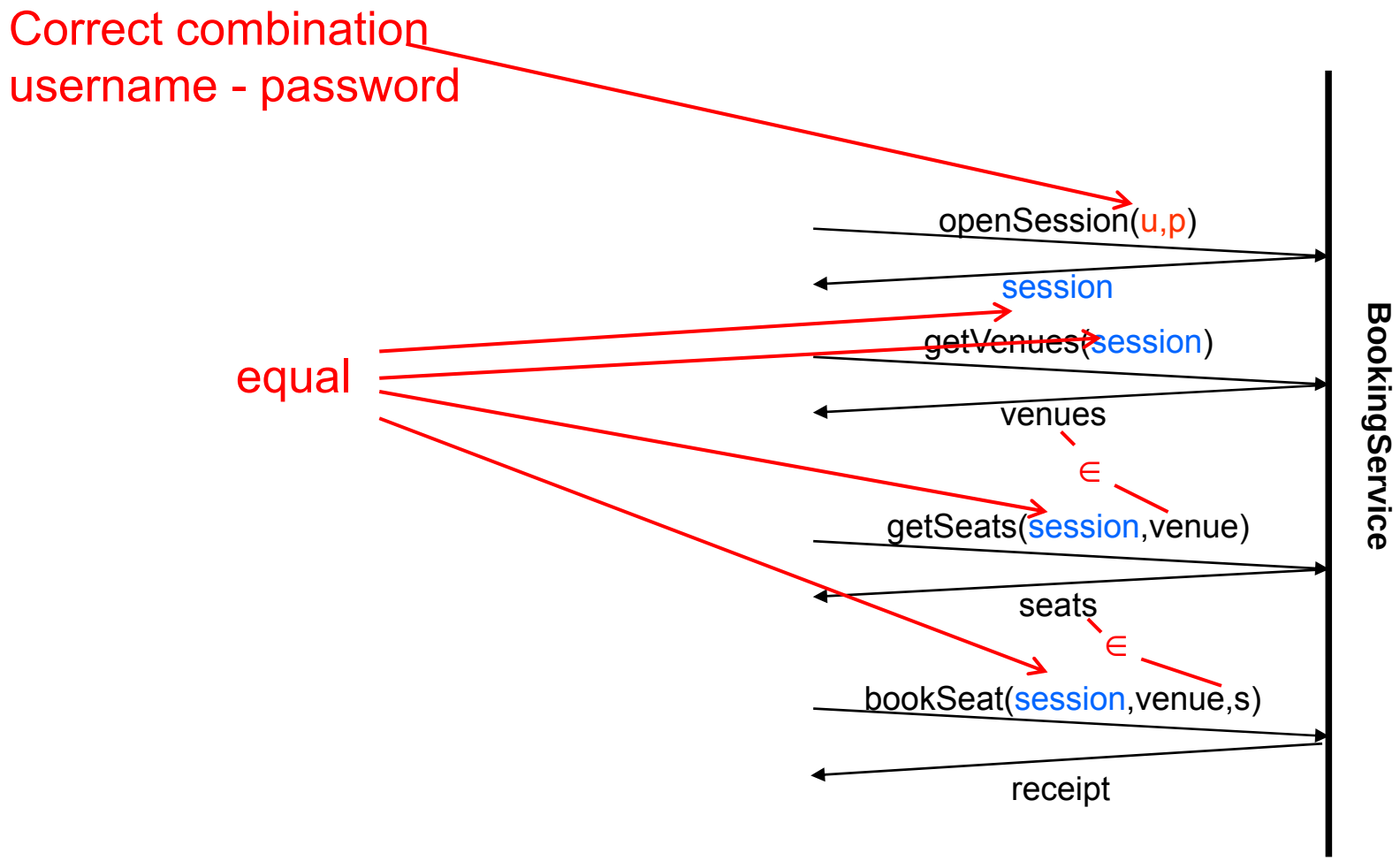
Outline

- Motivation
- Formalisms for Automata with Data
- Abstraction
- Learning Setup
- Some Completeness Result
- Abstraction Refinement
- Applications and Evaluation
- Conclusion and Future Work

Motivating Use Case



Data Relationships

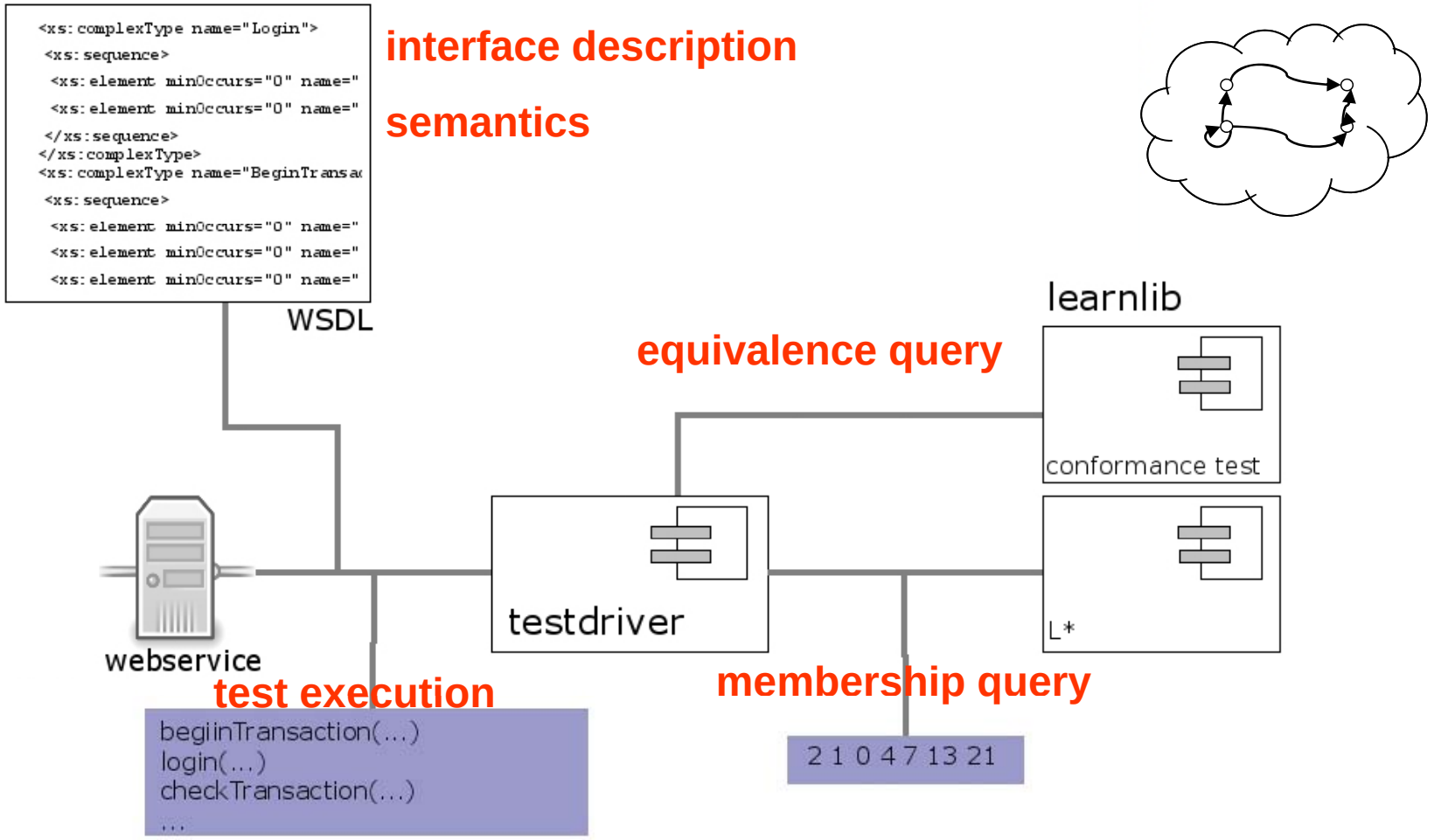


Motivation: More examples

Interface Specifications

- Container classes
  - must keep track of identities of data
  - relate data in input to data in subsequent output
- Communication protocols
  - SIP, TCP, …
  - sequence numbers, identifiers, ..

Practical Learning Scenario



Finite-State Mealy Machines

Finite State Machines w. input & output

Σ_I input symbols

Σ_O output symbols

Q states

q_0 initial state

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

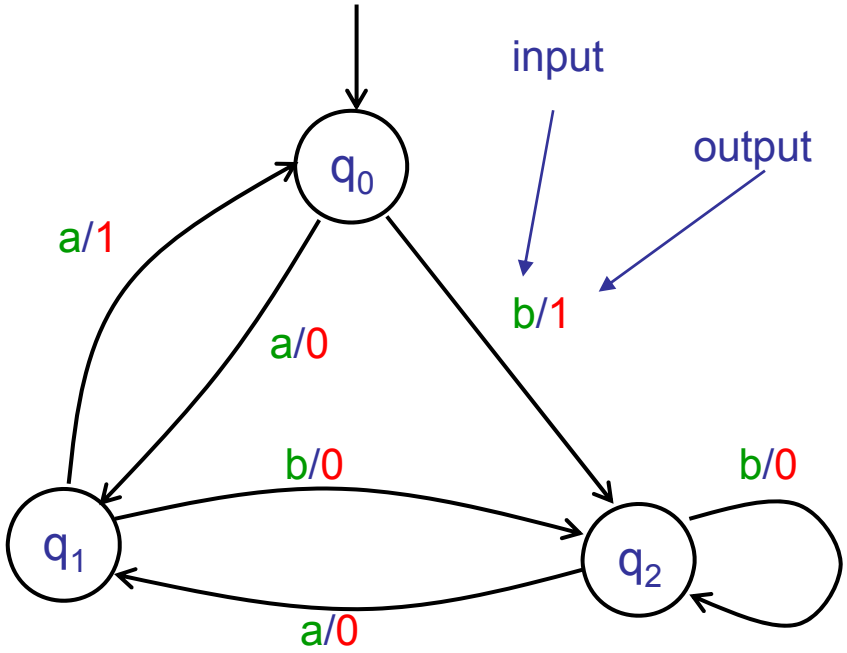
λ: $Q \times \Sigma_I \rightarrow \Sigma_O$ output function

Notation: $q \xrightarrow{a / b} q'$

- Often used for protocol modeling

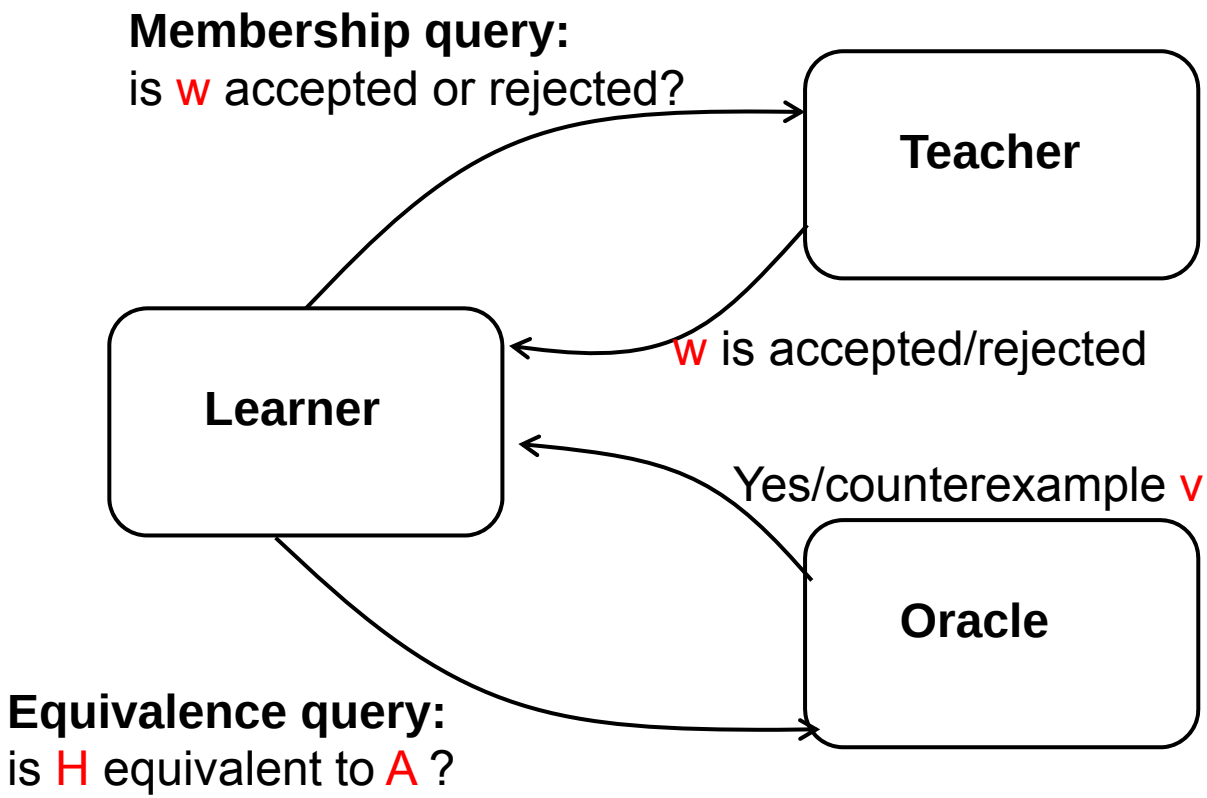
Assumptions:

- Deterministic
- Completely specified



Basic Learning Setup

Same as in L*



Baseline: Automata Learning

L* infers Finite State Machine from membership queries:

1. Pose membership queries until “saturation”
2. Construct Hypothesis from obtained information
3. Pose equivalence query
4. if no(counterexample) goto 1 else return Hypothesis end

- Needs $O(n^3)$ queries to form Hypothesis of size n
  - In practice, often $O(n^2 \log n)$ queries
  - Domain-specific optimizations can help a lot
- Has been used to learn large automata (≥20 kstates)
- Adapted for Mealy Machines (by Niese et al. 2003)

How to Extend w. Data?

