Model Learning and Model Checking of SSH Implementations

Radboud University

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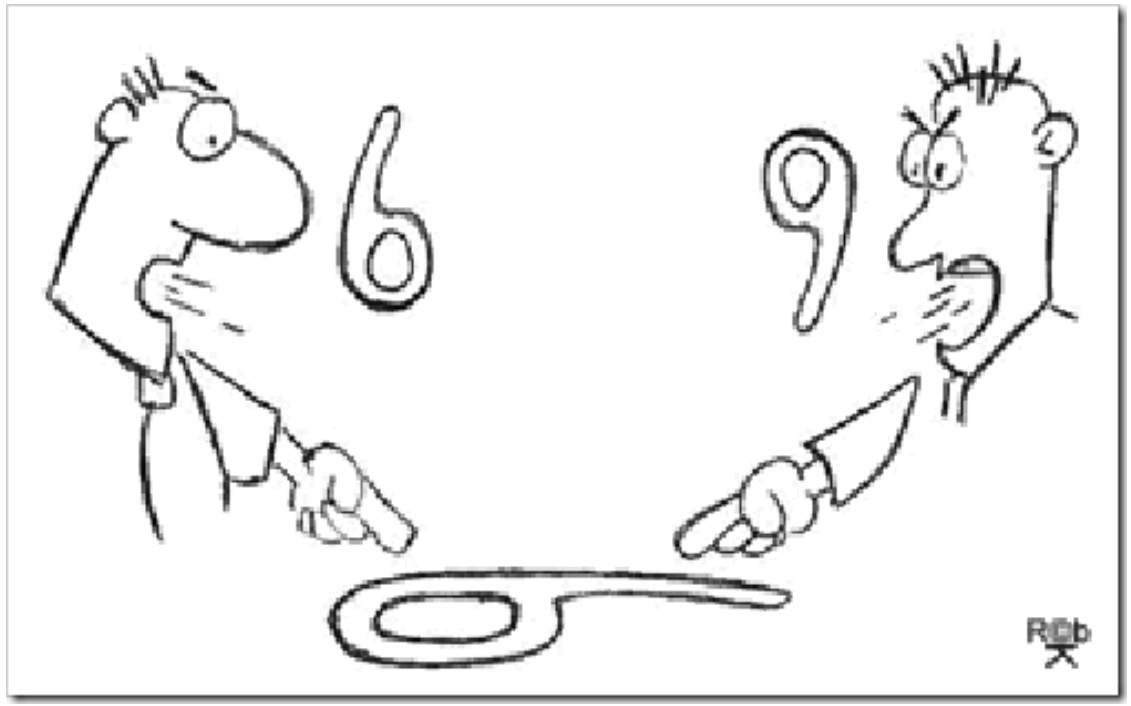
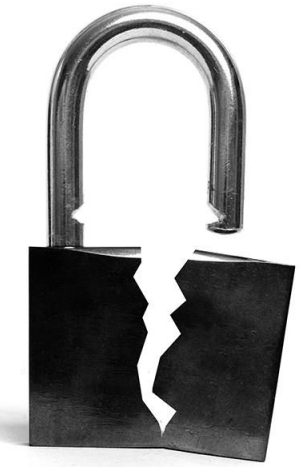
Patrick Verleg

Introduction

- protocols: SSH, TLS, SMTP, FTP, TCP, UDP…
- many implementations per protocol
  - ➢implementations MUST/SHOULD/MAY ***adhere*** to the specifications…





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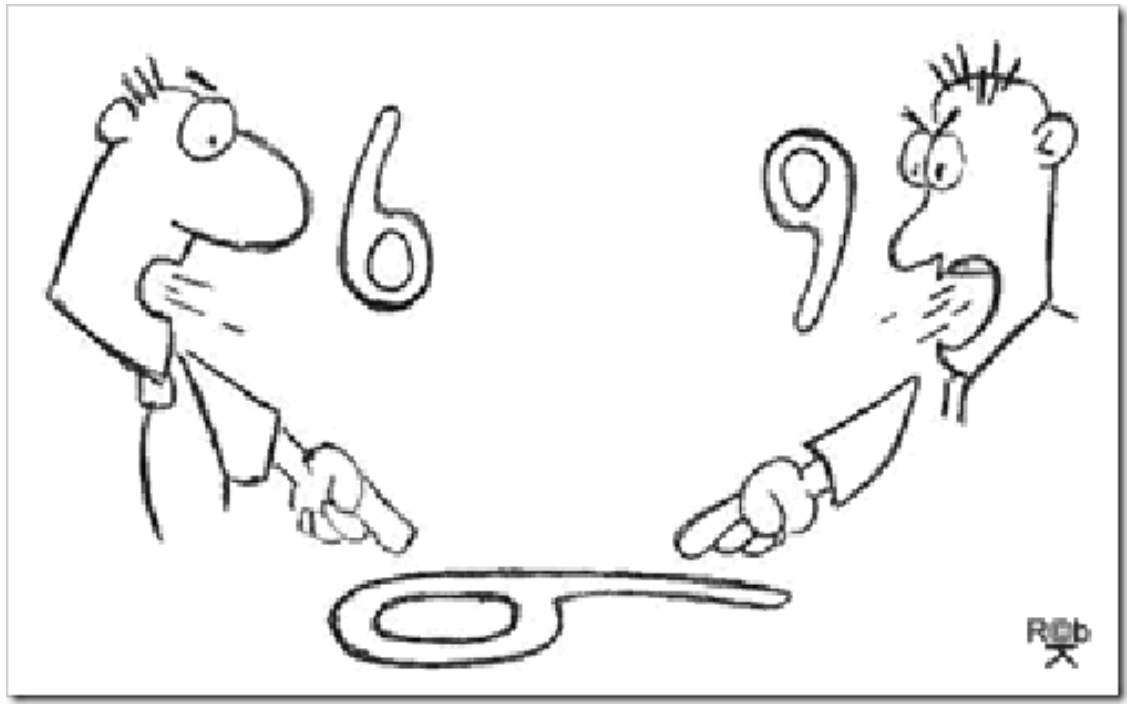
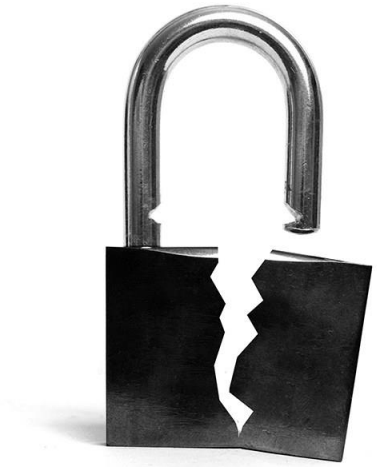
conformance testing





Motivation

Model Learning

→*automatically* infers models for concrete implementations

→checking conformance of models may be difficult

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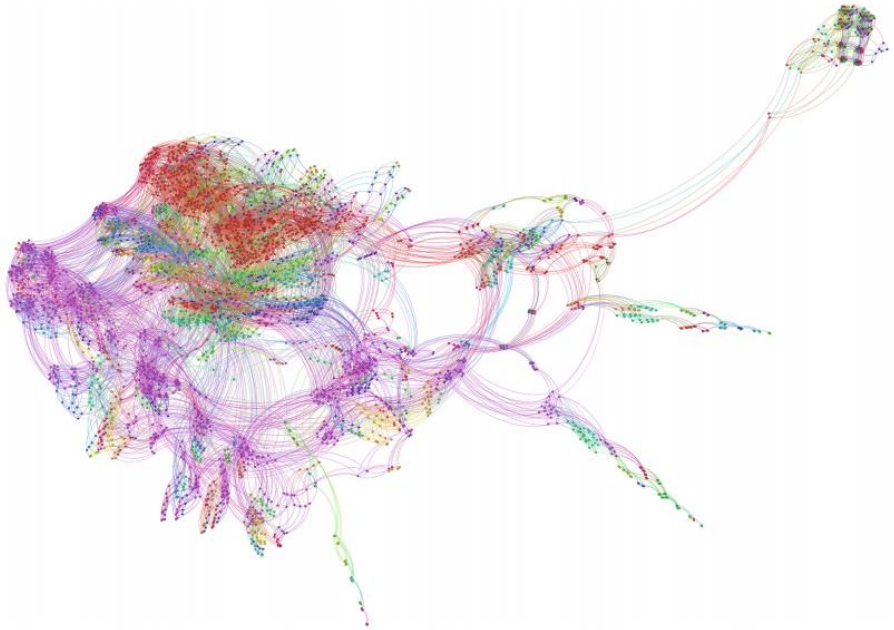

Motivation

Model Checking

→*automatically* checks conformance of models to specifications

→*requires* models and formalized specifications

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Model Learning + Model Checking

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What was done

Model Learning + Model Checking

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Application of ML+MC on SSH (a real world protocol):

1. use Model Learning to infer models of 3 SSH server implementations
2. formalize specifications from the SSH RFC standards
3. use Model Checking to verify models against these specification

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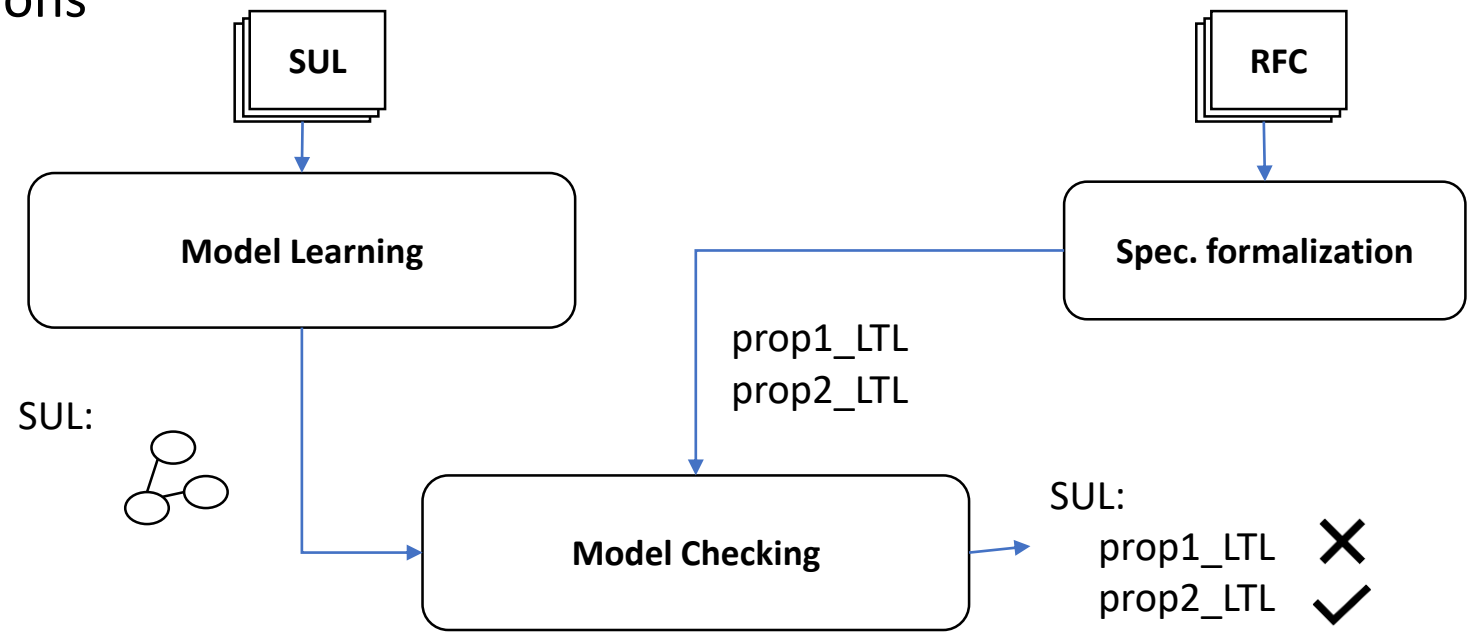
Schematic Overview



What was done

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→*automatically* infers models for concrete implementations

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enough for a publication?

What was done

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Model Learning:

→*requires* mapper component

→*requires* thorough testing

Model Checking:

→*requires* model transformation

→*requires* counterexample validation

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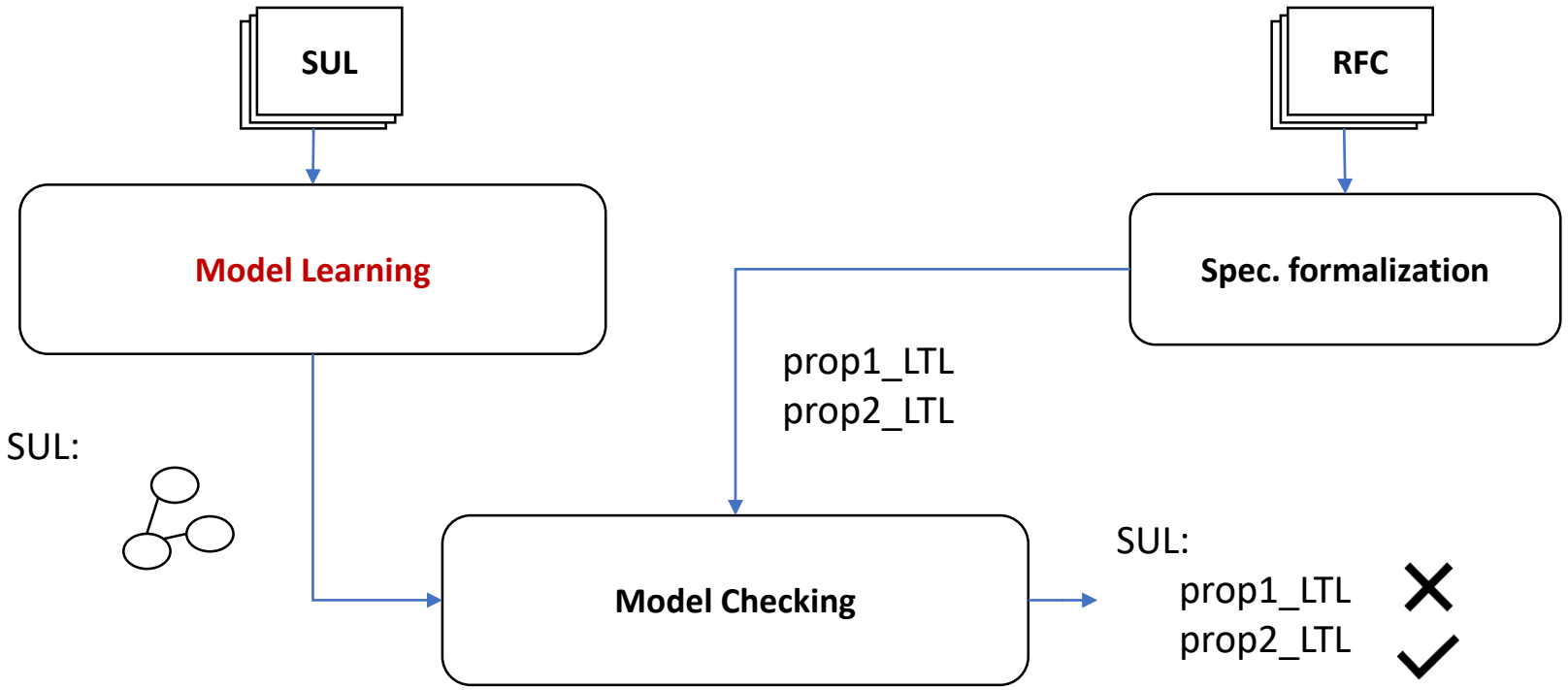
Patrick's M. Thesis

