Some Complexity Results for Stateful Network Verification

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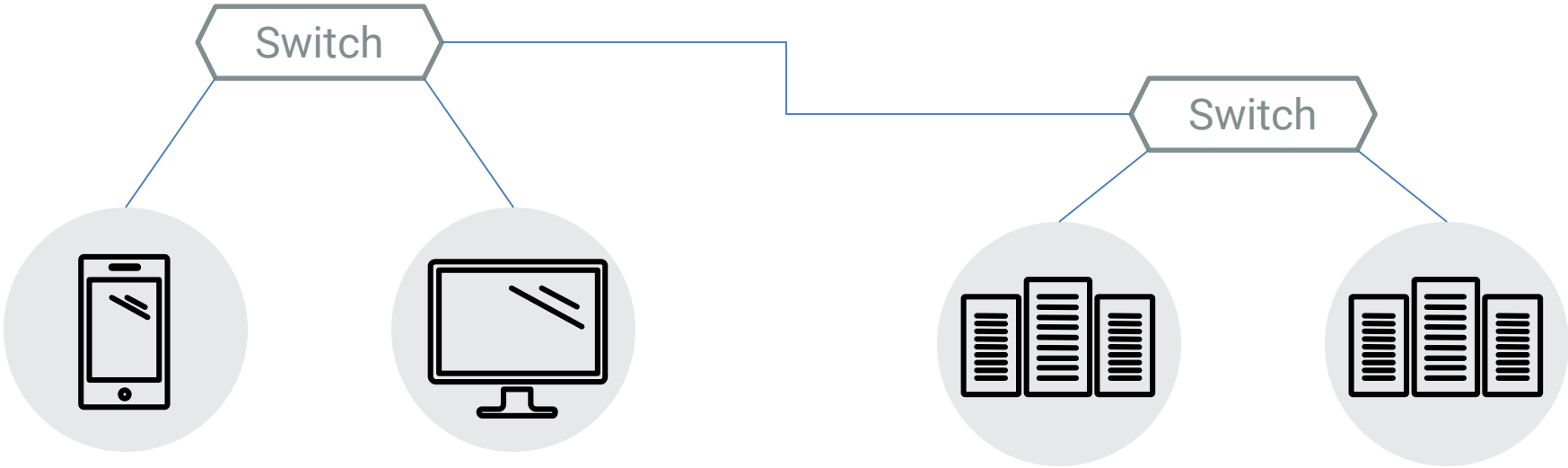
- Scott Shenker

Problem Statement

- Given a network topology
- Task: Verify the safety of the network
  - Isolation



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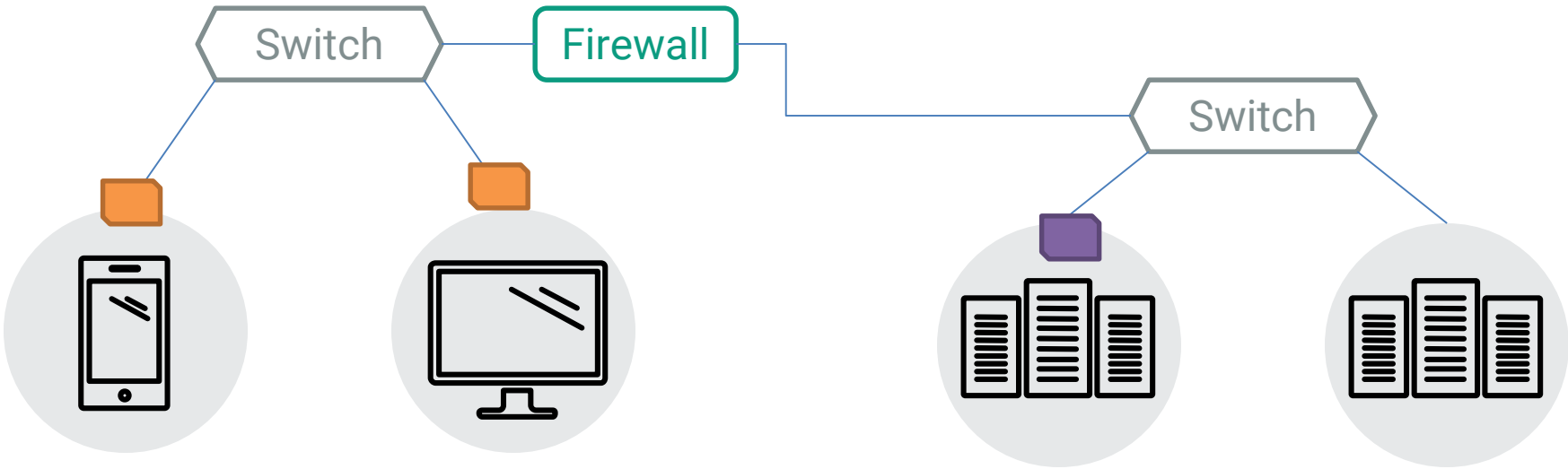