Extend Mealy Machine Model

- 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

Extend Learning Techniques

- Several conceivable approaches
- We will attempt to reuse L* approach
  - Augment by Abstraction Techniques

Input and Output Symbols

Assume

- Domains, e.g.,
  - STRING e.g., ‘Mary’, ‘174’, …
  - SESSION e.g., 0,1,2,3, …
  - SEAT e.g., 1,2,3, …., 167
- (Input and Output) Actions: with arities, e.g.,

openSession	STRING x STRING x SESSION
getSeat	SESSION x SEAT

- Symbols

openSession(‘Mary’, ’188H#4’, 42)

action parameters

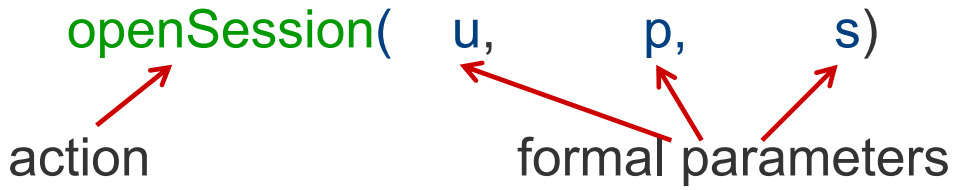
Input and Output Symbols

Assume

- Domains, e.g.,
  - STRING e.g., ‘Mary’, ‘174’, …
  - SESSION e.g., 0,1,2,3, …
  - SEAT e.g., 1,2,3, …., 167
- (Input and Output) Actions: with arities, e.g.,

openSession	STRING x STRING x SESSION
getSeat	SESSION x SEAT

- Parameterized Symbols



Guards and Expressions

Assume

- Domains, e.g.,
  - STRING e.g., ‘Mary’, ‘174’, …
  - SESSION e.g., 0,1,2,3, …
  - SEAT e.g., 1,2,3, …., 167
- Relations on Data, e.g.,

=	
∈	SEAT x SEATS
has_passwd	STRING x STRING

Symbolic Mealy Machine

A Symbolic Mealy Machine consists of

- I Input Actions
- O Output Actions
- L Locations
- l_0 Initial location
- X State variables (typed)
- → Symbolic Transitions

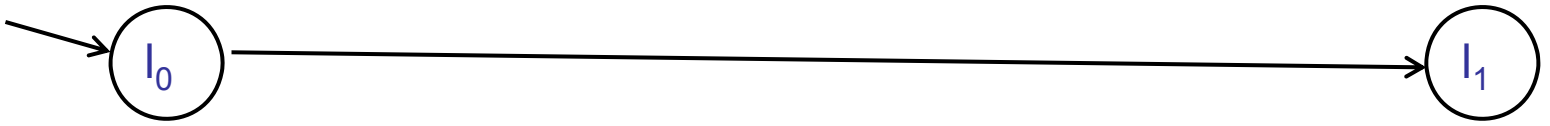
State Variables
cur_session : SESSION
cur_seats : SEATS
booked : SEATS

Input Action

Formal parameters

getSeat(s,seat)
[s = cur_session ∧ seat ∈ cur_seats]/
booked := booked ∪ seat ;
bookedSeat(seat)

Parameterized input symbol
guard
assignment
output expression



Example

State Variables
cur_session : SESSION
cur_seats : SEATS
booked : SEATS

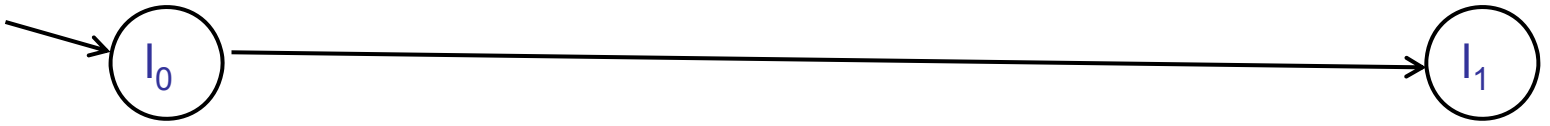
(Maybe complete the Example Here *)*

Input Action

Formal parameters

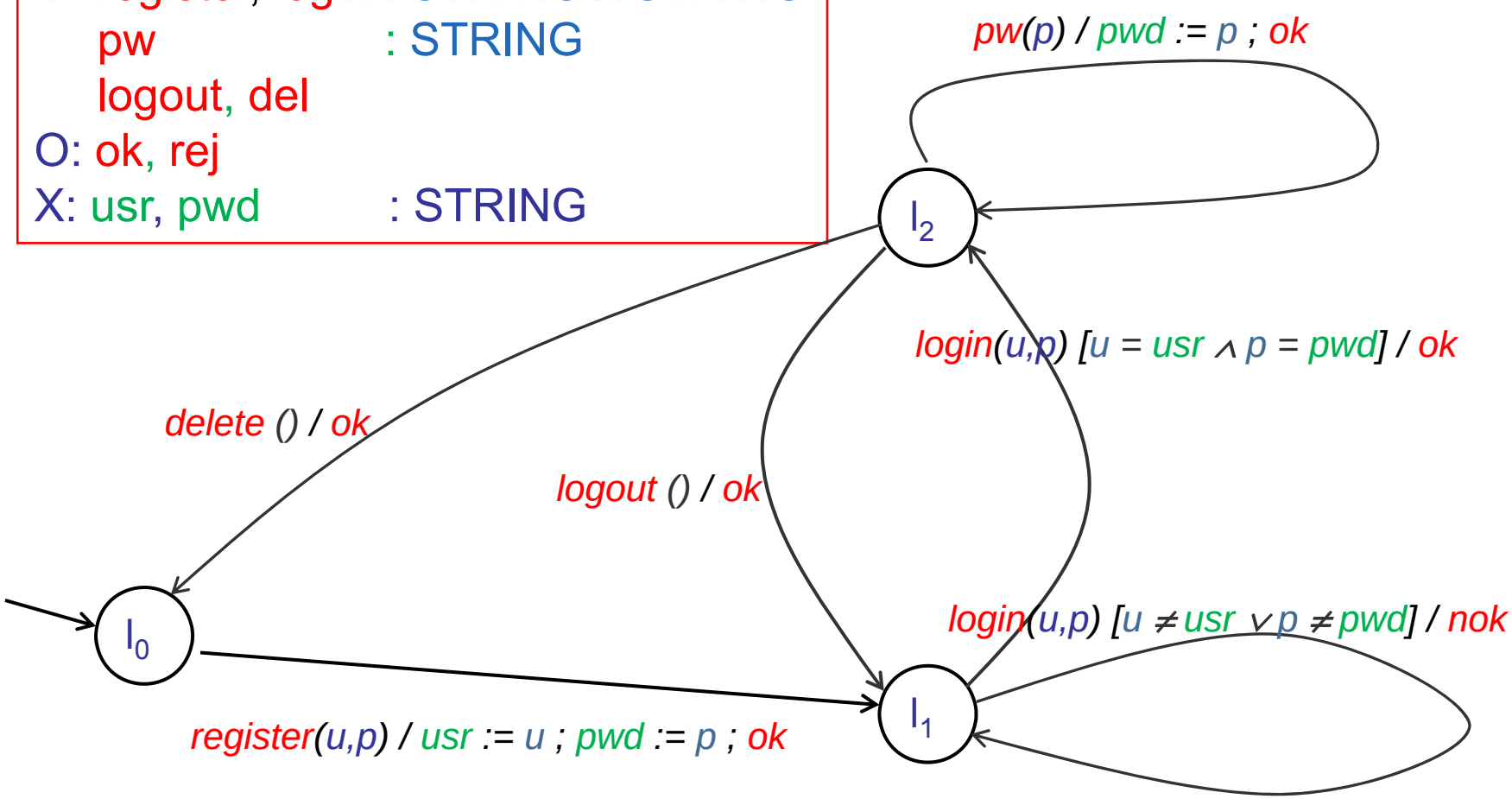
getSeat(s,seat)
[s = cur_session ∧ seat ∈ cur_seats]/
booked := booked ∪ seat ;
bookedSeat(seat)

Parameterized input symbol
guard
assignment
output expression



Example: XMPP protocol

I: register, login : STRING x STRING
pw : STRING
logout, del
O: ok, rej
X: usr, pwd : STRING



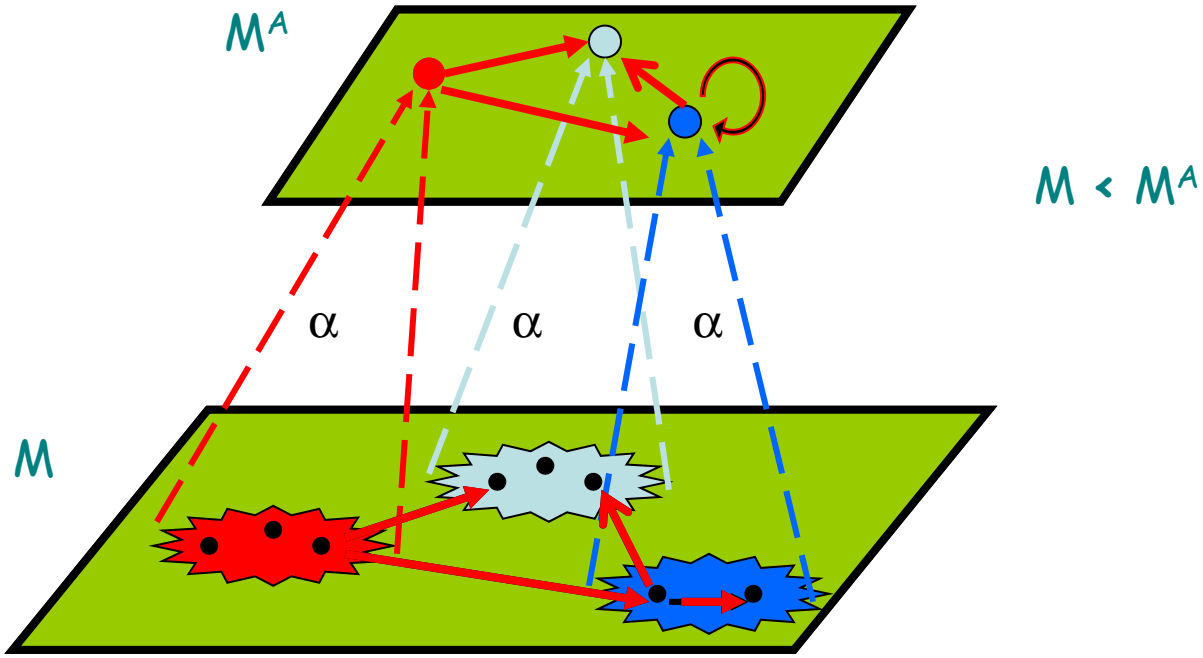
How to Adapt Learning?