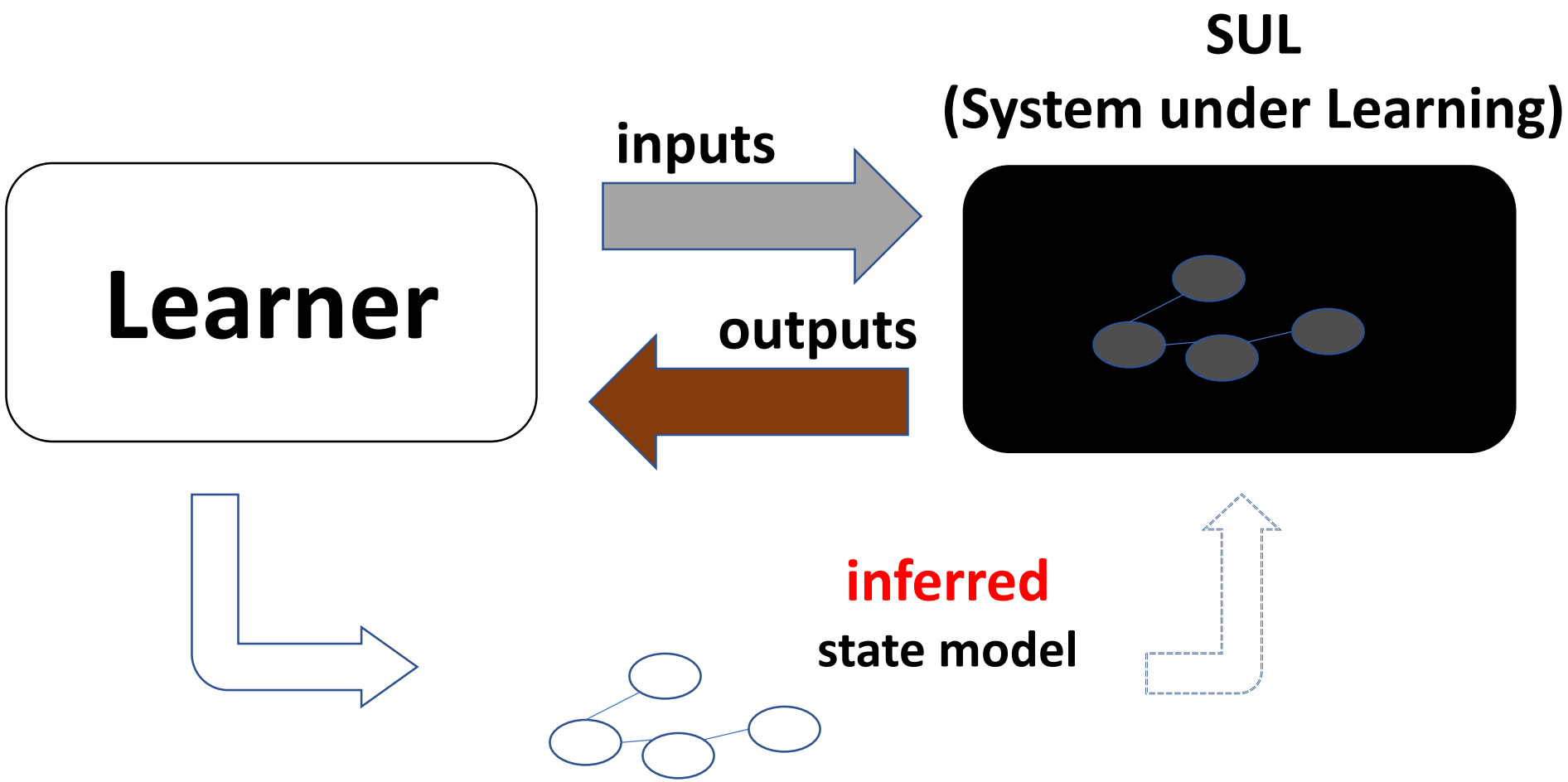
Toon's B. Thesis

Publication

What was done

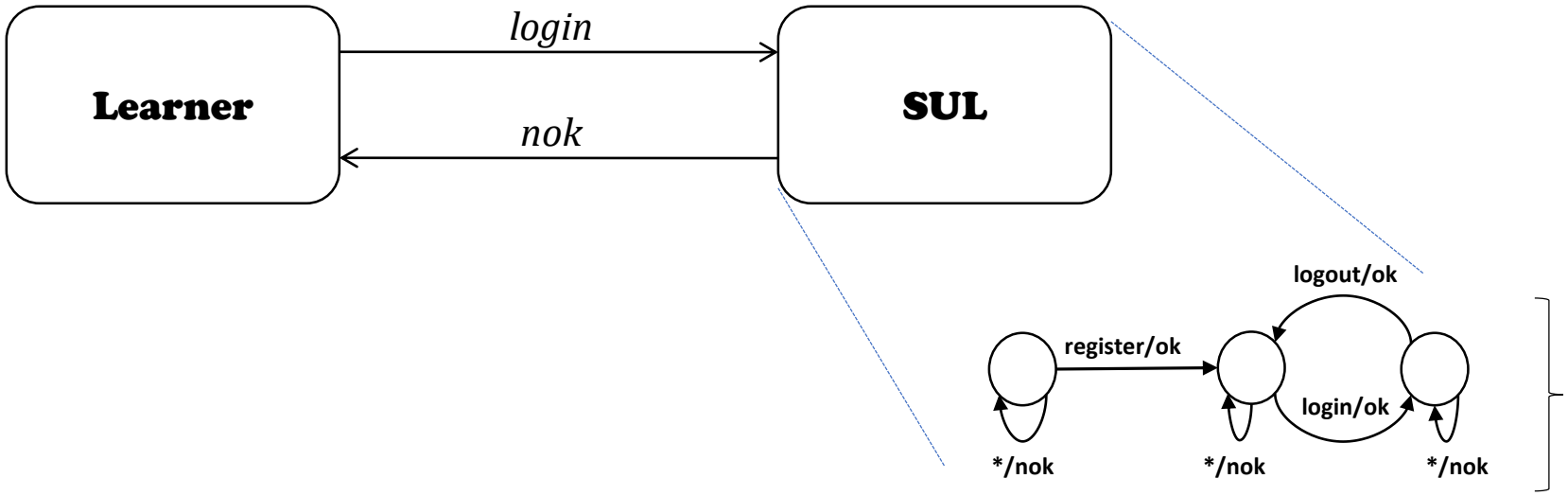


Model Learning



Model Learning

Learner Queries:
register/ok



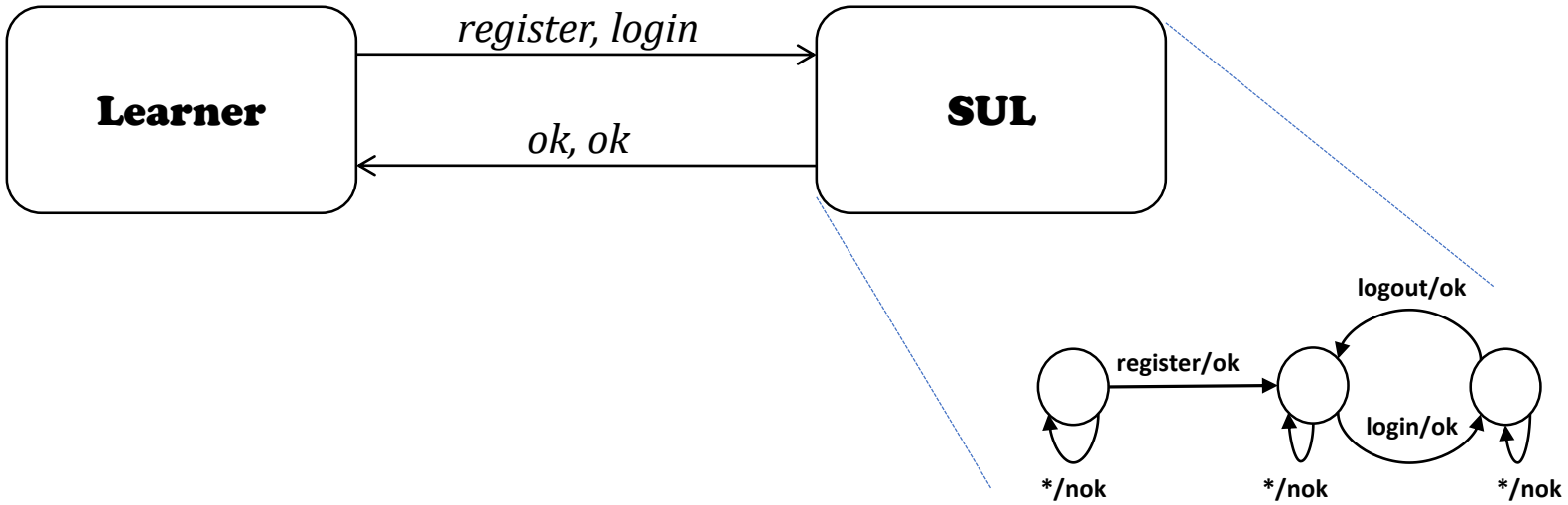
Mealy Machine

Input Alphabet:
[register, login, logout]
Output Alphabet: [ok, nok]

Model Learning

Learner Queries:

register/ok
login/nok
logout/nok
register/ok register/nok



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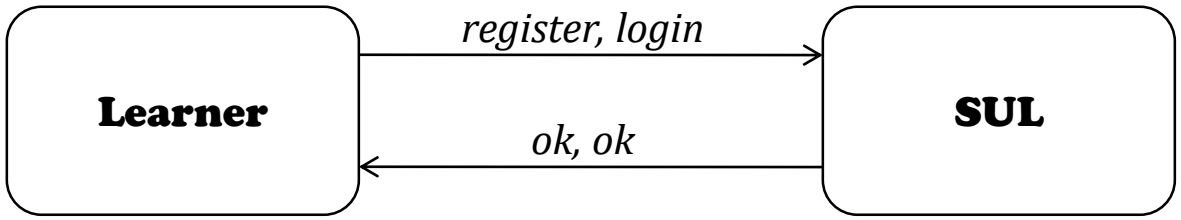
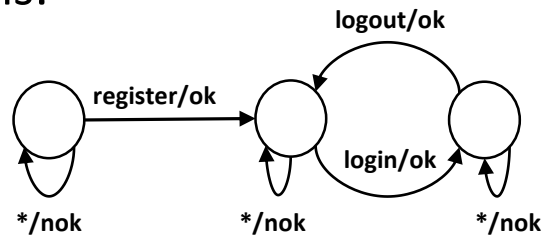


Hypothesis:



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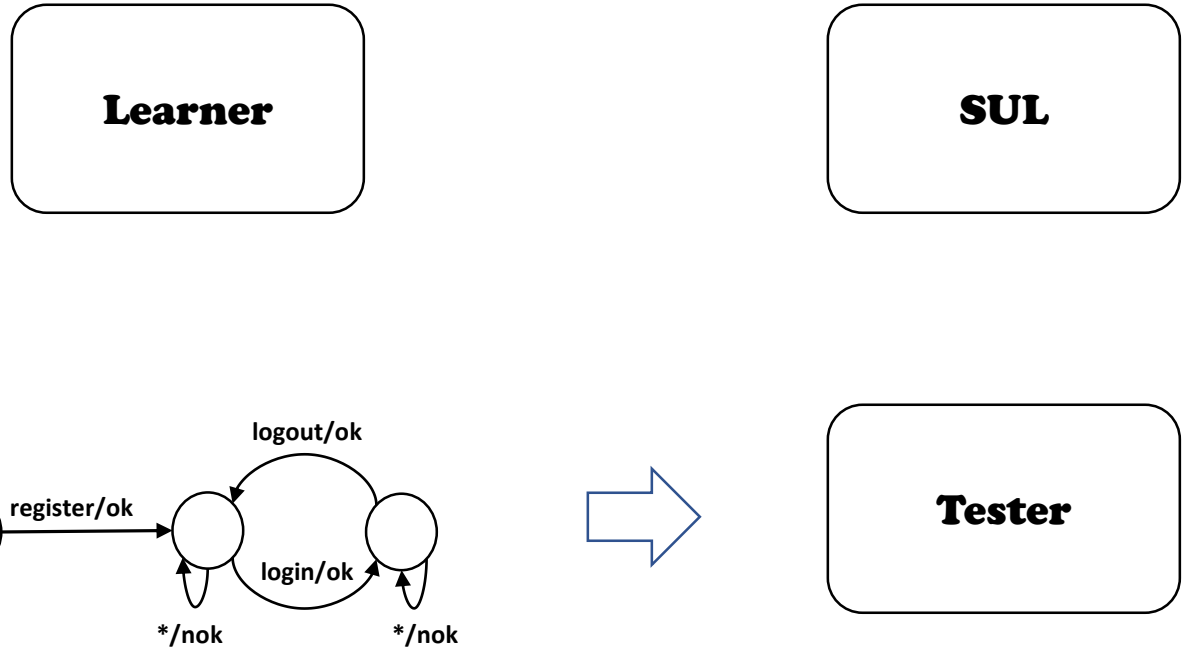
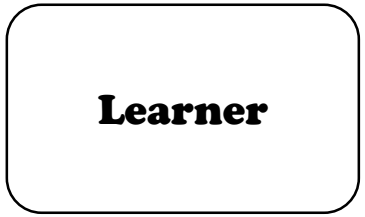
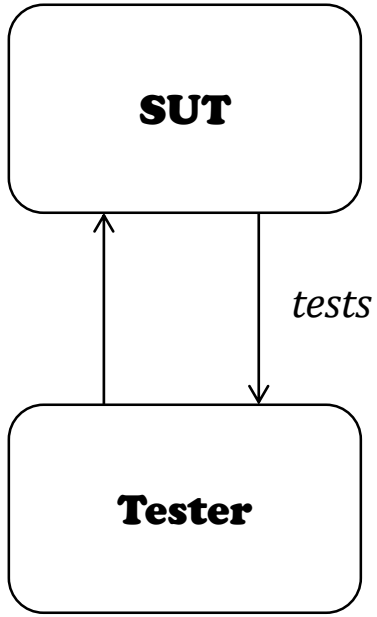