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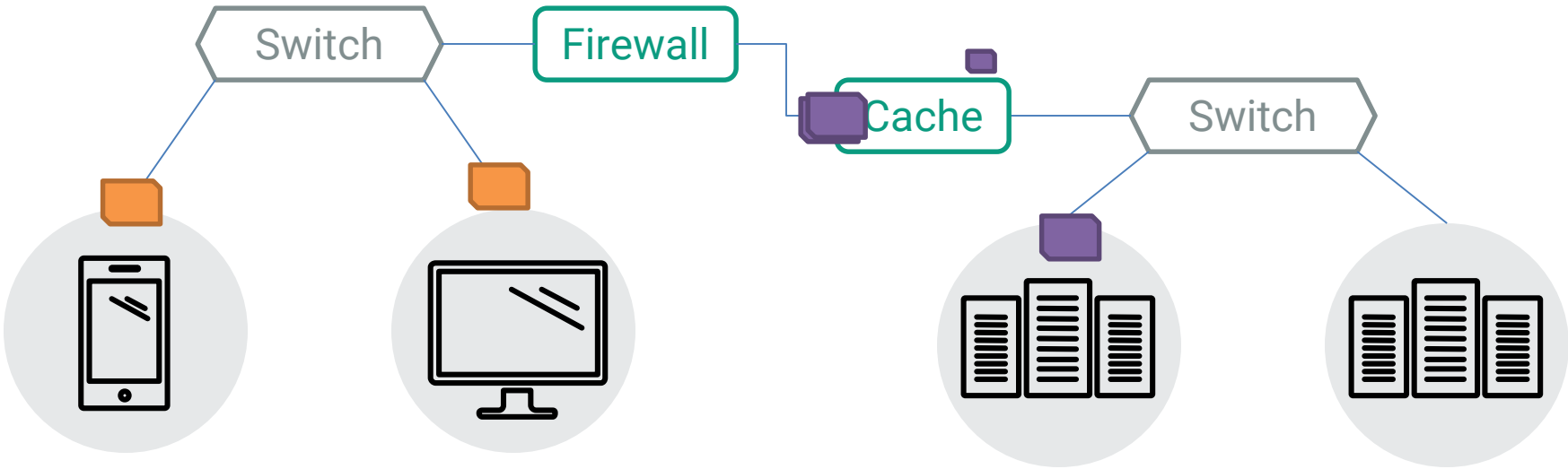