- How to use L* to infer Symbolic Mealy Machines?
- L* works on finite-state Mealy machines
- SMMs are infinite state, with infinite alphabets.

IDEA: Use abstraction (from Verification/Model Checking)

- Fides Aarts, Bengt Jonsson, and Johan Uijen: *Generating Models of Infinite-State Communication Protocols using Regular Inference with Abstraction.* ICTSS 2010
- Falk Howar, Maik Merten, Bernhard Steffen *Automata Learning with Automated Alphabet Abstraction Refinement,* VMCAI 2011

Abstraction: the General Idea



Abstraction in Verification

Problem:

$$M \quad \text{satisfies} \quad \varphi \quad ?$$

Transformed into:

$$M^A \quad \text{satisfies} \quad \varphi^A \quad ?$$

Adaptation in Learning

Define an abstraction α

- α transforms the Model M into M^A

Use L* to infer M^A

- works if M^A is deterministic and finite-state

Reverse effect of α on M^A

- i.e., $M = \alpha^{-1}(M^A)$

If M^A is not adequate, refine α

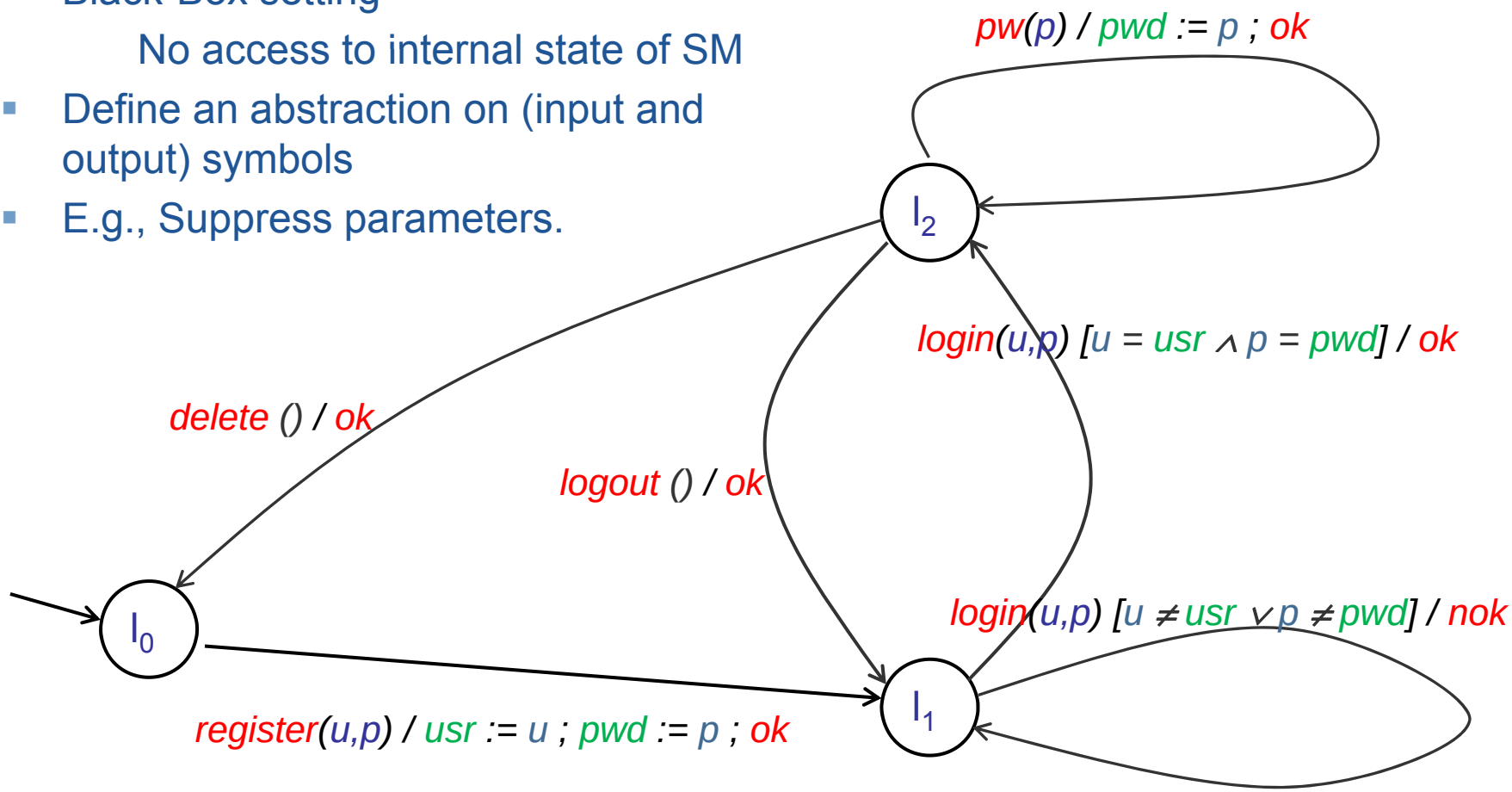
Abstraction in Learning?

- Black-Box setting -> We do not have access to internal state of SM
- Define an abstraction on (input and output) symbols

- E.g., Suppress parameters.

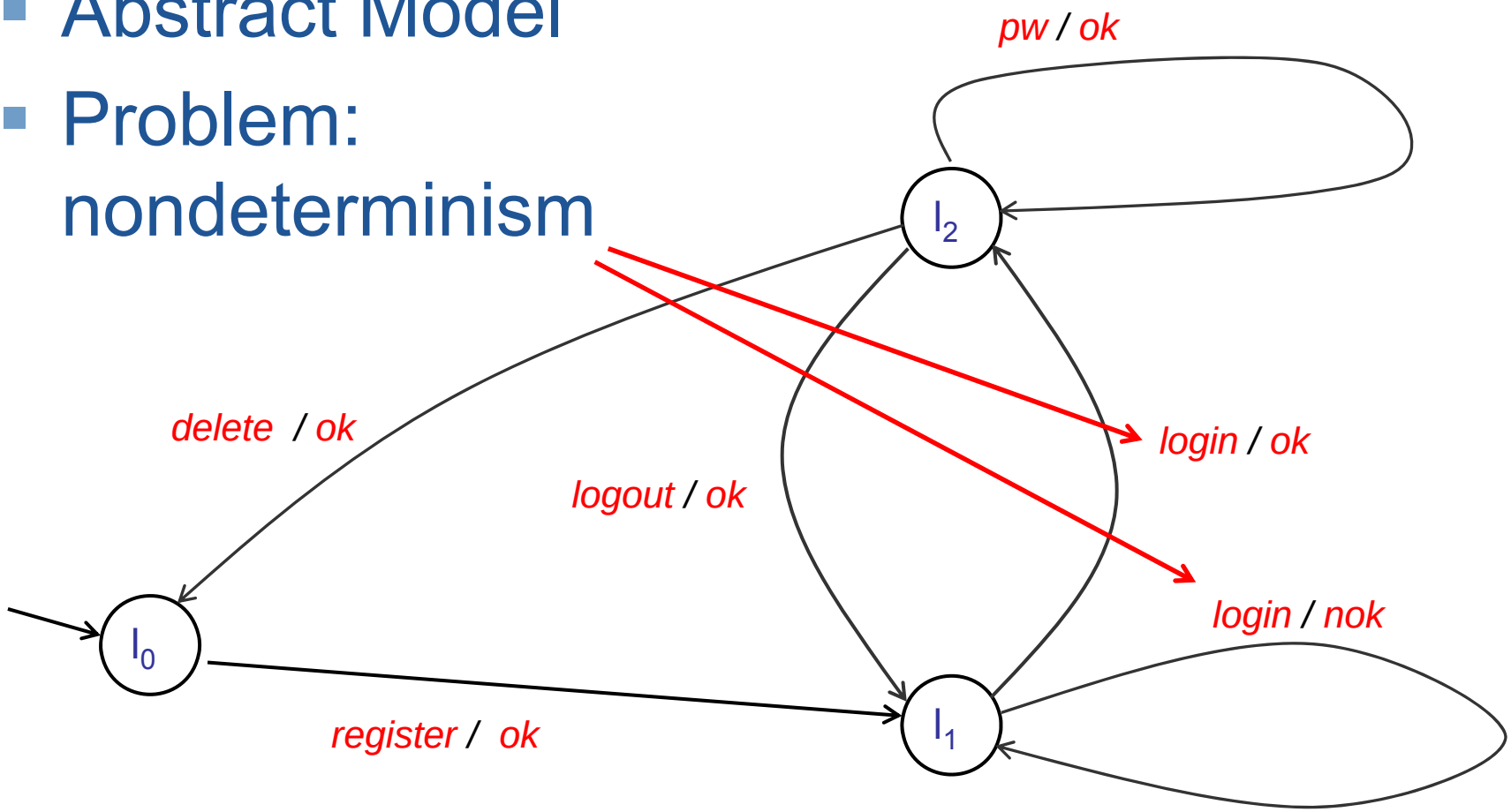
Application to Example

- Black-Box setting ->
  No access to internal state of SM
- Define an abstraction on (input and output) symbols
- E.g., Suppress parameters.