Model Learning

Test Queries:
register register login/ok nok nok





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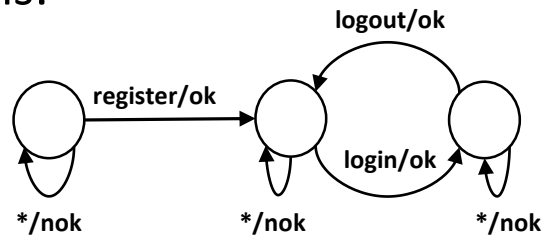

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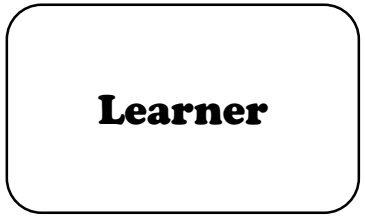

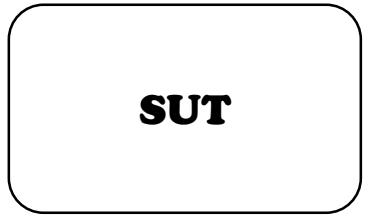

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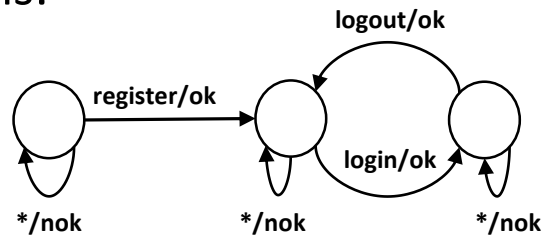

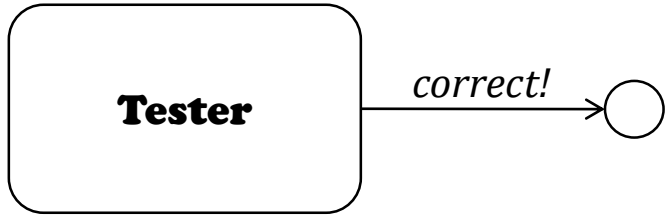

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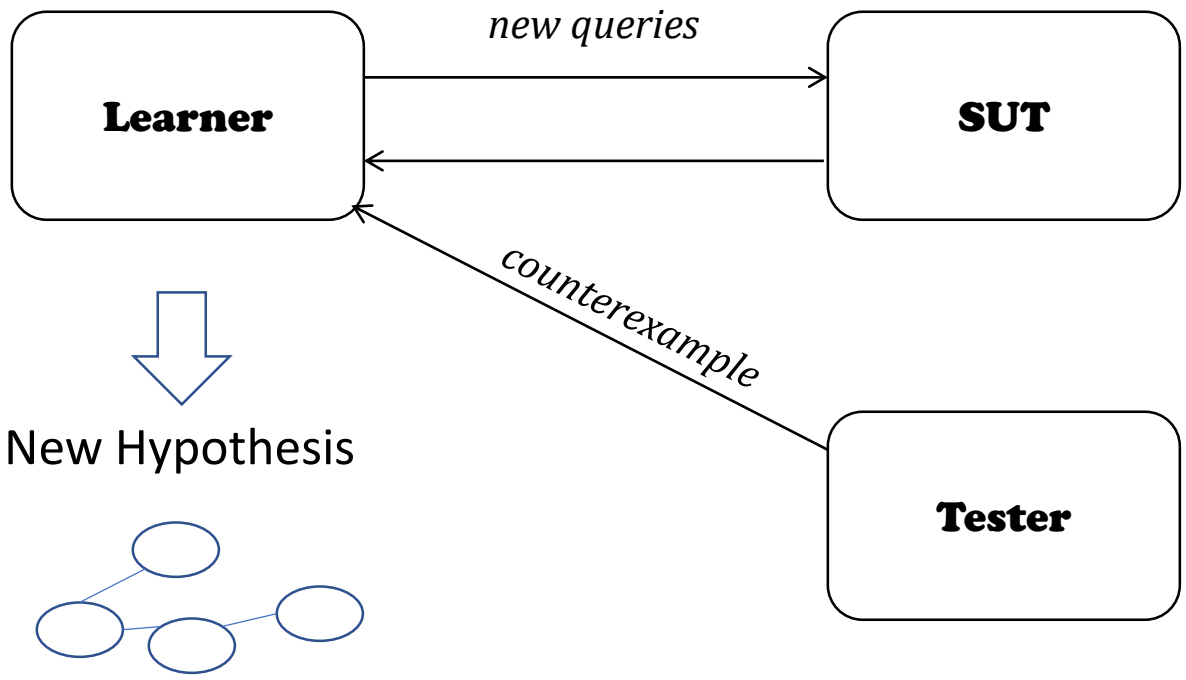

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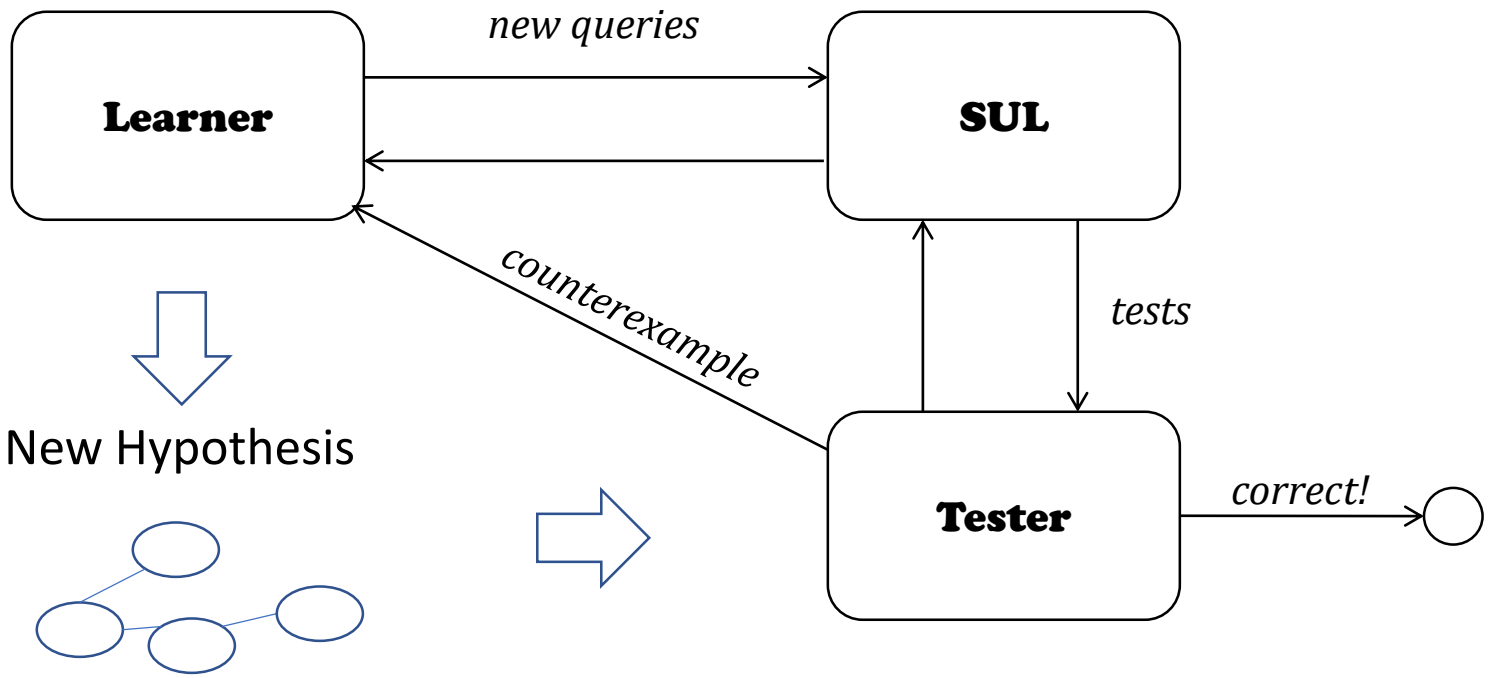

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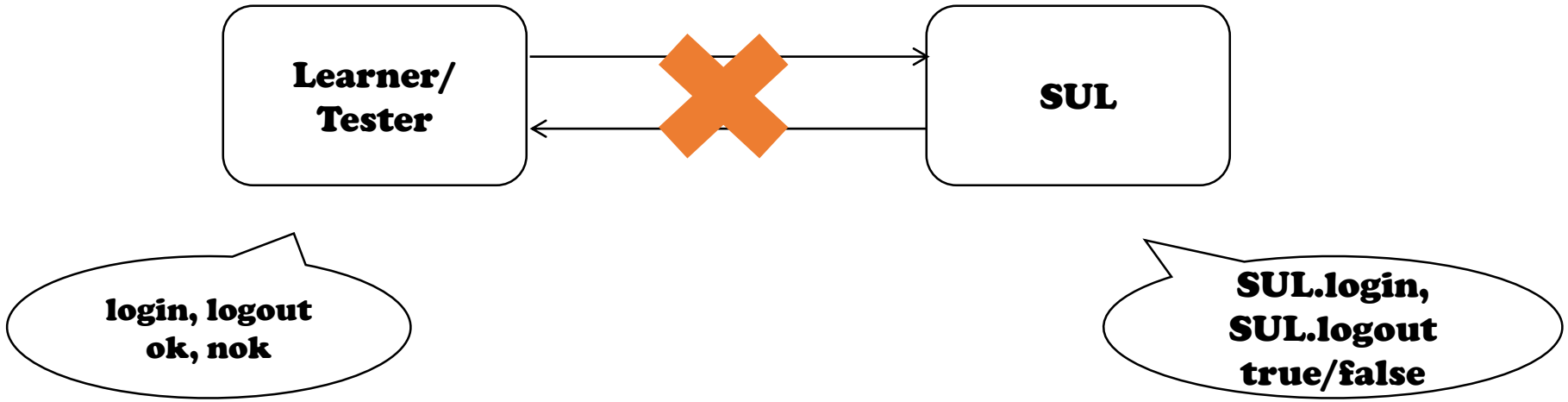
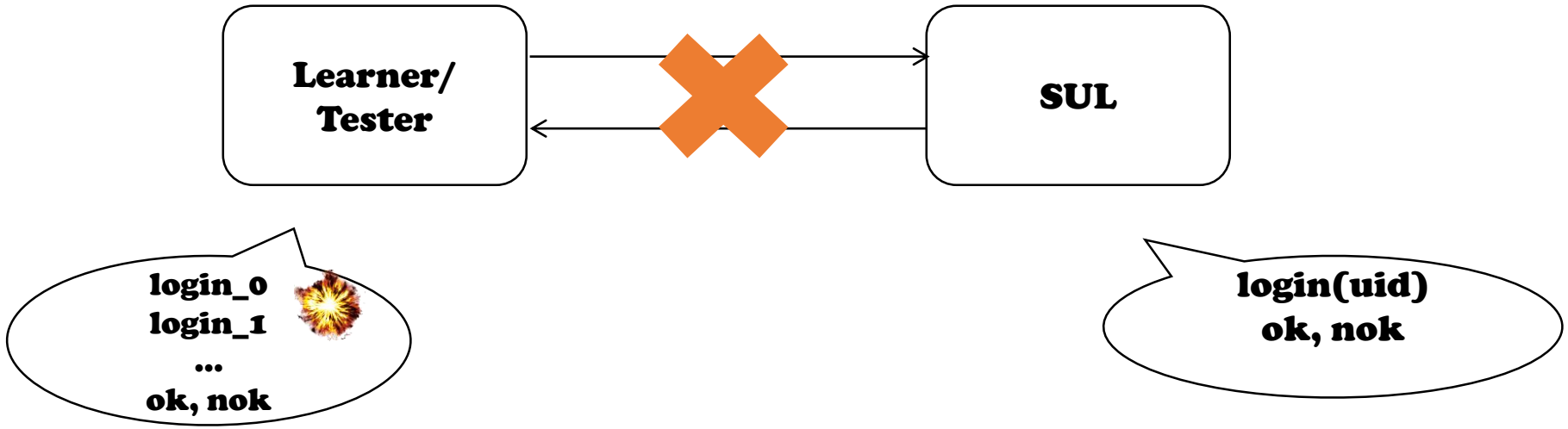


abstract i/o
(strings)

concrete i/o
method calls,
returned obj.
packets

Model Learning

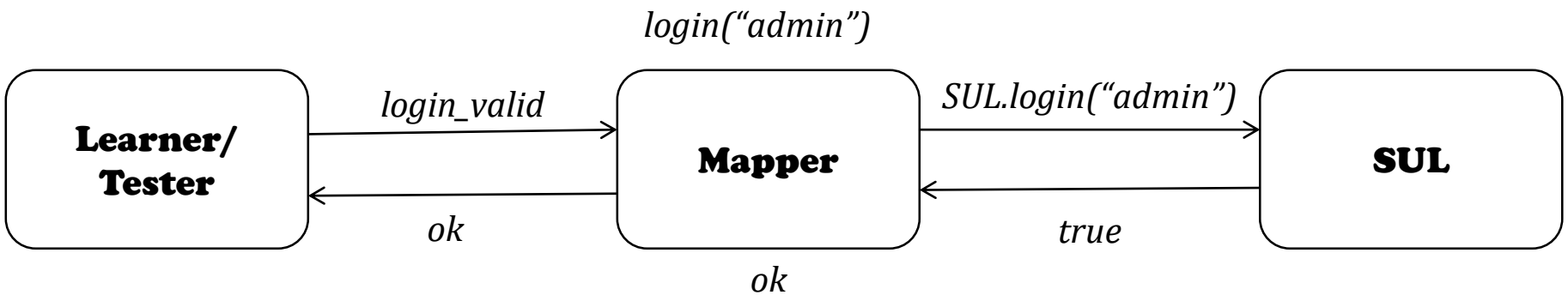


small abstract
i/o alphabet

parameterized
i/o alphabet

Model Learning

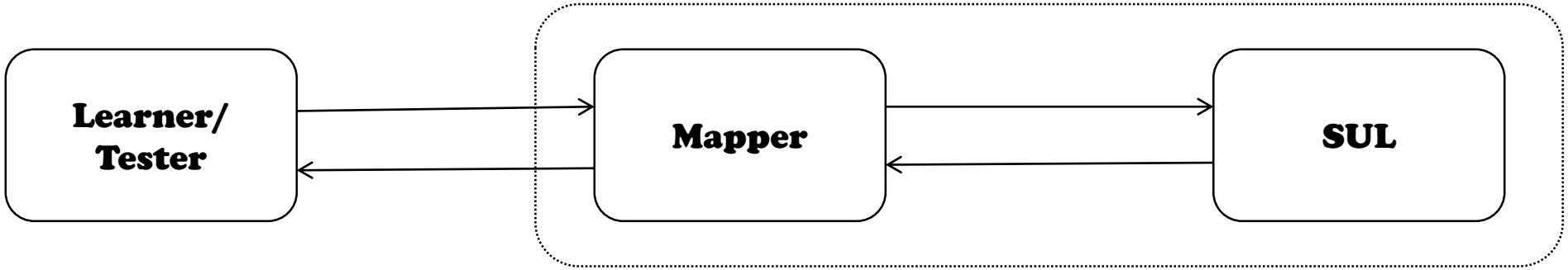
abstract i/o param i/o concrete i/o



Mapper

1. translates:
   - between abstract and param. i/o
   - between param. i/o and concrete i/o