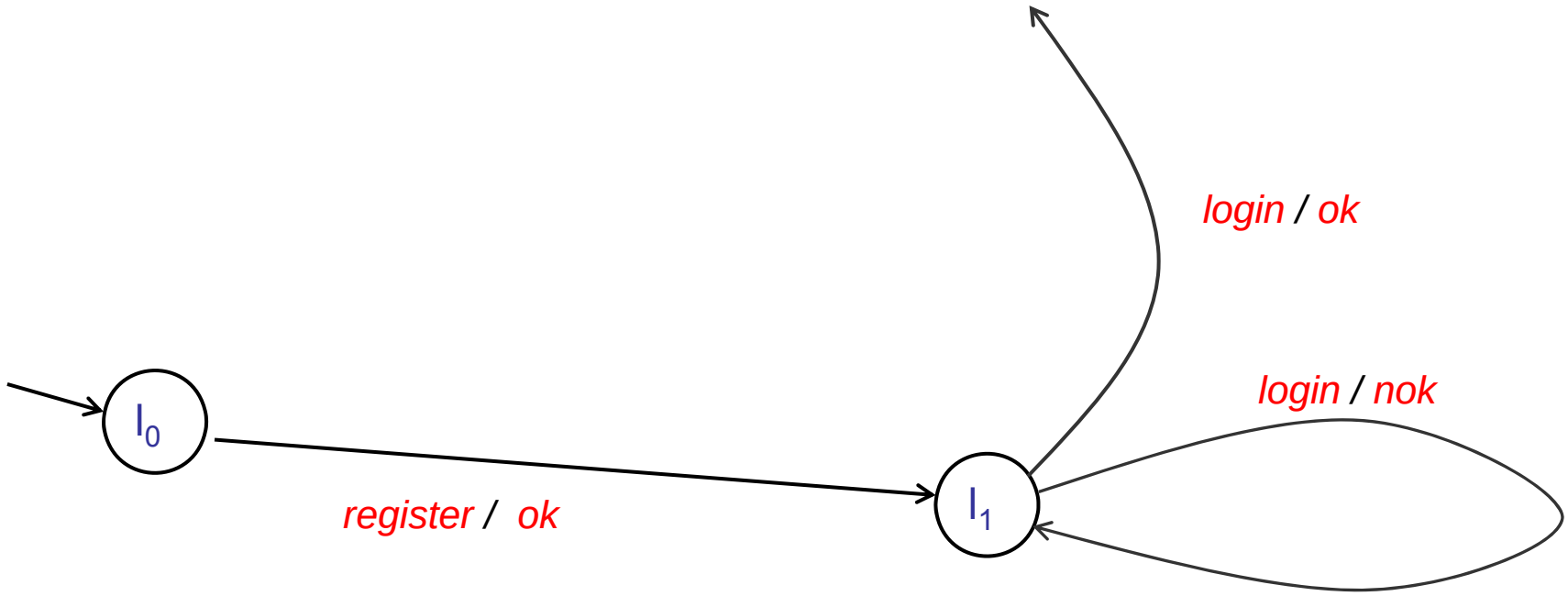


Inadequate Model

- Abstract Model
- Problem: nondeterminism

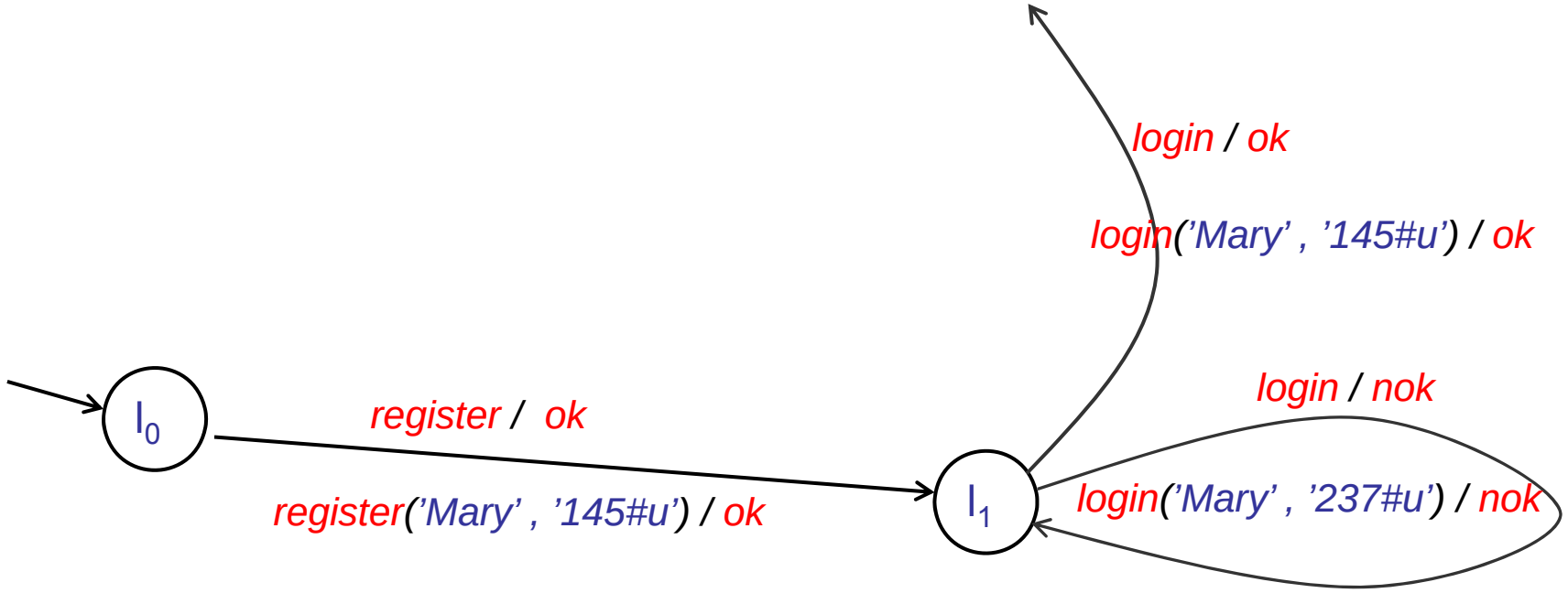


Fixing Nondeterminism-Problem



Fixing Nondeterminism-Problem

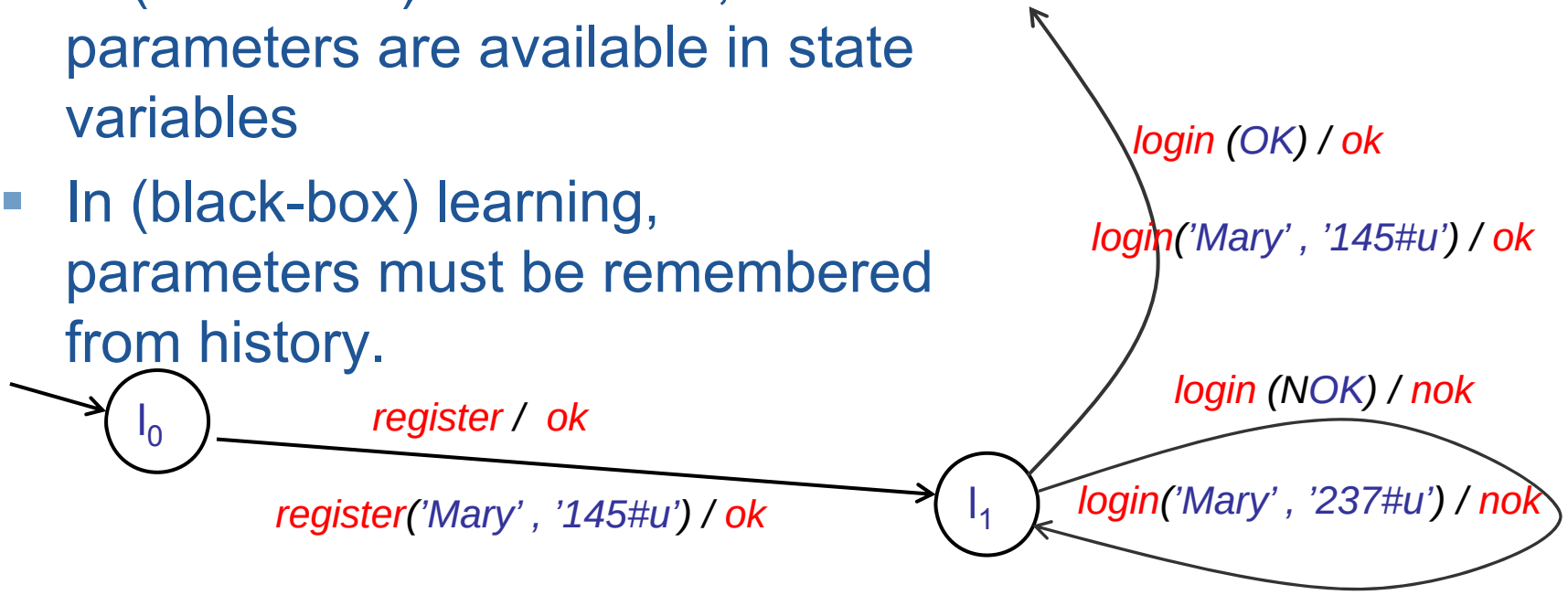
Abstraction depends on
parameters **and**
previous history



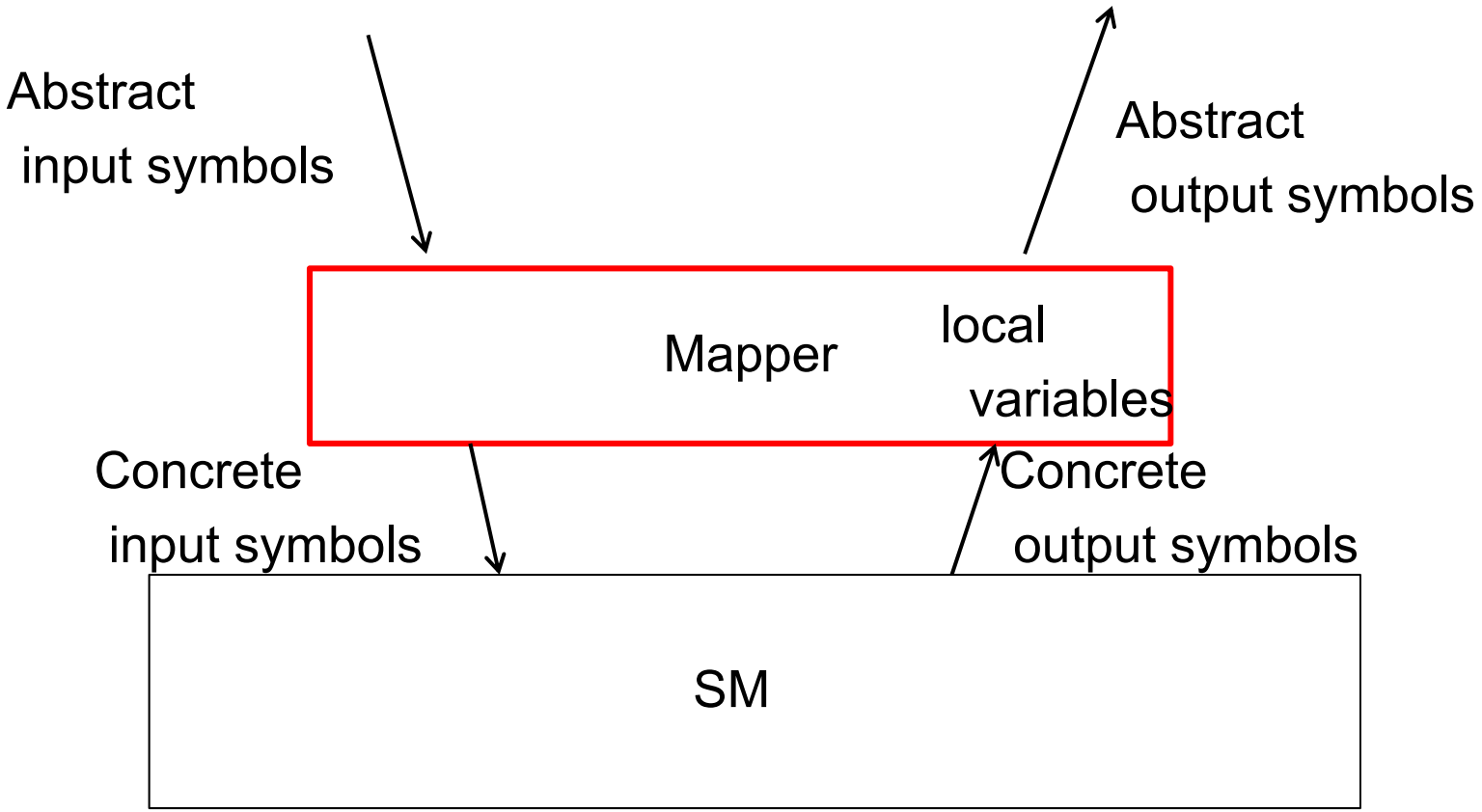
Fixing Nondeterminism-Problem

Abstraction depends on
parameters **and**
previous history

- In (white-box) verification, parameters are available in state variables
- In (black-box) learning, parameters must be remembered from history.



Organization of Abstraction



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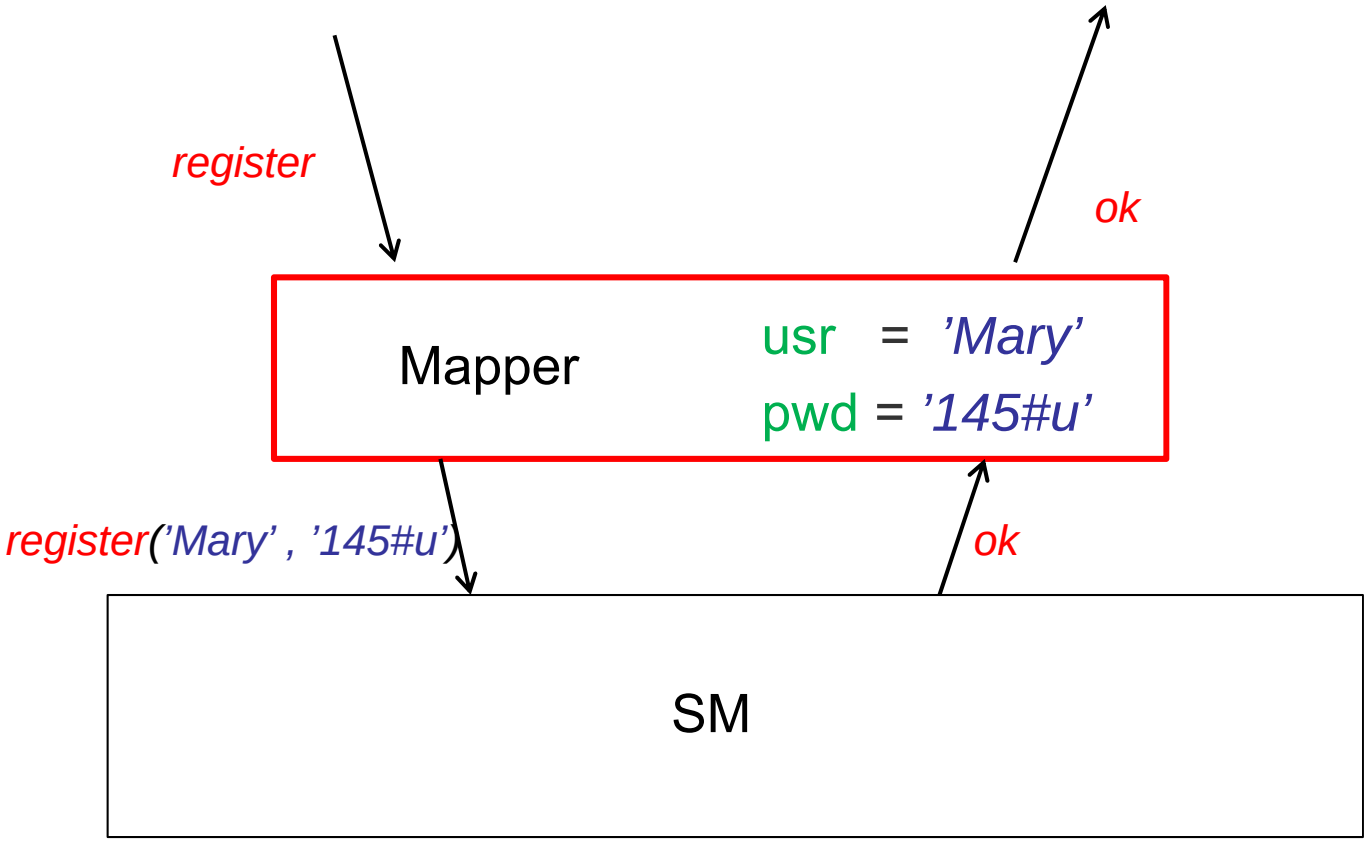

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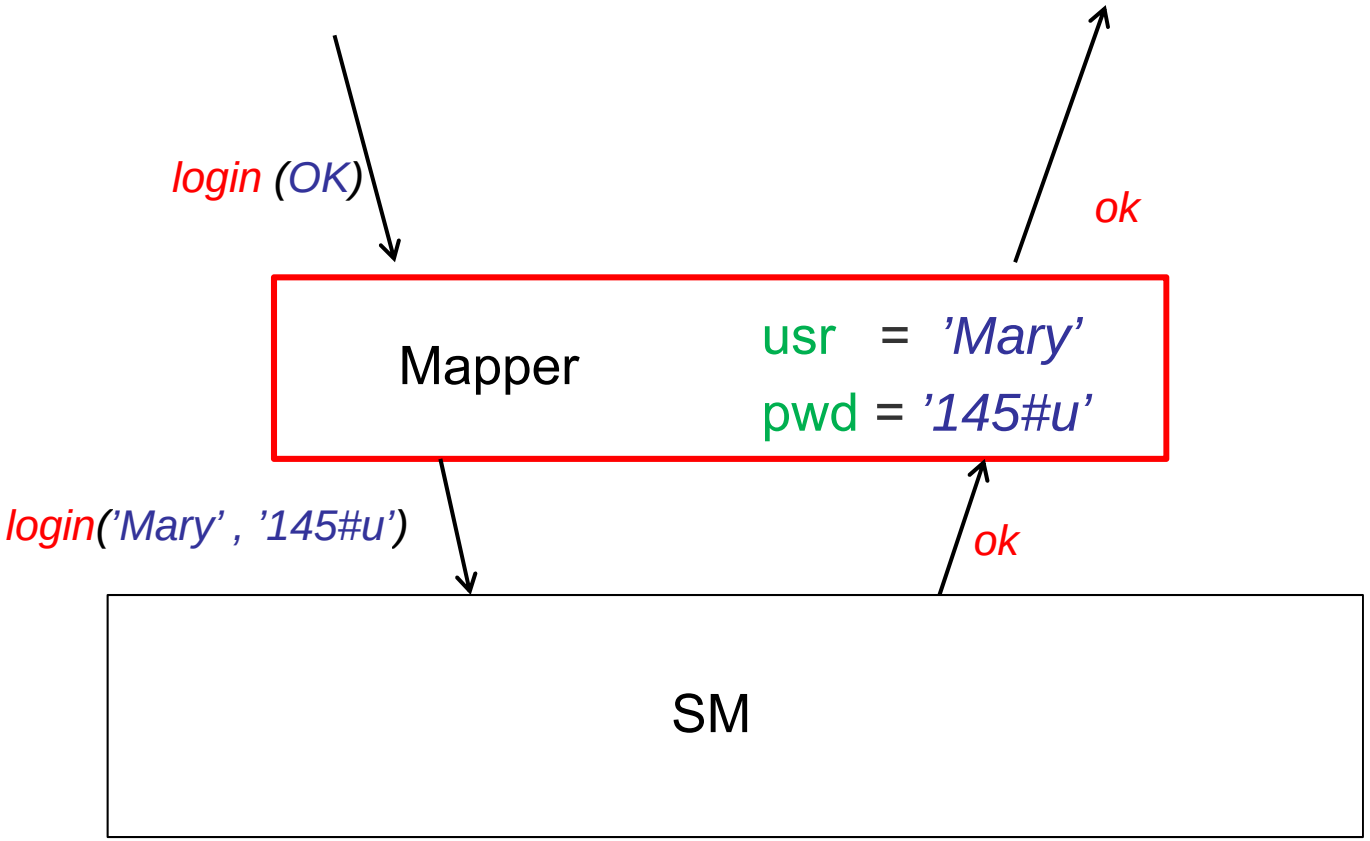

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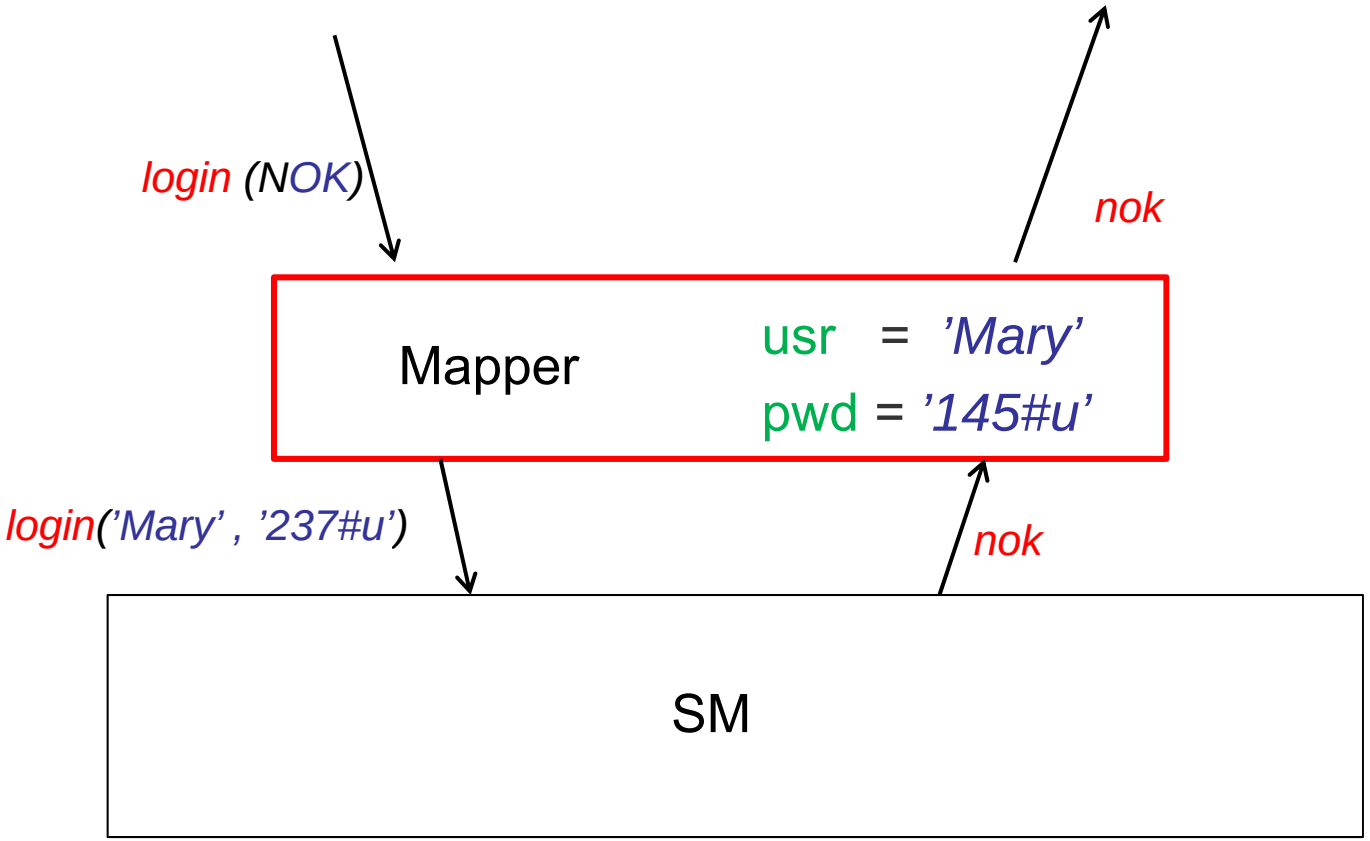


Abstraction: Formal definition

M

Σ_I , Σ_O symbols

Q , q_0 states , initial state

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

λ: $Q \times \Sigma_I \rightarrow \Sigma_O$ output function

Mapper

Σ_I^A , Σ_O^A abstract symbols

R , r_0 states , initial state

δ^R: $R \times (\Sigma_I \cup \Sigma_O) \rightarrow R$ update

α_I: $R \times \Sigma_I \rightarrow \Sigma_I^A$ input abstraction

α_O: $R \times \Sigma_O \rightarrow \Sigma_O^A$ output abstraction

Combined Mealy Machine

Σ_I^A , Σ_O^A abstract symbols

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

In general Nondeterministic

Whenever

$$q \xrightarrow{a \,/\, b} q'$$

we have

$$\langle q , r \rangle \xrightarrow{\alpha_I (r , a) \,/\, \alpha_O (\delta^R(r , a) , b)} \langle q' , \delta^R(\delta^R(r , a) , b) \rangle$$

Application to XMPP

XMPP:

$\langle l_0$, usr=⊥ , pwd=⊥$\rangle$ —*register('Mary' , '145#u') / ok*→ $\langle l_0$, usr = *'Mary'* , pwd = *'145#u'* $\rangle$

Mapper:

Maps *register('Mary' , '145#u')* *to* *register*

Assigns usr := *'Mary'* ; pwd:= *'145#u'*

Combination:

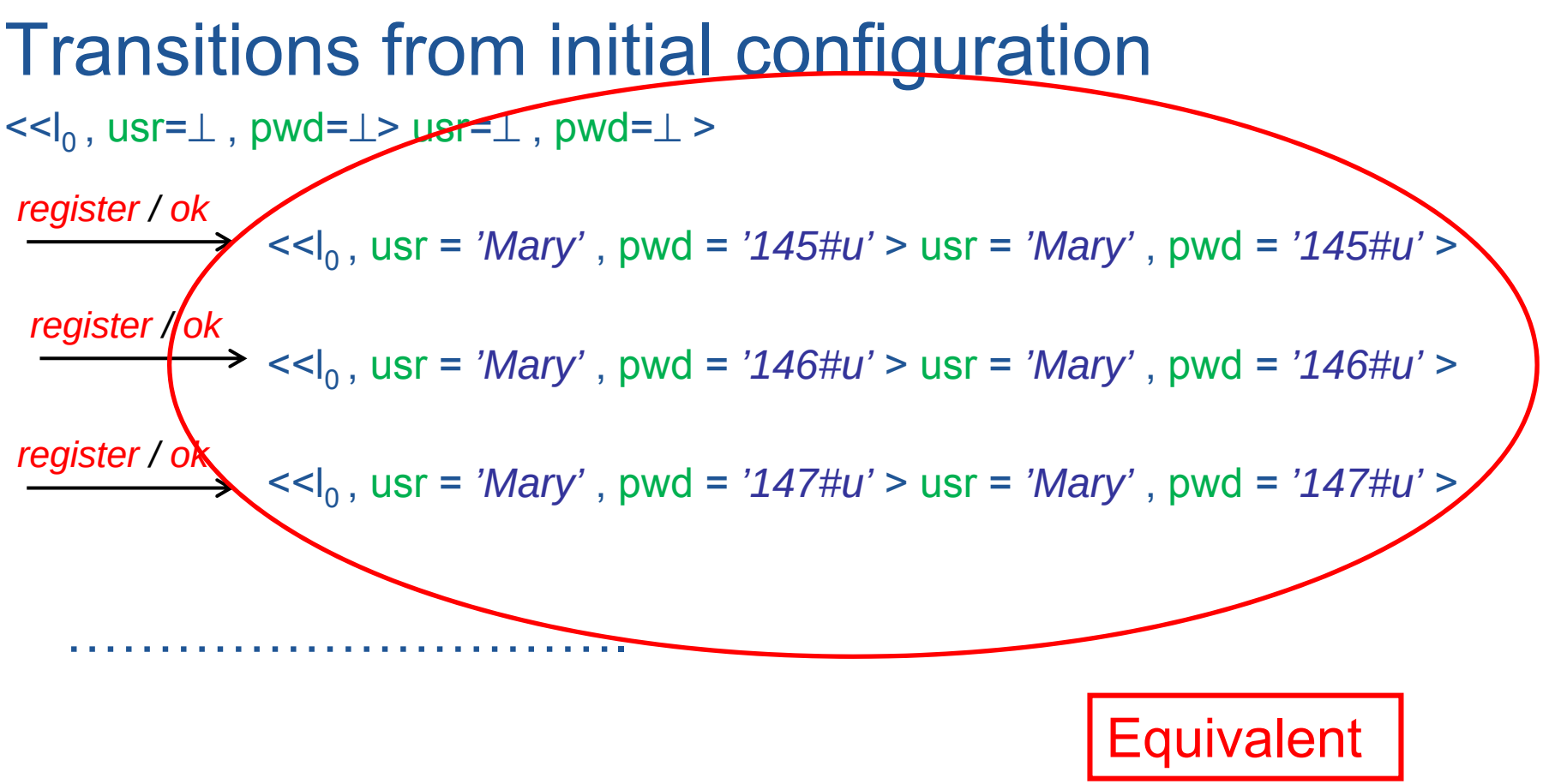
$\langle\langle l_0$, usr=⊥ , pwd=⊥$\rangle$ usr=⊥ , pwd=⊥ $\rangle$