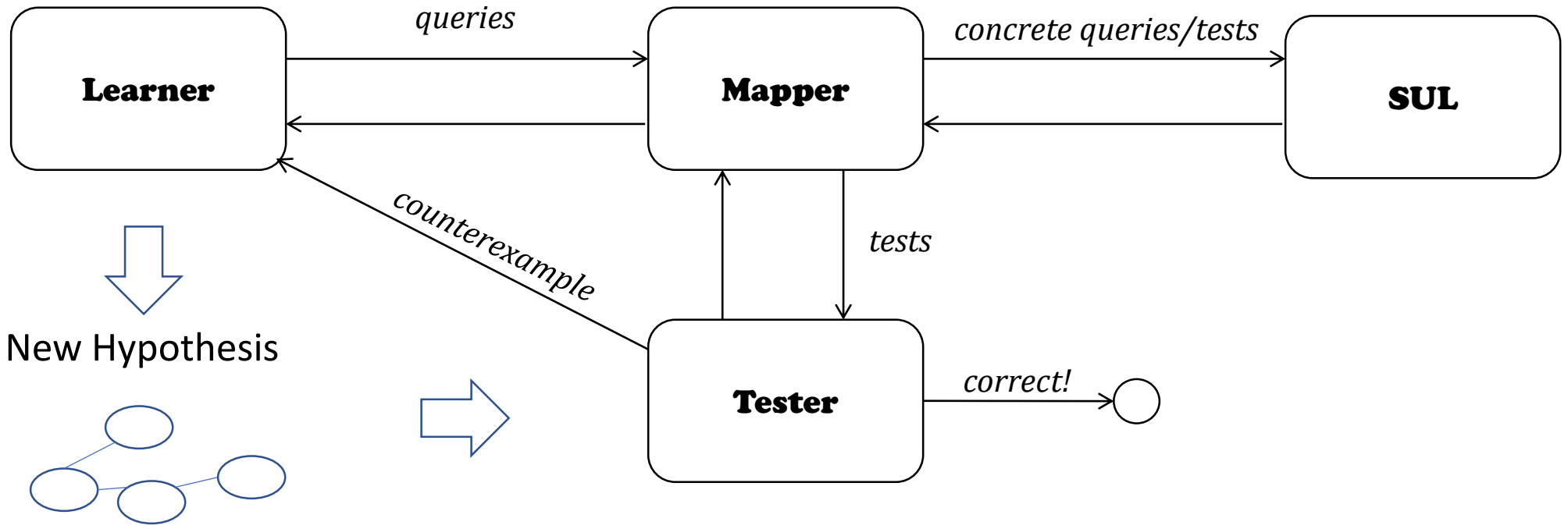
Model Learning

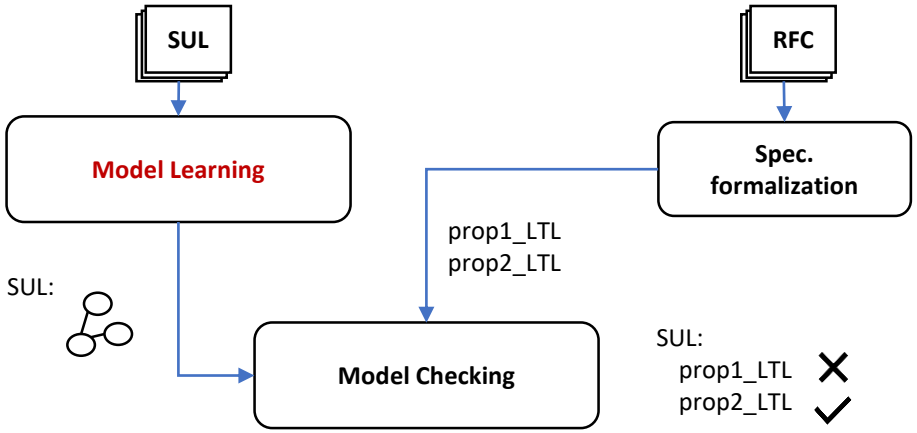


Mapper

1. translates:
   - between abstract and param. i/o
   - between param. i/o and concrete i/o
2. gives a (deterministic) Mealy Machine representation
   - removes time dependencies, non-determinism..

Model Learning





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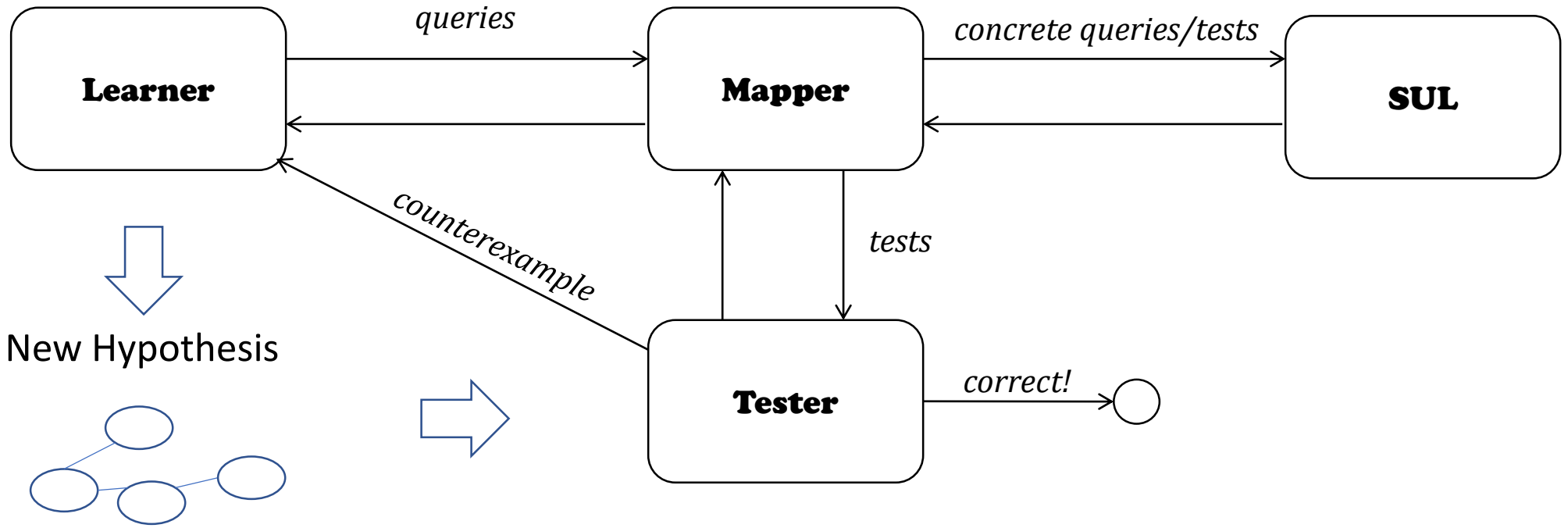

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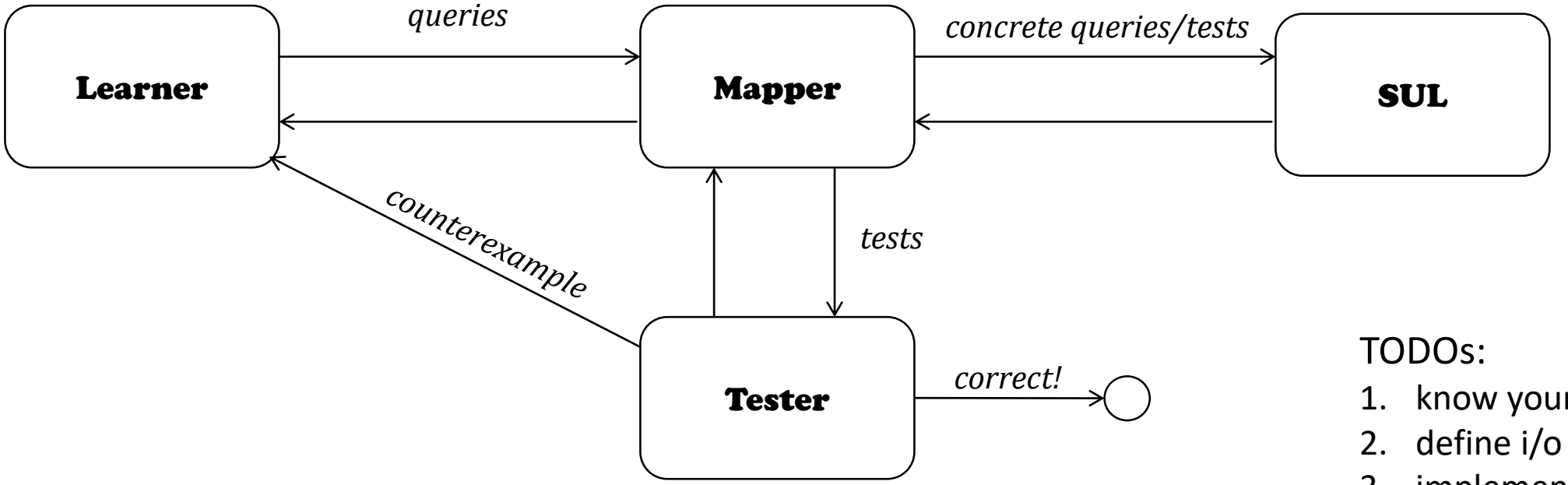
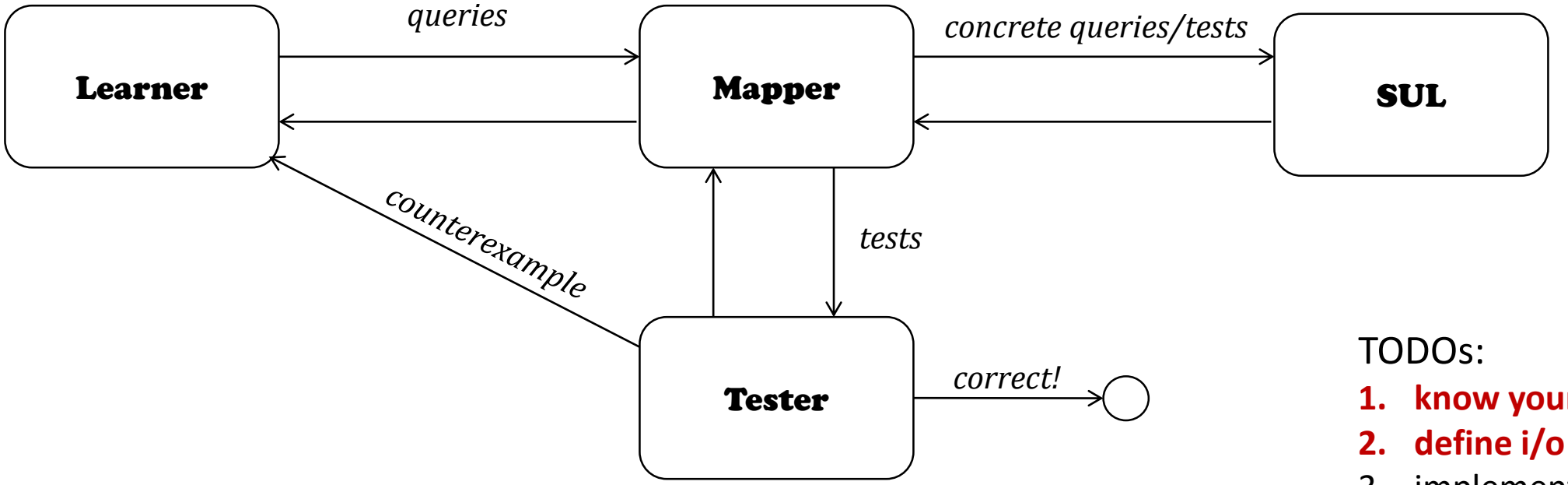


TODOs:

1. know your SUL
2. define i/o alphabet
3. implement mapper
4. choose learner and tester algorithms
5. connect and execute!