—*register / ok*→

$\langle\langle l_0$, usr = *'Mary'* , pwd = *'145#u'* $\rangle$ usr = *'Mary'* , pwd = *'145#u'* $\rangle$

Potential Nondeterminism

Transitions from initial configuration



Equivalent

Result of Good Abstraction

- Combined Model is equivalent to a finite-state Mealy Machine M^A
- If so, we can obtain M by reversing effect of introducing Mapper

Combined Mealy Machine

Whenever

$$q \xrightarrow{a/\,b} q'$$

we have

$$\langle q , r\rangle \xrightarrow{\alpha_I(r,a)\,/\,\alpha_O(\delta^R(r,a),\,b)} \langle q' , \delta^R(\delta^R(r,a),b)\rangle$$

Result of Good Abstraction

Combined Mealy Machine

Whenever

$$q \xrightarrow{a \,/\, b} q'$$

we have

$$\langle q , r \rangle \xrightarrow{\alpha_I (r , a) \,/\, \alpha_O (\delta^R(r , a) , b)} \langle q' , \delta^R(\delta^R(r , a) , b) \rangle$$

Removing Effect of Mapper

Whenever

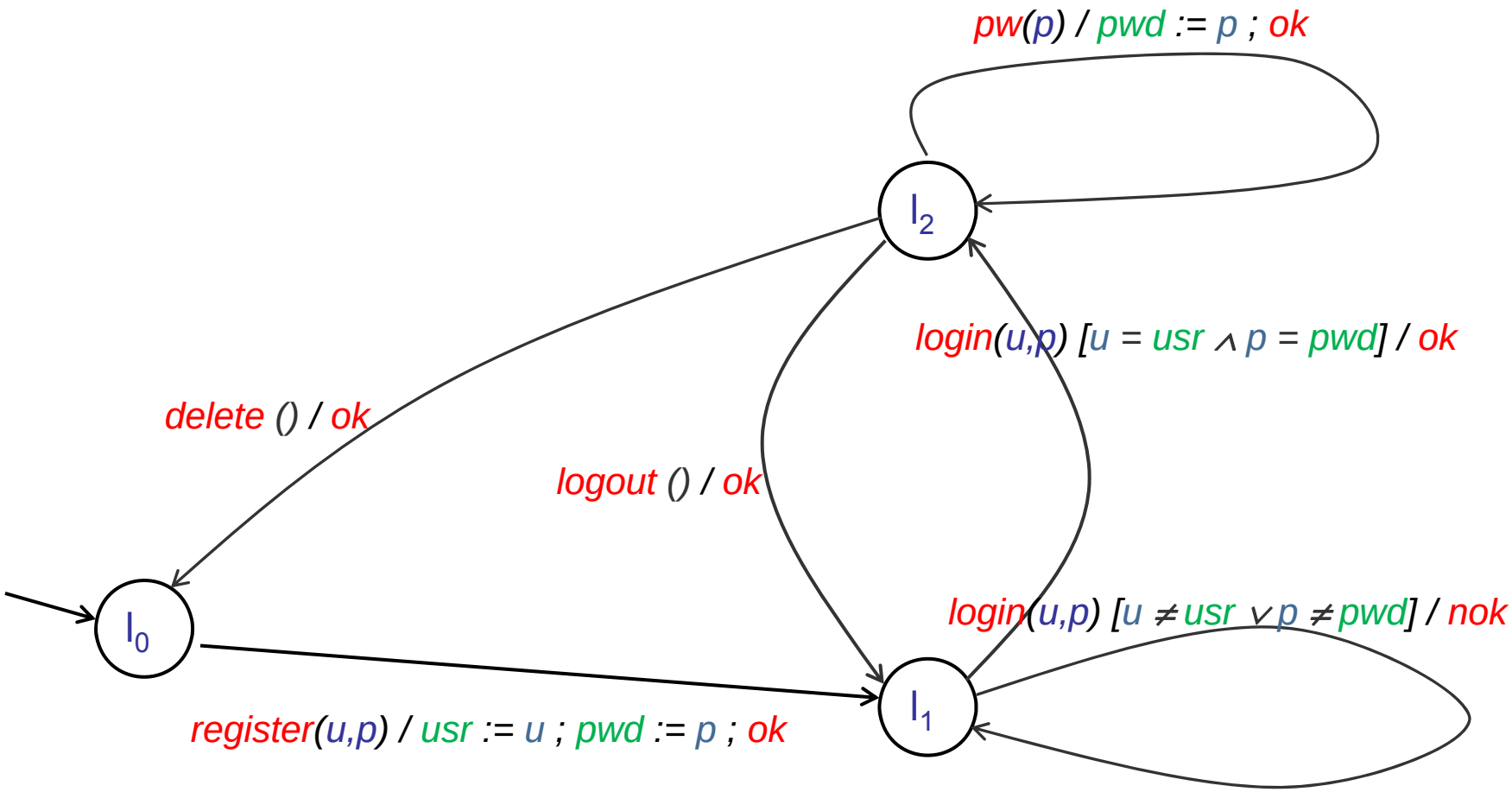
$$q^A \xrightarrow{\alpha_I (r , a) \,/\, \alpha_O (\delta^R(r , a) , b)} q^{A'}$$

Can be Nondeterministic

we have

$$\langle q^A, r \rangle \xrightarrow{a \,/\, b} \langle q^{A'}, \delta^R(\delta^R(r , a) , b) \rangle$$

Application to XMPP Example



Adaptation of Learning

Definition of Mapper

State Variables:

- usr , pwd
- Updated after *register*(*u*,*p*), *pw*(*p*)

Abstractions of symbols:

- *login*(*u*,*p*)

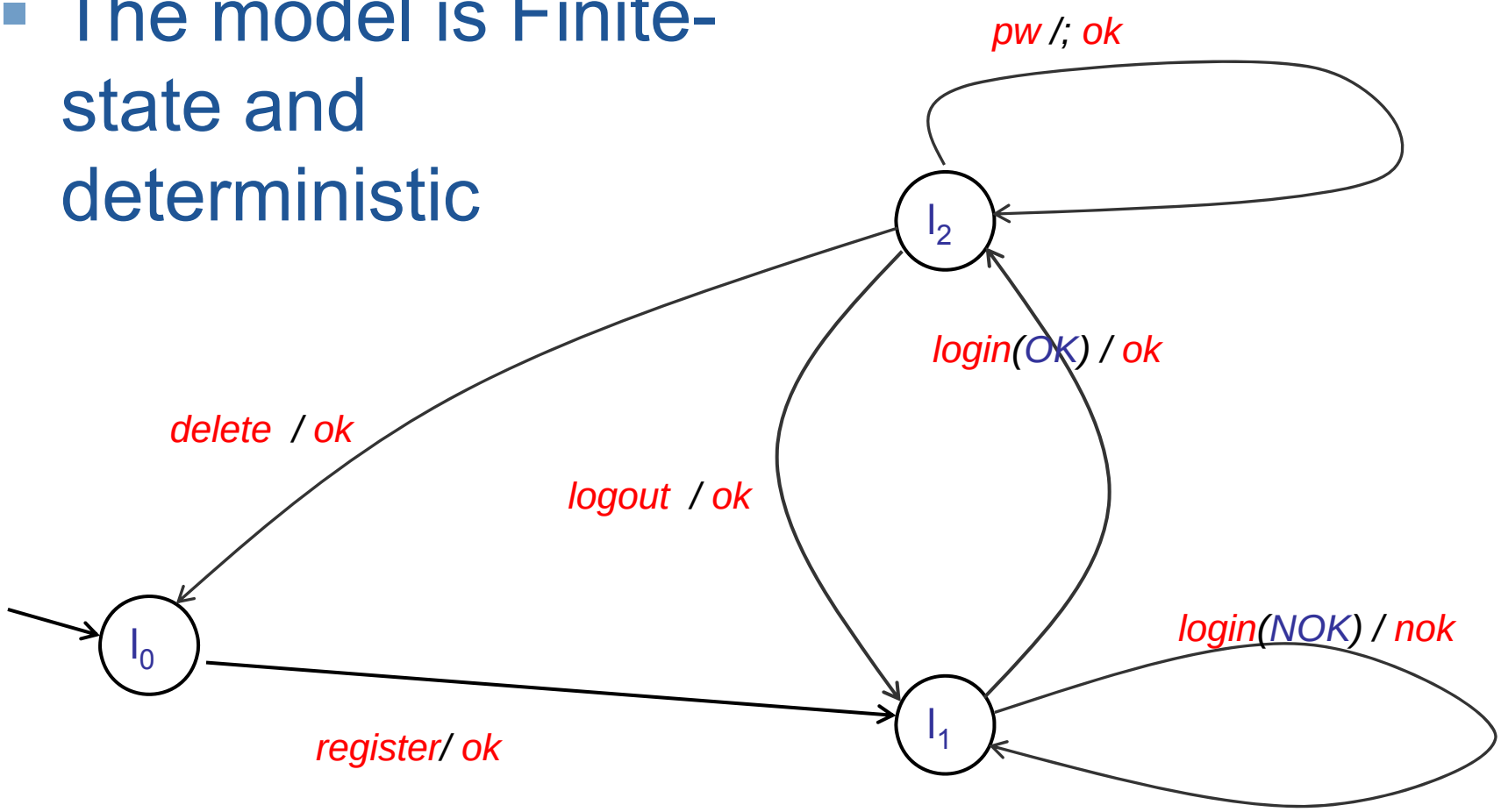
  mapped to *login*(*OK*) *or* *login*(*NOK*)

- *All other symbols:*

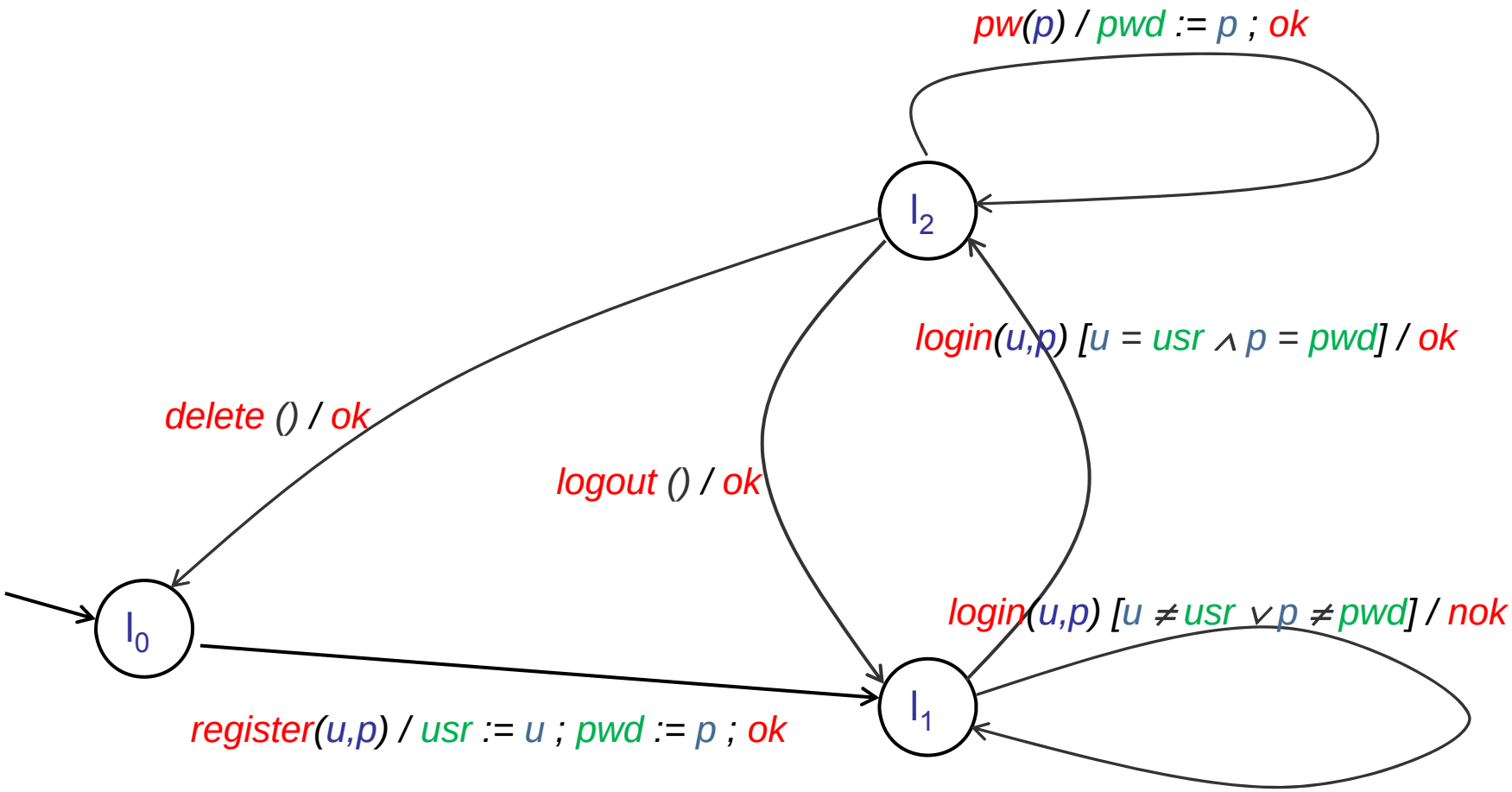
  mapped by suppressing parameters

Abstract Model

- The model is Finite-state and deterministic



Reverse effect of Abstraction



Systematic Construction of Abstractions

Simplifying assumption (for this presentation):

- Outputs do not have parameters

For SMMs with simple operations on data, abstractions can be constructed systematically

- Analogy: “region-graph-like” techniques for model checking infinite-state models
- Assume that we know
  - which parameters M stores from input symbols
  - signature of tests (assume no operations)

Designing a Mapper

We know which parameters M stores

-> define sufficient mapper variables $y_1, \ldots, y_j$

We know signature of tests

-> define *complete guard* as maximal consistent conjunction

-> Mapper maps each input symbol symbol $a\ (d_1, \ldots, d_n)$

to $a\ (p_1, \ldots, p_n)\ [\ g\ ]$

where g is appropriate complete guard over $y_1 \ldots\ y_j\ p_1 \ldots\ p_n$

Designing a Mapper

Assume:

any complete guard over $y_1, \ldots, y_j$ determines

for each input symbol $\alpha\ (p_1, \ldots, p_n)$

the complete guards over $y_1 \ldots y_j\ p_1 \ldots\ p_n$

any complete guard over $y_1, \ldots, y_j\ p_1 \ldots\ p_n$ determines

a unique complete guard over any subset

This assumptions make M^A finite-state and deterministic

Why it works

These assumptions make M^A finite-state and deterministic

because in state of combined model

$$\langle\langle l, x_1=d_1, \ldots x_k = d_k\rangle \;\; , y_1 = d_1', \ldots y_j = d_j'\rangle$$

- control location l
- complete guard g satisfied by $y_1 , \ldots , y_j$
- mapping from $y_1 , \ldots , y_j$ to $x_1 , \ldots , x_k$

uniquely determine future behavior

Why uniquely determined

Namely

in state of combined model

$$\langle\langle l, x_1=d_1, \ldots x_k = d_k\rangle \;, y_1 = d_1', \ldots y_j = d_j'\rangle$$

- An input $a(d_1, \ldots, d_n)$ is mapped to $a(p_1, \ldots, p_n) : g$
- Chosen symbolic transition of M is uniquely determined
- Location, guard and mapping in next state are uniquely determined

Example from XMPP

Abstractions of *pw(d)*

pw(p) [p = usr = pwd]

pw(p) [p = usr ≠ pwd]

pw(p) [p ≠ usr = pwd]

pw(p) [p = pwd ≠ usr]

pw(p) [p ≠ pwd ≠ usr ∧ p ≠ usr]

Inferring Information to Store

- Principle:
  - A parameter is memorable if it influences future behavior
- First case:
  - Parameter appears in output

register('Mary' , '145#u') / ok … askpwd('Mary') / reply('145#u')

- Second case:
  - Parameter influences decision

register('Mary' , '145#u') / ok … login('145#u') / ok

register('Mary' , '145#u') / ok … login('fresh') / nok

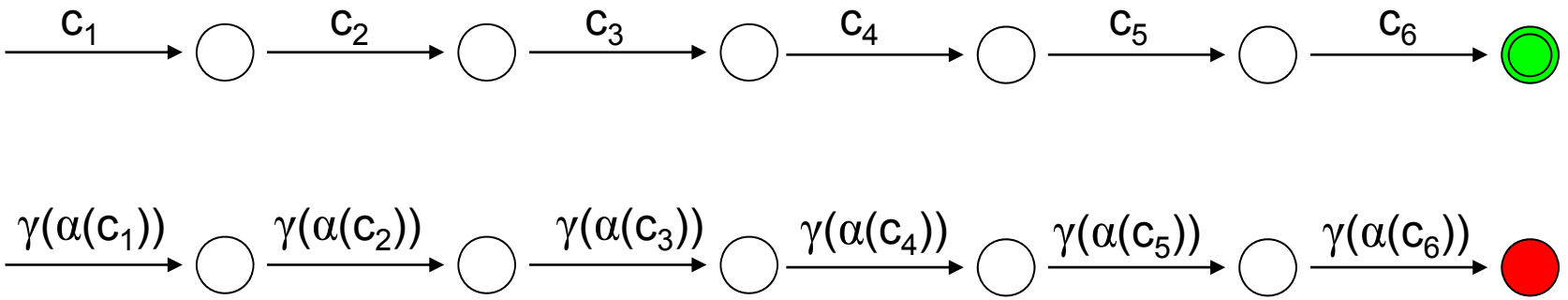
Inferring Guards

Alphabet Abstraction Refinement:

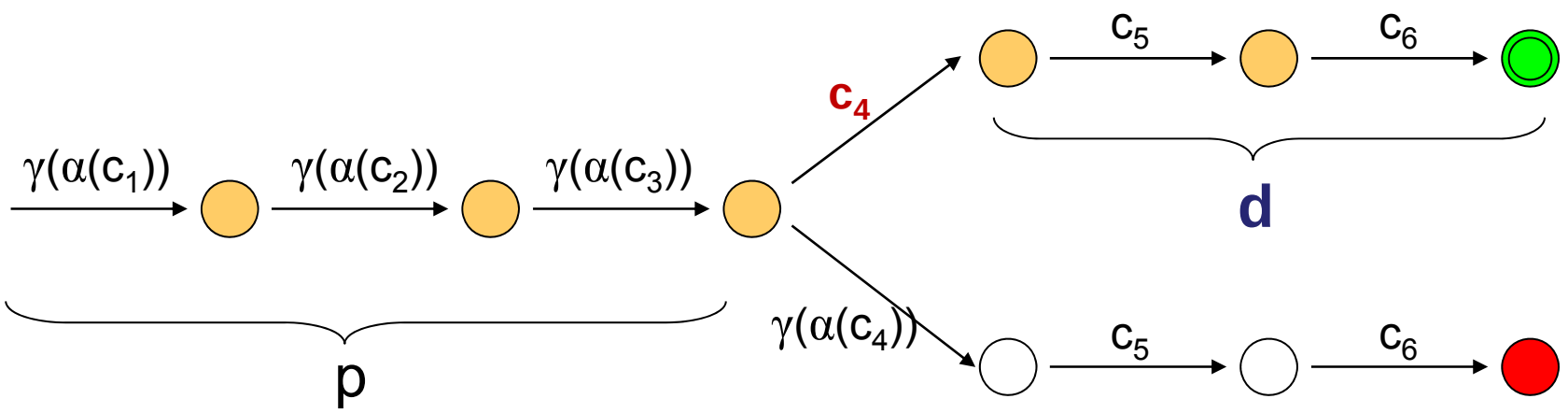
- Start without guards
- Add guards whenever nondeterminism appears.

register/ *ok* … *login*/ *ok* *nok*

Counter Examples and Witnesses



Counter Examples and Witnesses



Separating Pattern

p	c_4	d
state	representation	future

Abstraction Refinement

$$\alpha_{new}(\mathbf{x}) =_{df} \begin{cases} \alpha_{old}(\mathbf{x}) & \textbf{if } \alpha_{old}(\mathbf{x}) \mathbf{<>} \alpha_{old}(c) \\ a_c & \textbf{if } \alpha_{old}(\mathbf{x}) = \alpha_{old}(c) \text{ and} \\ & \quad \gamma(\alpha(p))\ \mathbf{x}\ d \in F \Leftrightarrow \gamma(\alpha(p))\ \mathbf{c}\ d \in F \\ \alpha_{old}(\mathbf{c}) & \textbf{else} \end{cases}$$

where a_c is a new abstract alphabet symbol.

$$\gamma_{new}(a) =_{df} \begin{cases} \gamma_{old}(a) & \textbf{if } a \neq \alpha_{old}(c) \\ \mathbf{c} & \textbf{if } a = a_c \\ \gamma_{old}(a) & \textbf{else} \end{cases}$$

Inferring Guards

Alphabet Abstraction Refinement:

- Start without guards
- Add guards whenever nondeterminism appears.

register/ *ok* … *login*/ *ok* / *nok*

register(*'Mary'* , *'145#u'*) / *ok* … *login*(*'Mary'* , *'145#u'*) / *ok*

register(*'Mary'* , *'145#u'*) / *ok* … *login*(*'Mary'*, *'fresh'*) / *nok*

Inferring Guards

Alphabet Abstraction Refinement:

- Start without guards
- Add guards whenever nondeterminism appears.