Model Learning



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The SSH Protocol

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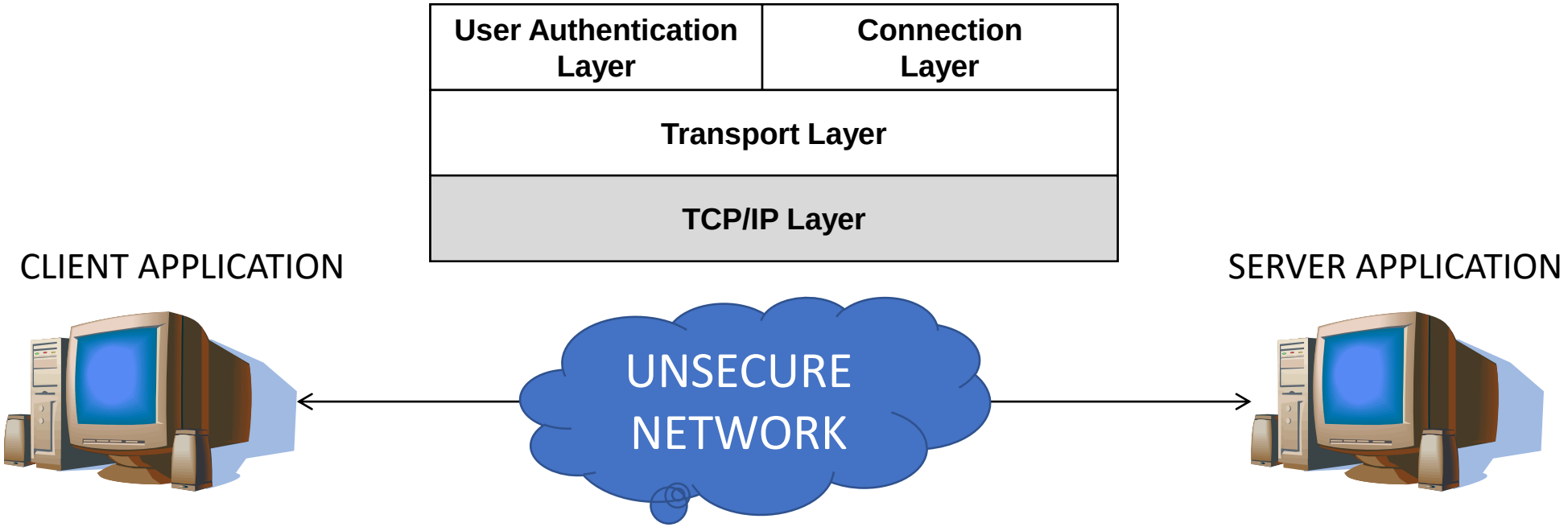
- client/server application layer protocol, runs on top of TCP
- Learner + Mapper replaces the SSH CLIENT, goal learn the SSH Server!

The SSH Protocol

- comprises three layers which *interoperate (no encapsulation)*
- each layer responsible for each of the 3 protocol steps,
- for each we define the *happy flow* at an abstract level



The SSH Protocol

- 3 steps
  1. establish a secure connection (by exchanging keys)

User Authentication Layer	Connection Layer
Transport Layer	
TCP/IP Layer	

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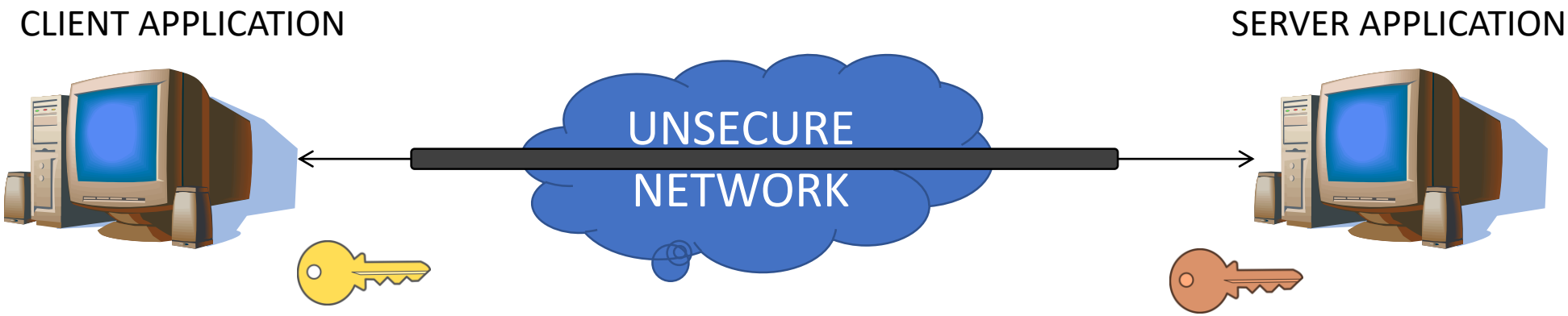

The SSH Protocol

User Authentication Layer	Connection Layer
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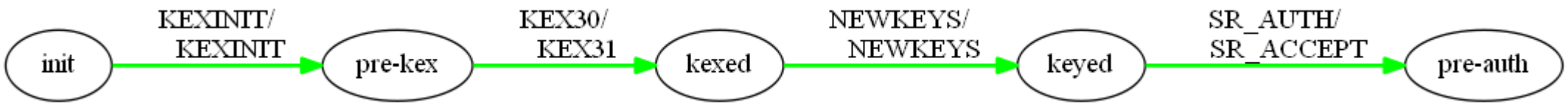
- 3 steps
  1. establish a secure connection (by exchanging keys)

     1. exchange preferences (KEXINIT)
     2. perform key exchange (KEXxx)
     3. put new keys to use (NEWKEYS)
     4. engage the auth. service (SR_AUTH)

Happy flow:



Other inputs: DEBUG, IGNORE, DISCONNECT..
Other outputs: DEBUG, IGNORE, DISCONNECT..

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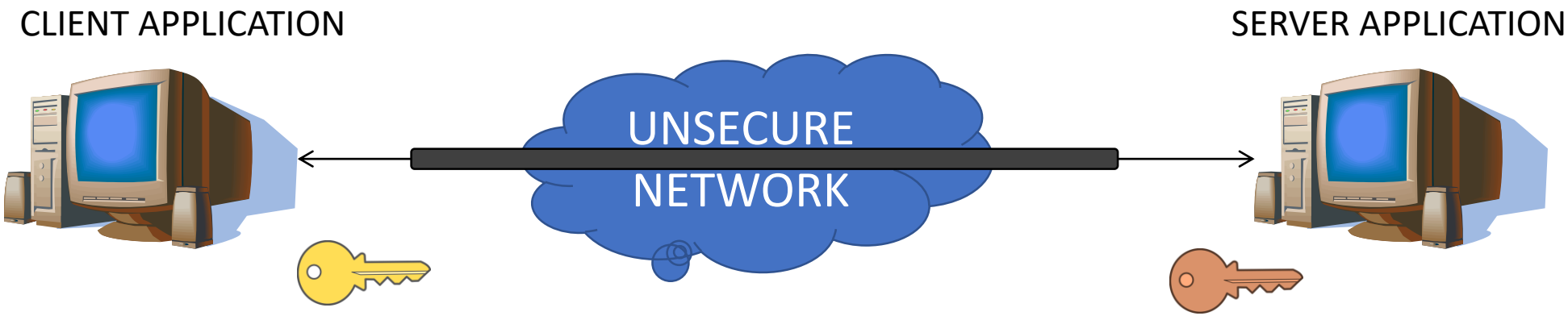

The SSH Protocol

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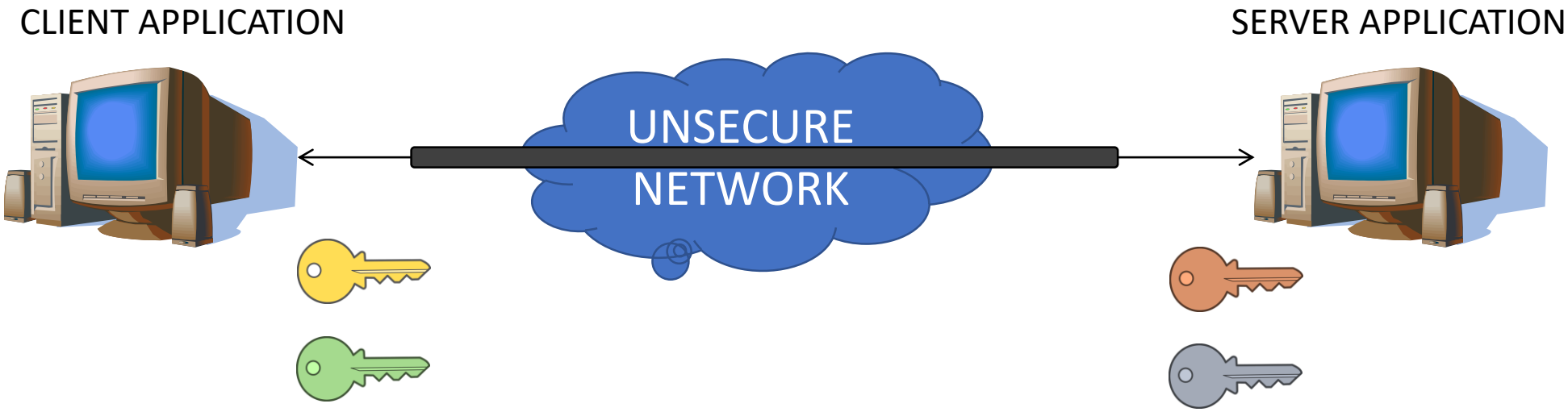
- 3 steps
  1. establish a secure connection (by exchanging keys)

     key re-exchange (rekey): same procedure, old keys

     are replaced by new ones

     can happen any time after the initial key exchange protocol

     should not affect operation of higher layer protocols



The SSH Protocol

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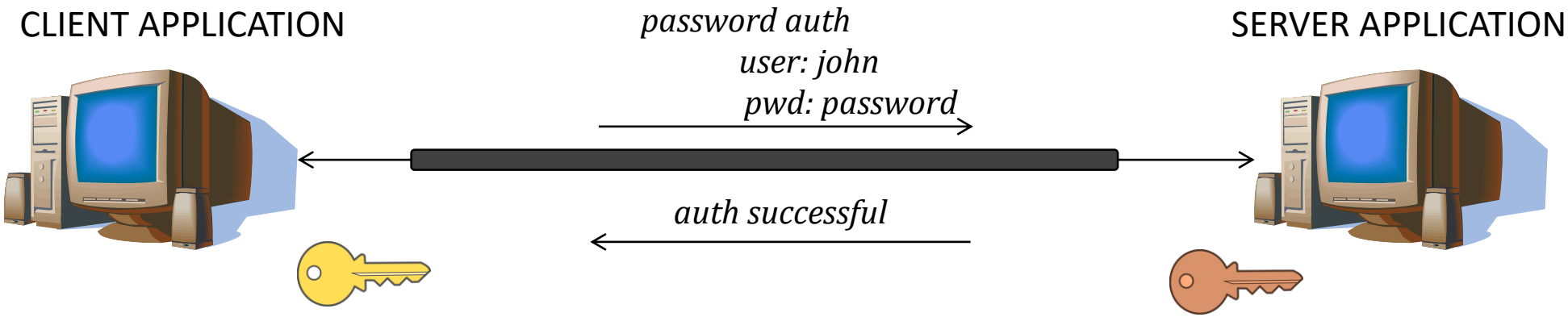
- 3 steps
  1. establish a secure connection (by exchanging keys)
  2. authentication with server



The SSH Protocol

User Authentication Layer	Connection Layer
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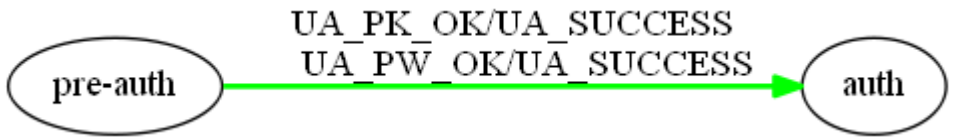
- 3 steps
  1. establish a secure connection (by exchanging keys)
  2. authentication with server
     - user/public key auth. UA_PK_OK
     - user/password auth. UA_PW_OK
     - none auth. UA_NONE

Happy flow:



Other inputs: UA_NONE, UA_PK_NOK, UA_PW_NOK…
Other outputs: UA_FAILURE

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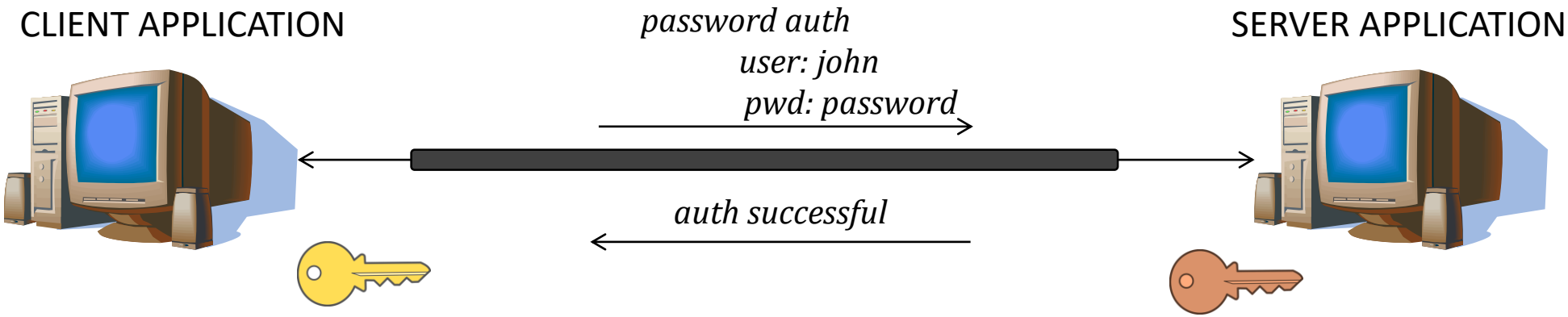