- Split *login* into
  - *login*(*u*,*p*) [*u* = *usr* ∧ *p* = *pwd*]
  - *login*(*u*,*p*) [*u* ≠ *usr* ∨ *p* ≠ *pwd*]

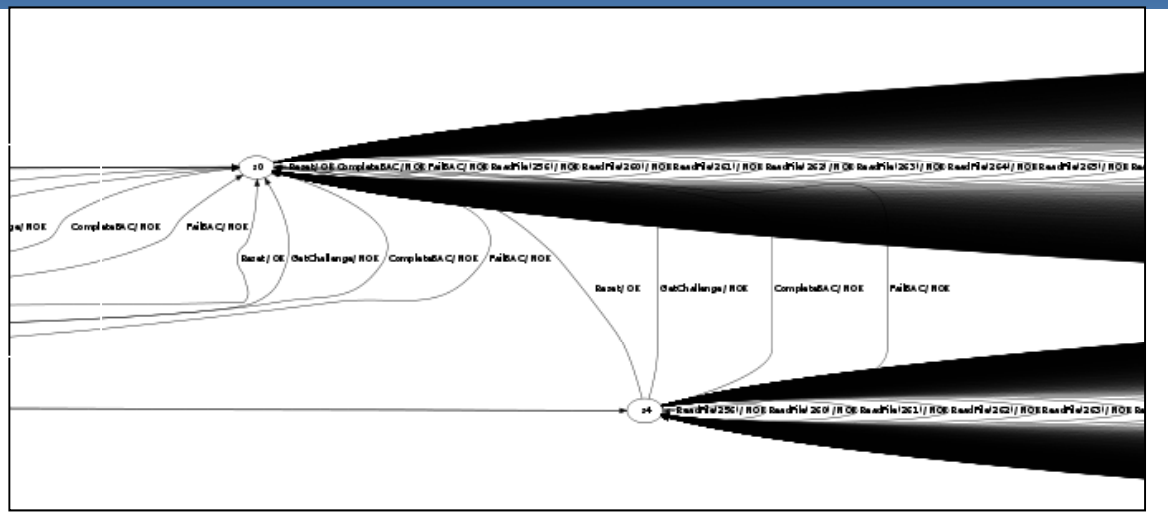
Applications of These Ideas

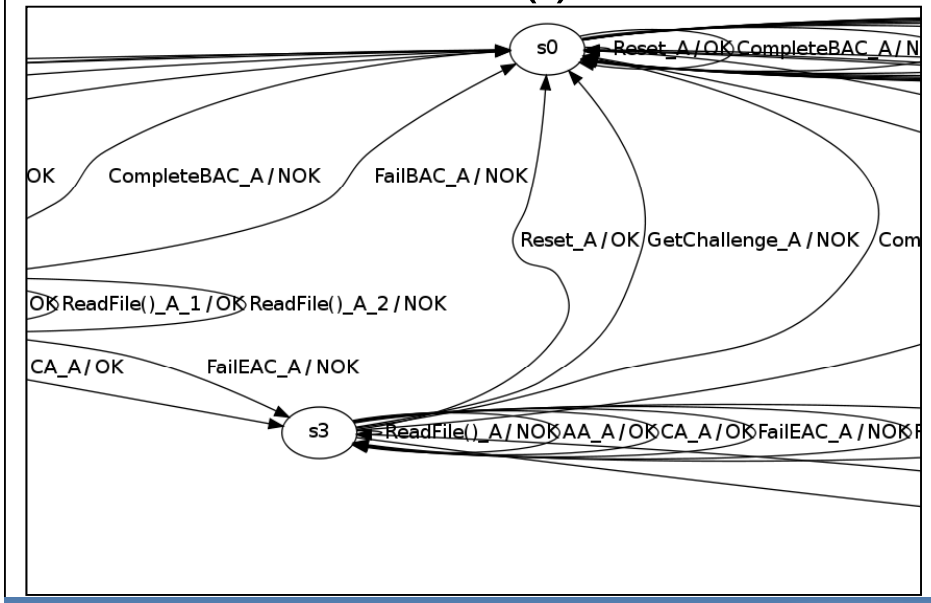
- Feasability studies on fragments of SIP and TCP
  - Implementations from ns-2 [Aarts, Jonsson, Uijen]
- Biometric Passport
  - w. manual abstraction [Aarts, Schmaltz, Vaandrager]
  - w. automated abstraction refinement [Howar, Steffen, Merten]

Passport [Howar et al]

Biometric Passport
[Aarts et. al, 2010]

262 Concrete symbols,
256 x readFile(i).



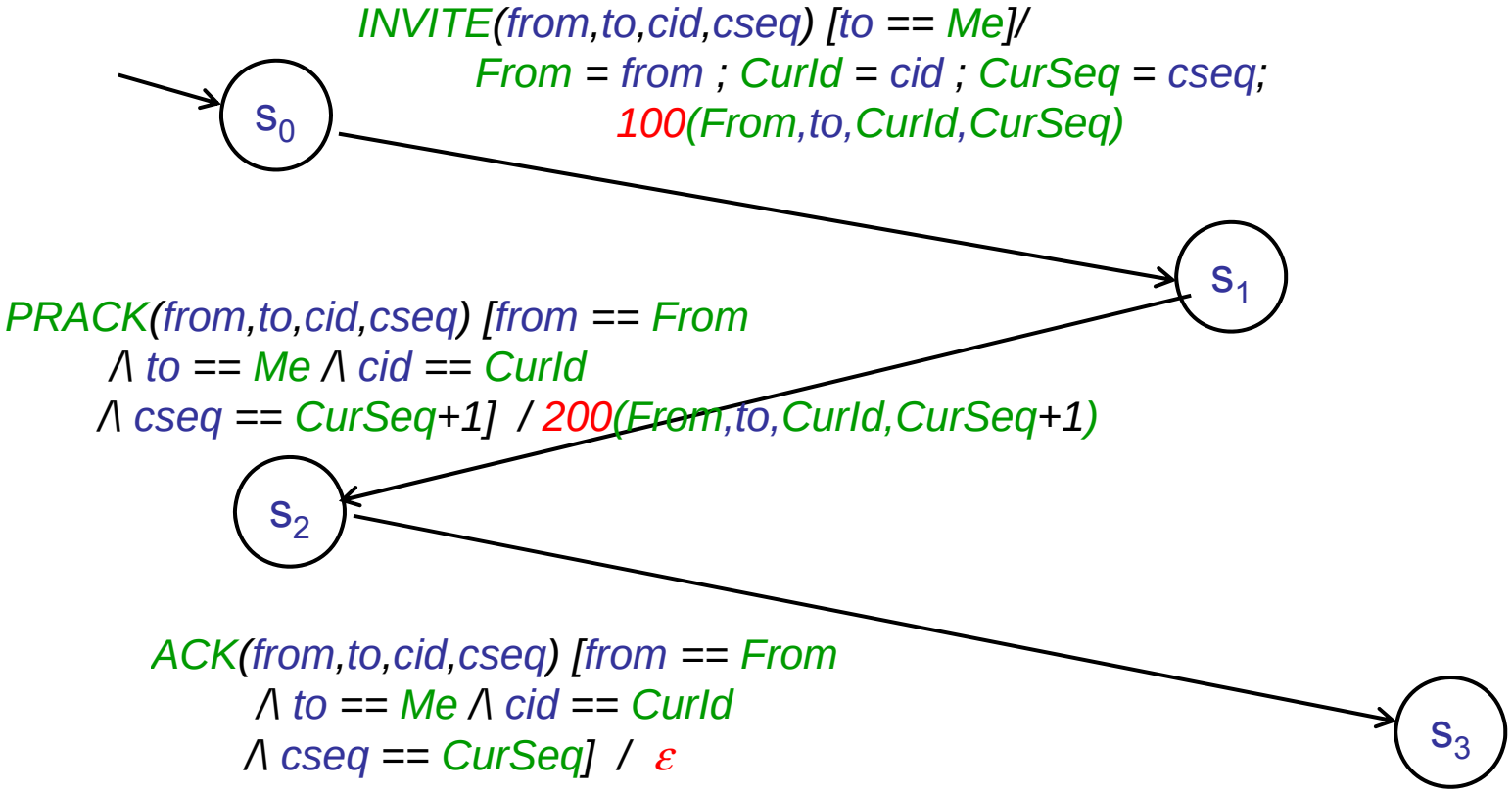


- **1** initial abstract symbols
- **8** alphabet refinements,
  to split readFile
- **9** final abstract symbols

*‚**read file(i)**‘ aggregated according to the required* ***Authentication***

part of SIP Server

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



Resulting Model

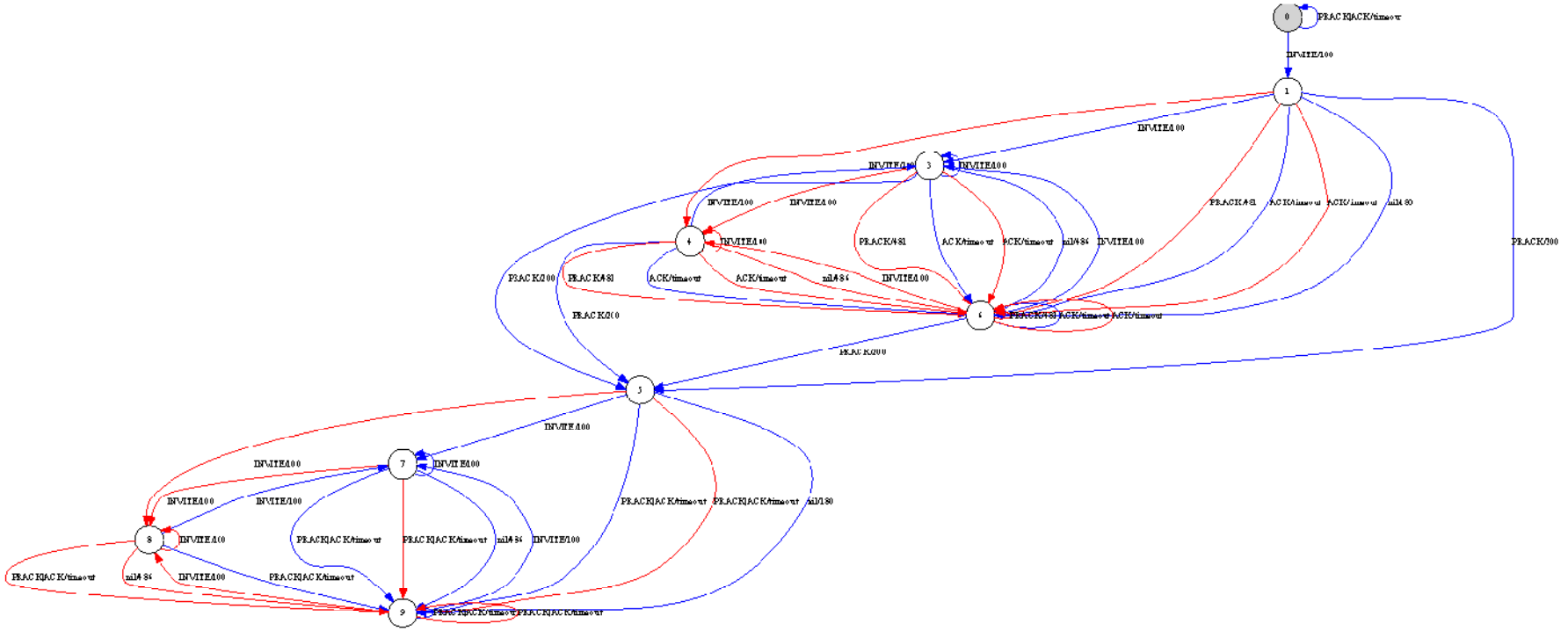
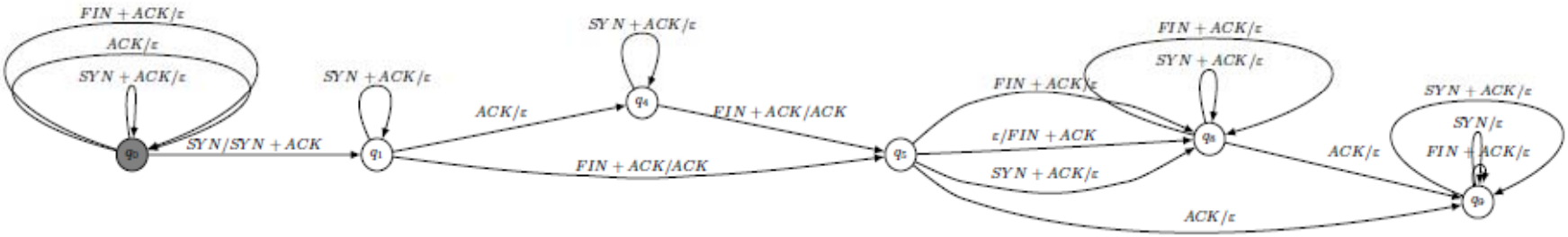


Fig. 3. Full SIP model

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 and Future Work

- Data (and data dependencies) Important for Modeling Components and Interfaces
- Abstraction Techniques can be used to make L* Applicable
- In Black-Box Situation, the techniques are less robust
  - Abstraction needs to be carefully designed
- Construction of Abstractions need to combine
  - Storing of “right” information
  - Partitioning of input symbols using guards
- In Progress: Systematic Combination of these for particular signatures, also obtaining canonical models

General Challenges

- Nondeterministic Models/Loose Specifications
- Automated Test-Driver Synthesis