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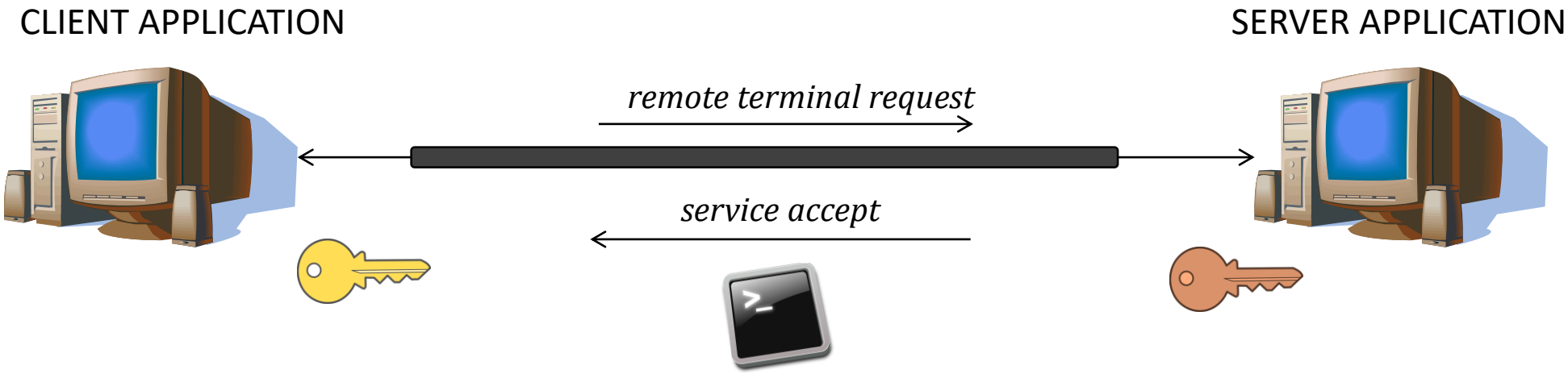
  3. access network services (say remote terminal)

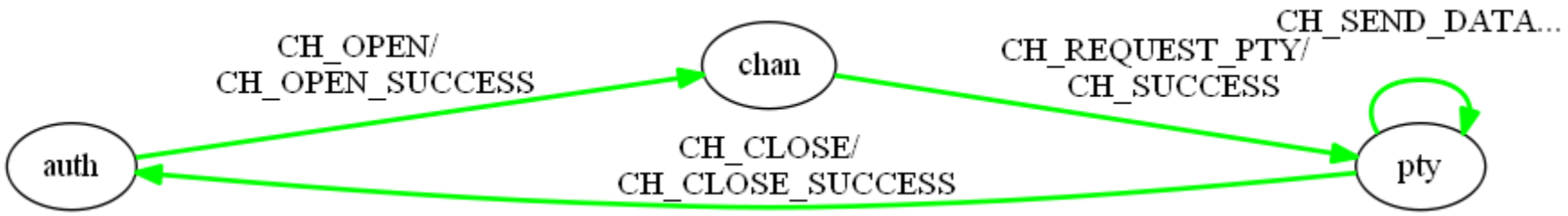


Learning SSH

User Authentication Layer	Connection Layer
Transport Layer	
TCP/IP Layer	

- 3 steps
  1. establish a secure connection (by exchanging keys)
  2. authentication with server
  3. access network services (say remote terminal)

     1) open channel (CH_OPEN)
     2) request term. service over channel (CH_REQUEST_PTY)
     3) channel data management (CH_SEND_DATA)
     4) close channel (CH_CLOSE)



Learning SSH

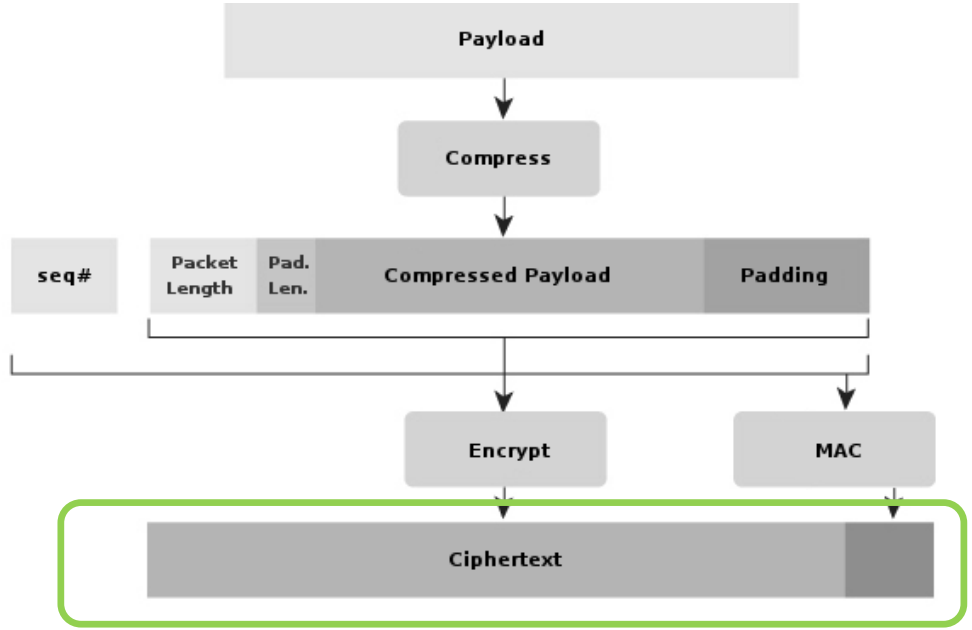
TODOs:

1. know your SUL
2. define i/o alphabet
3. **implement mapper**
4. choose learner and tester algorithms
5. connect and execute!

Mapper task

1. *translate between abstract, parametrized and concrete i/o*

AUTH_PW_OK AUTH_REQUEST(“password”, “john”…)



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Mapper task

1. *translate between abstract, parametrized and concrete i/o*
   - *needs to be able to encrypt/decrypt compress/decompress*
   - *stores information in variables: encryption keys, session ID, sequence number…*

     ➔ *implemented by adapting an existing SSH suite implementation (Paramiko)*

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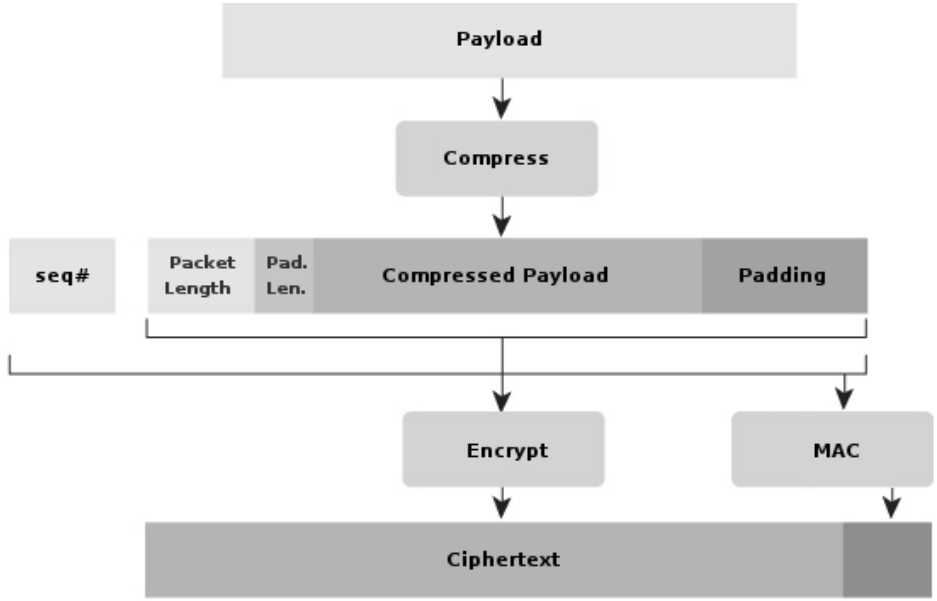

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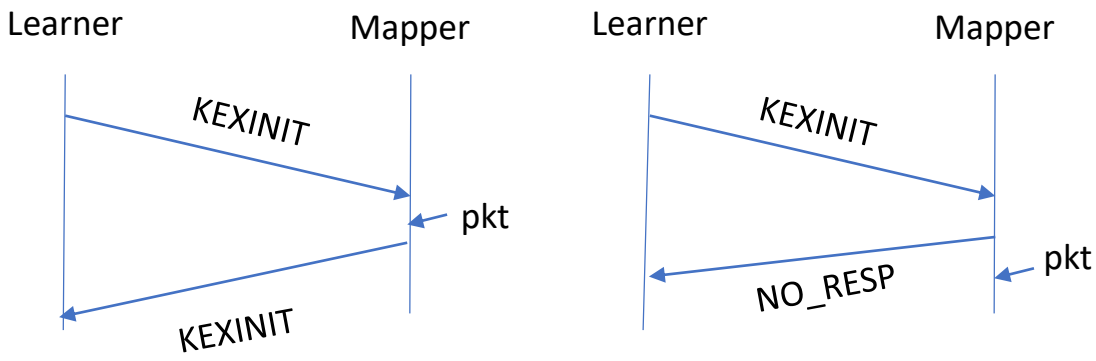
   - *reliable setting of timing parameters (e.g. NO_RESP timing parameter)*



false NO_RESP, mapper should have waited longer

Learning SSH

TODOs:
1. know your SUL
2. define i/o alphabet
3. **implement mapper**
4. choose learner and tester algorithms
5. connect and execute!

Mapper task

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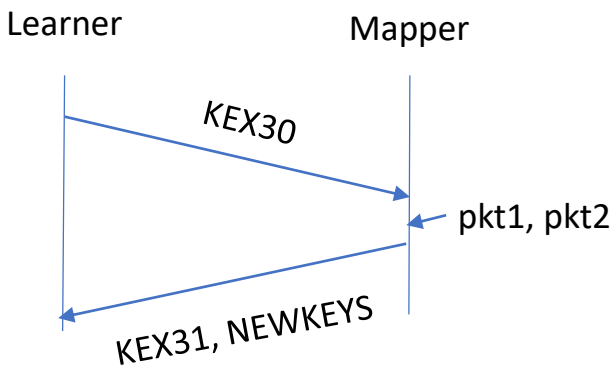

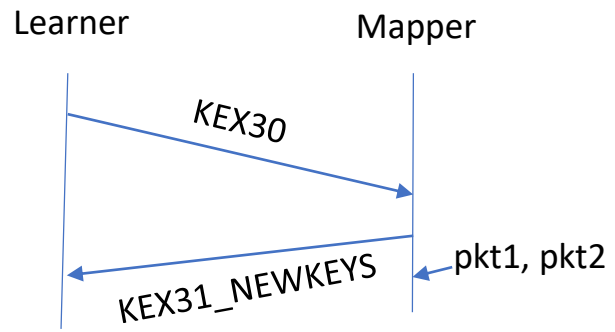

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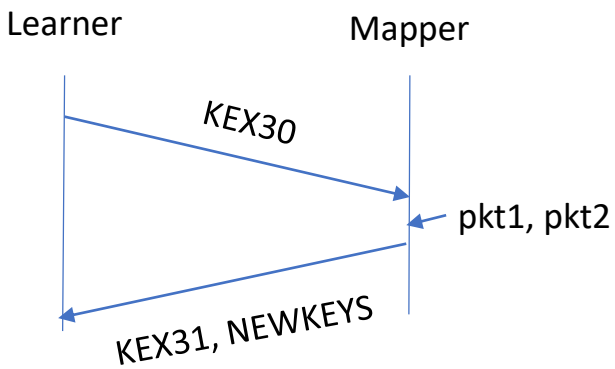

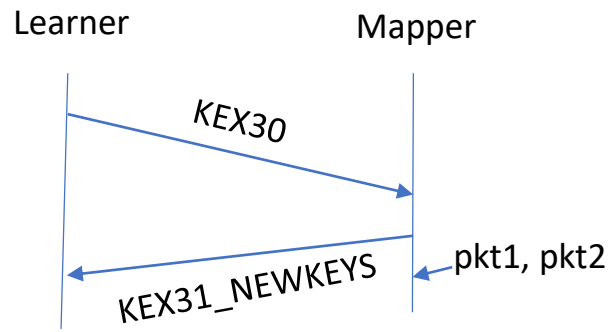

Learning SSH

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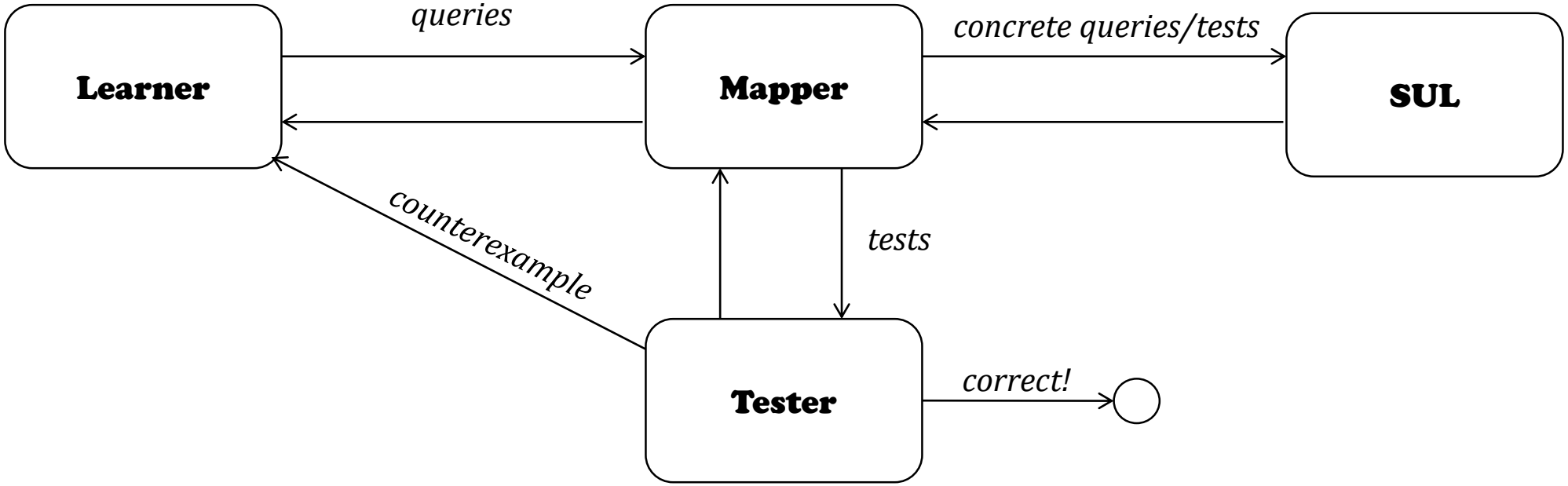
LearnLib algorithms:

L* , **Observation Pack**



Tester Algorithms:

Random Walk, W Method,

Yannakakis (Random + Exhaustive)

Learning SSH

TODOs:

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2. define i/o alphabet
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4. **choose learner and tester algorithms**
5. connect and execute!

Note on testing:

- testing can never guarantee correctness
- exhaustive test algs. ensure a well defined level of confidence
  - *but lack penetration*
- random test algs. have penetration ➔ more likely to find CEs
  - *but give no formal confidence*

Learning SSH

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5. connect and execute!

Example Yannakakis

→random:

- choose bigger k
- random mid sequences

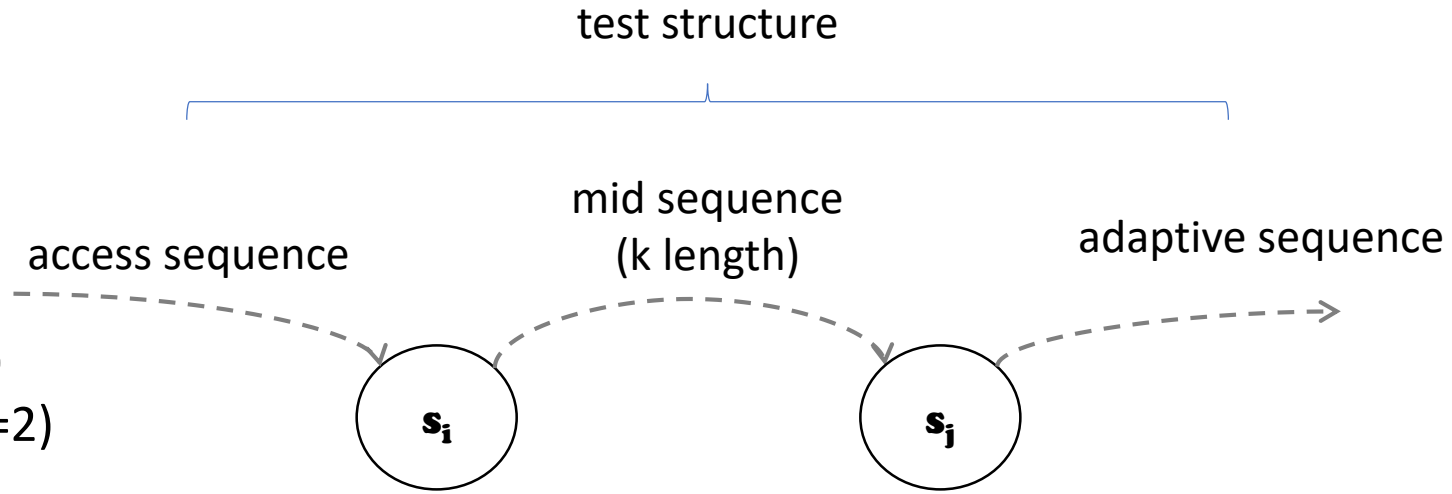
→exhaustive

- choose smaller k
- generate for all mid-sequences
- attain confidence

We used:

Random Yannakakis(k=4)

Exhaustive Yannakakis(k=2)



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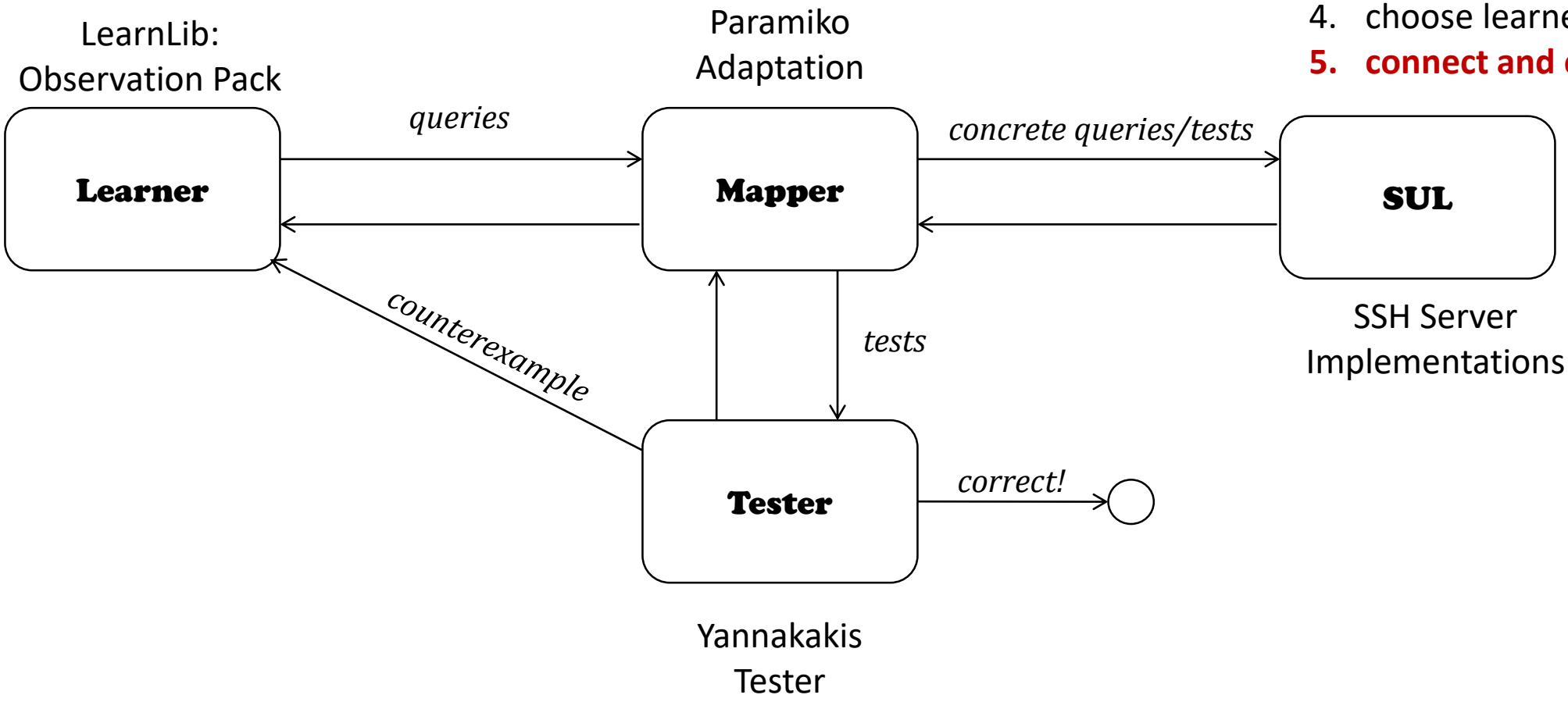
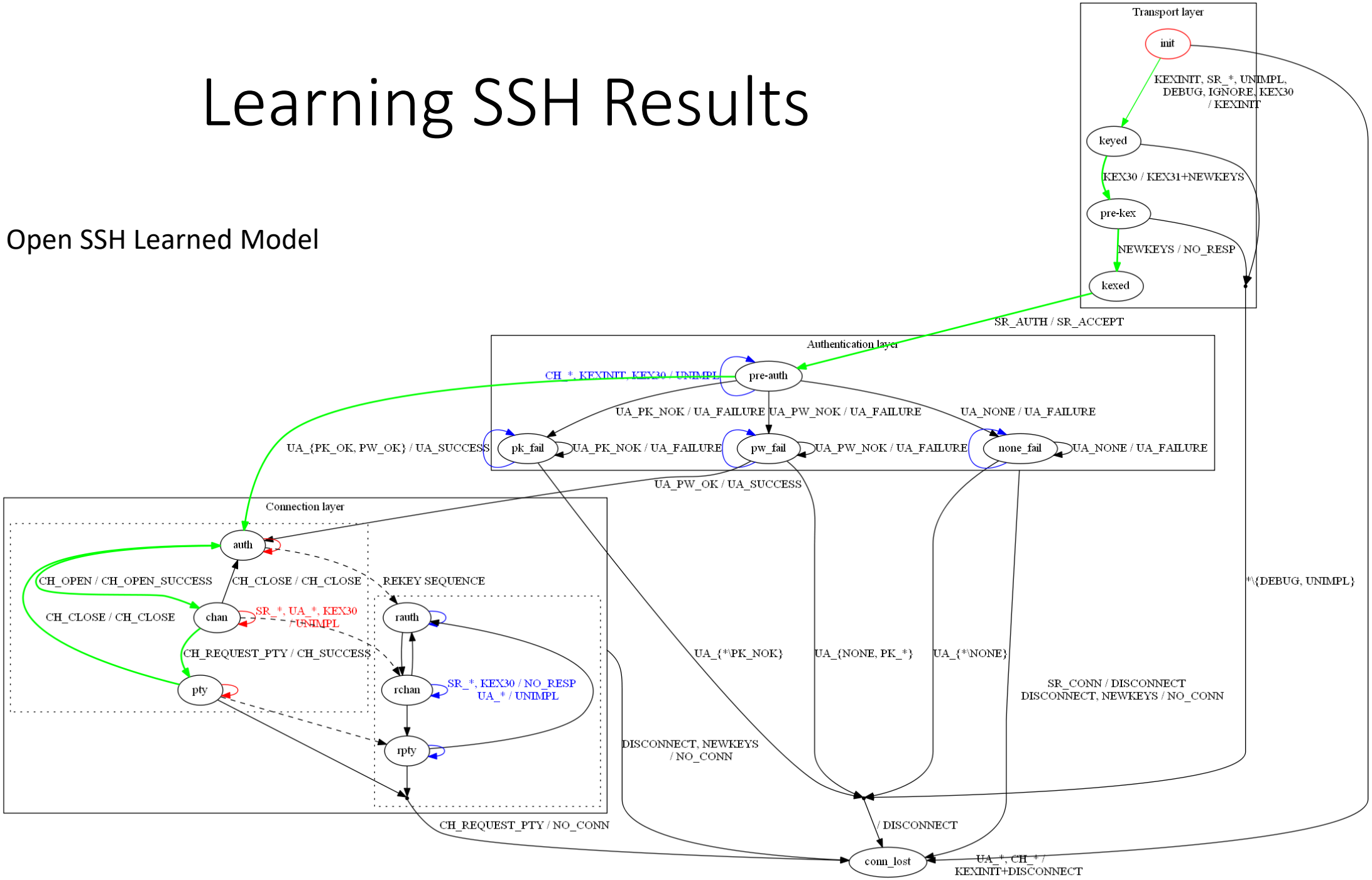


Learning SSH Results

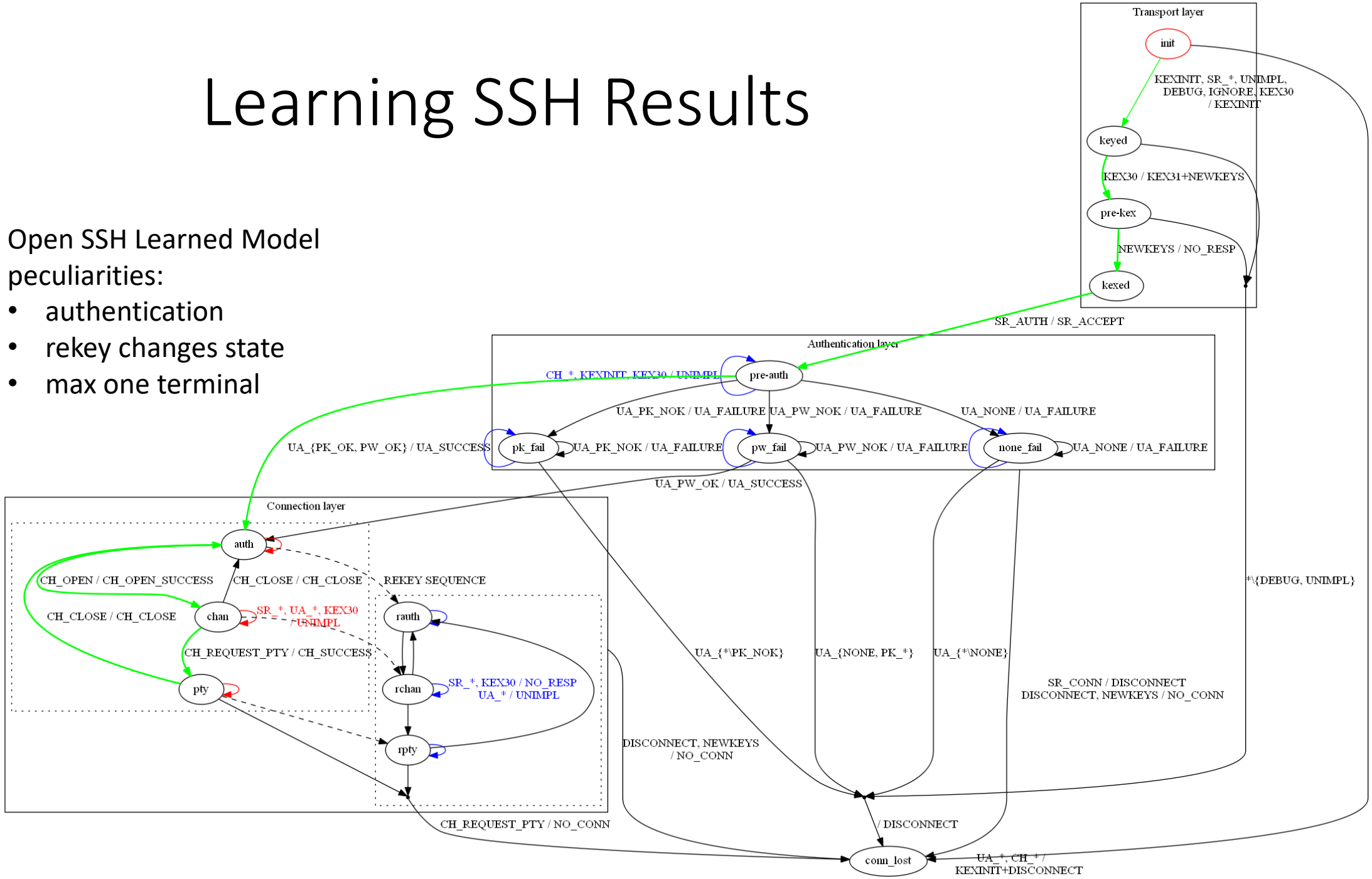
Open SSH Learned Model



Learning SSH Results

Open SSH Learned Model peculiarities:

- authentication
- rekey changes state
- max one terminal



Learning SSH Results

SUT	States	Hypotheses	Mem. Q.	Test Q.
OpenSSH 6.9p1-2	31	4	19836	76418
BitVise 7.23	65	15	24996	58423
DropBear v2014.65	29	8	8357	64478

- rekey (3 step sequence)
- buffering
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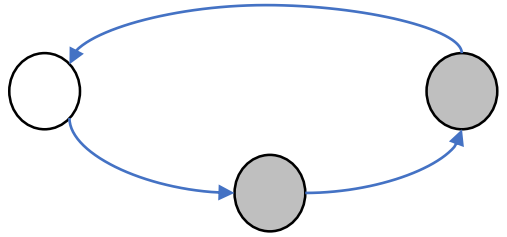

state permitting rekey

rekey state

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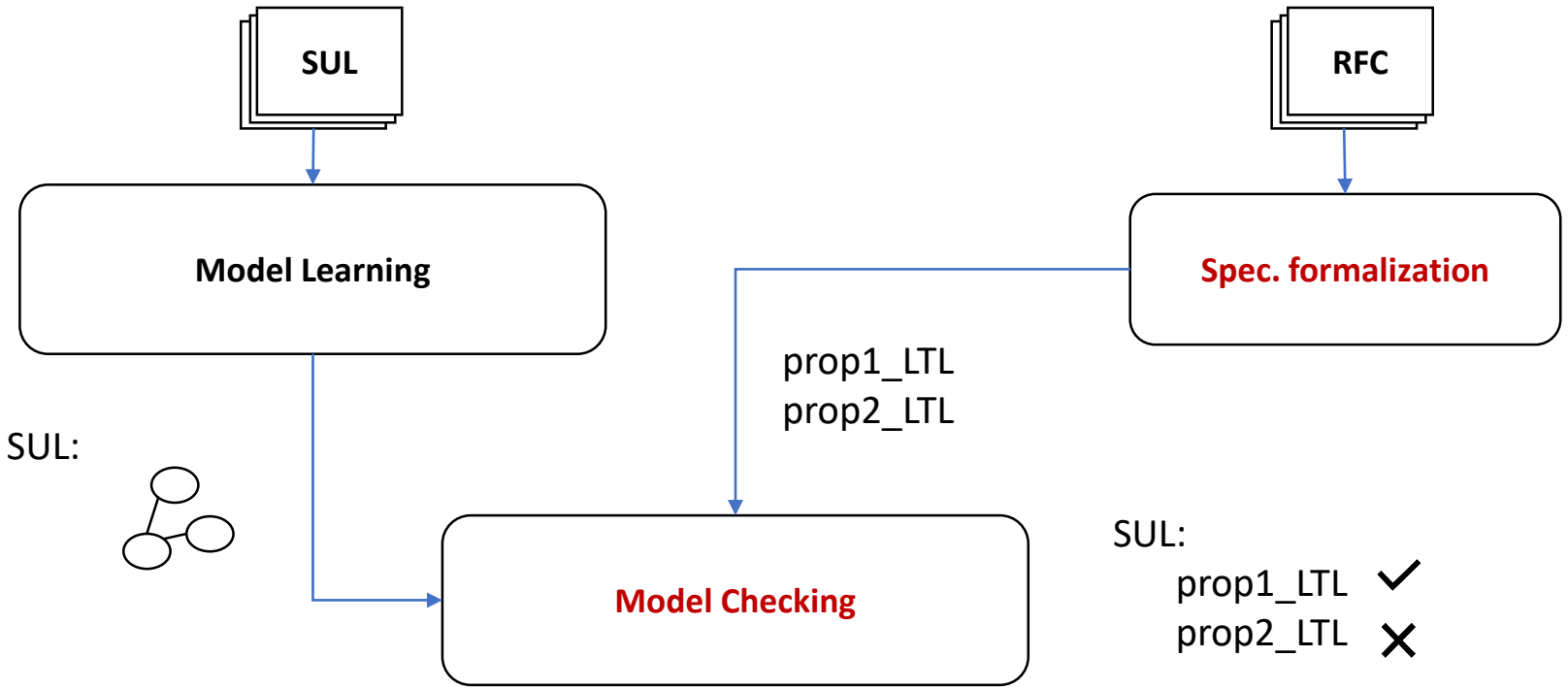
- rekey (3 step sequence)
- buffering
- **mapper induced behavior**
  - remember, we learn SUL + mapper, not SUL alone

What was done



Model Checking

- we used NuSMV:
  - supports LTL, CTL and Real Time CTL specifications
  - requires conversion to a .SMV model

Model Checking

- we used NuSMV:
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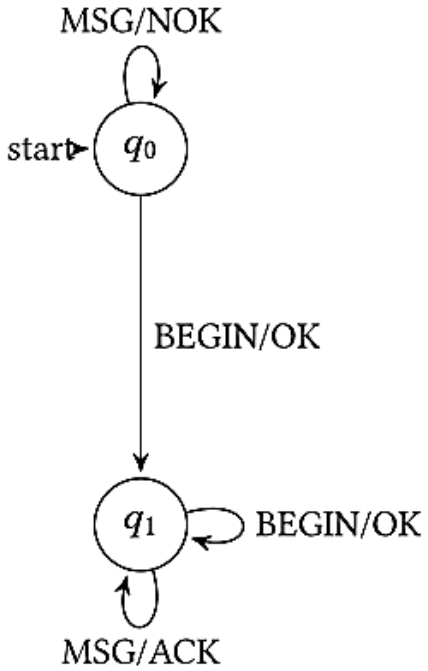
  - requires conversion to a .SMV model
  - wrote script to automatically perform this conversion

Mealy Machine



NuSMV Model

```
MODULE main
  VAR state : {q0, q1};
  inp : {BEGIN, MSG};
  out : {OK, NOK, ACK};
  ASSIGN
  init(state) := q0;
  next(state) := case
    state = q0 & inp = BEGIN: q1;
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➔kripke structure with:
- state function(next)
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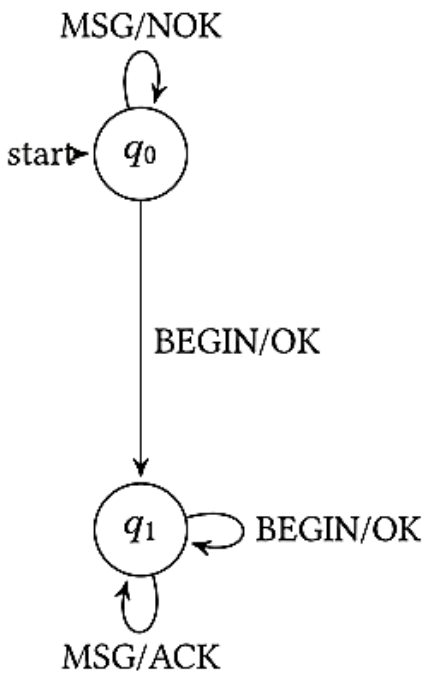

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➔kripke structure with:
- state function(next)
- output function(out)

G (inp=BEGIN -> out=OK)

G (out=OK ->
X (inp=MSG -> out=ACK))

G U (out=OK ->
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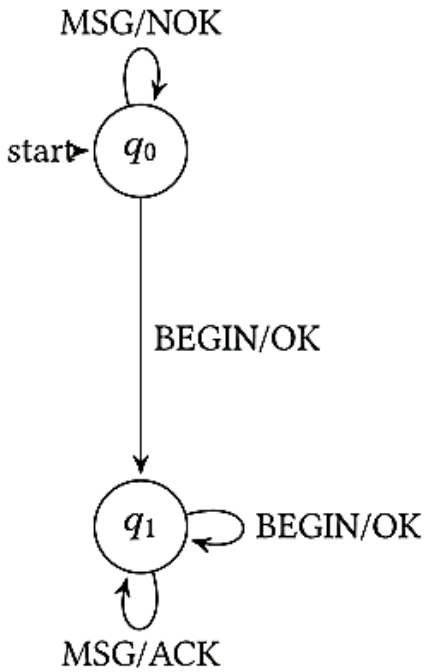

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➔kripke structure with:
- state function(next)
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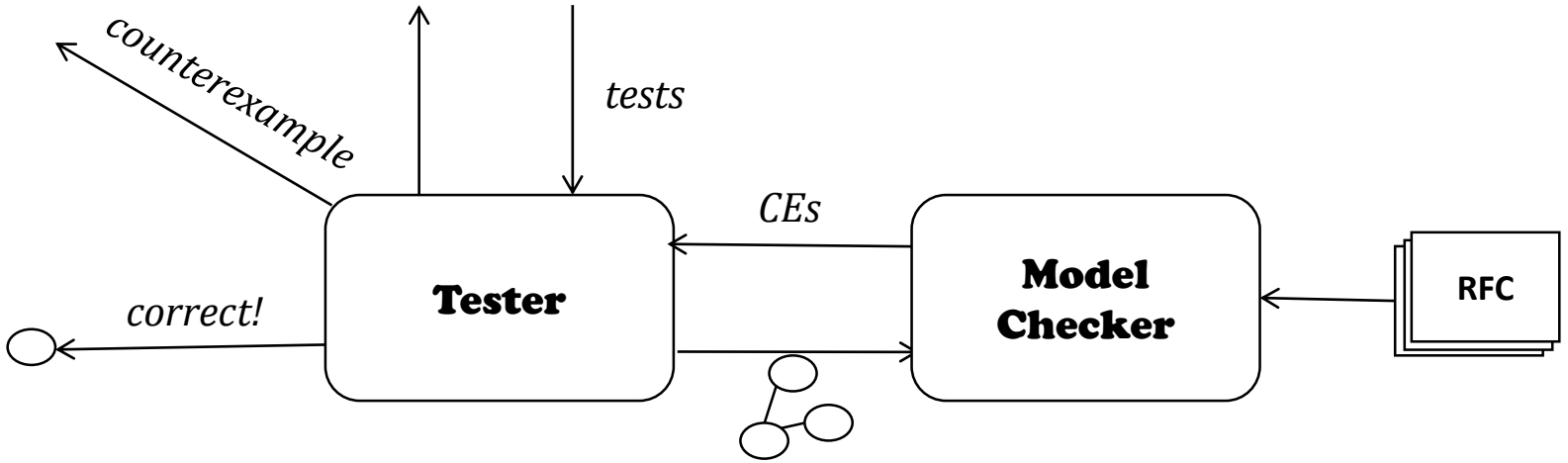
G (inp=BEGIN -> out=OK) ✓

G (out=OK ->
X (inp=MSG -> out=ACK)) ✓

G U (out=OK ->
X (inp=MSG -> out=NOK)) ✗

Model Checking

- we used NuSMV:
  - supports LTL, CTL and Real Time CTL specifications
  - requires conversion to a .SMV model
- specification either holds or counterexample (CE) given
  - CE may
    - agree with the SUL ➔ non-conformance
    - disagree with the SUL ➔ a CE for the learner
  - thus, all CEs must first be confirmed by running it on the system
    - integrated model checker into testing s.t. all CEs are confirmed



Formalizing SSH Specifications

- LTL formulas with both forward and past modalities
- checked on the mapper + SUL assembly (not only on the SUL itself), thus
  results not fully translatable
- 4 types:
  - basic properties: describe the SUL + mapper setup, all true
  - security properties: define the overriding goal of each layer
  - rekey properties: is rekey allowed (does it not disconnect)
    does rekey preserve state?
  - functional properties: are MUST/SHOULD statements met

Formalizing SSH Specifications

Only one SSH connection is made
and once it is gone, it is gone.

- basic properties
- security properties
- rekey properties
- functional properties

connection
is gone

mapper outputs
(w/o SUL intervention)

G (out=NO CONN – >
G (out=NO CONN | out=CH MAX | out=CH NONE))

SUL no longer responds

Formalizing SSH Specifications

We consider an transport layer state machine secure if there is:

no path from the initial state to the point where the authentication service is invoked without exchanging and employing cryptographic keys.

- basic properties
- security properties
- rekey properties
- functional properties

G (hasReqAuth – >
O ((inp=NEWKEYS & out=NO RESP) &
O ((inp=KEX30 & out=KEX31_NEWKEYS) &
O (out=KEXINIT))))

Formalizing SSH Specifications

SSH_MSG_CHANNEL_CLOSE
Upon receiving this message, a party MUST send back an SSH_MSG_CHANNEL_CLOSE unless it has already sent this message for the channel.
(RFC 4254, p 9)

- basic properties
- security properties
- rekey properties
- functional properties

G (hasOpenedChannel – >
((inp=CH CLOSE) – > (out=CH CLOSE))
W (connLost | kexStarted | out=CH CLOSE))

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→ in red, predicates not expressed in RFC statement, yet deducted from context
→ formalization forces clarification

Formalizing SSH Specifications

SSH_MSG_USERAUTH_SUCCESS MUST be sent only once.
(RFC 4252 p. 5)

G (out=UA SUCCESS − > X G out != UA SUCCESS)

- basic properties
- security properties
- rekey properties
- functional properties

SSH_MSG_USERAUTH_SUCCESS has been sent, any further authentication requests received after that SHOULD be silently ignored.
(RFC 4252 p. 5)

G (out=UA SUCCESS − >
X ((authReq − > out=NO RESP) W (connLost | kexStarted)))

Formalizing SSH Specifications

key exchange does not affect the protocols that lie above the SSH transport layer.
(RFC 4253 p. 24)

- basic properties
- security properties
- rekey properties
- functional properties

- state based property:
  - ➔ cannot be efficiently formulated by LTL
  - ➔ checked using script

Model Checking Results

	Property	Key word	OpenSSH	Bitvise	DropBear
Security	Trans.		✓	✓	✓
	Auth.		✓	✓	✓
Rekey	Pre-auth.		X	✓	✓
	Auth.		✓	X	✓
Funct.	Prop. 6	MUST	✓	✓	✓
	Prop. 7	MUST	✓	✓	✓
	Prop. 8	MUST	X*	X	✓
	Prop. 9	MUST	✓	✓	✓
	Prop. 10	MUST	✓	✓	✓
	Prop. 11	SHOULD	X*	X*	✓
	Prop. 12	MUST	✓	✓	X

← UA_SUCC once

← NO_RESP after UA_SUCC

(*X sends UNIMPL)

← CH_CLOSE after CH_CLOSE

Conclusions and Future Work

Conformance checking of the SSH protocol,
using model learning & model checking

- inferred models for 3 SSH server implementations
- run extensive testing on models
- formalized and checked models against security properties, as well as server RFC MUST/SHOULD requirements
- found inconsistencies with limited security impact

Future work:

- formalize mapper so it is clear what it does (and a concretization can be made)
- make mapper abstraction less impactful ➔ reduce num. of mapper induced states
- learn SSH client, model check assembly client/server
- replace classical learner by a register automata learner, extract parameters and infer their related behavior