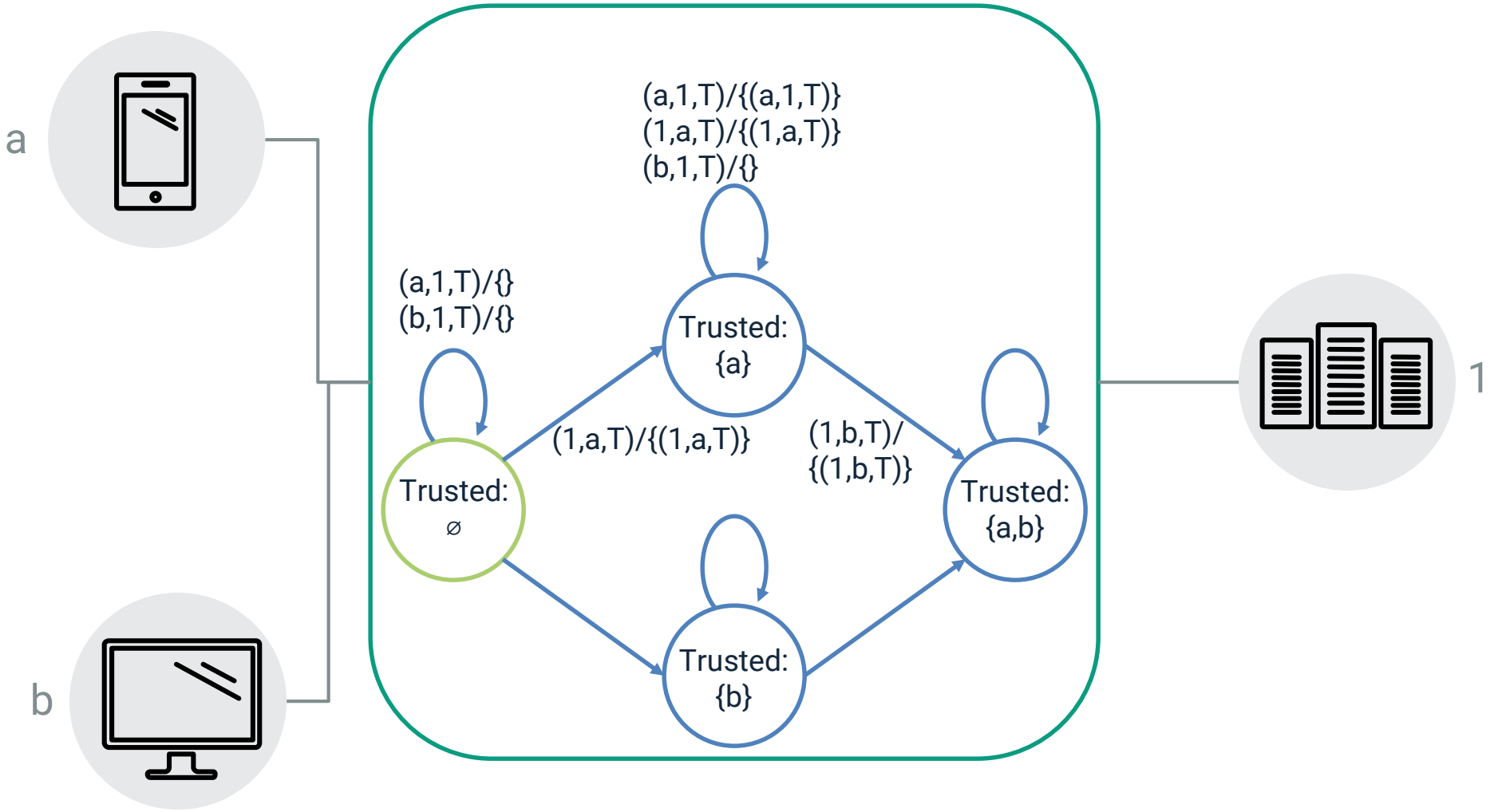
Examples of Middlebox

- Network address translators (NAT)
- Firewall
- Traffic shapers
- Intrusion detection systems (IDSs)
- Transparent web proxy caches
- Application accelerators

Middlebox ≈ FSM

- For the purpose of proving safety, the behaviour of the middlebox is essentially a finite state machine
  - Reason about middlebox behaviour, not implementation
- Network ≈ Communicating FSMs

Transducer Middlebox – Hole Punching Firewall



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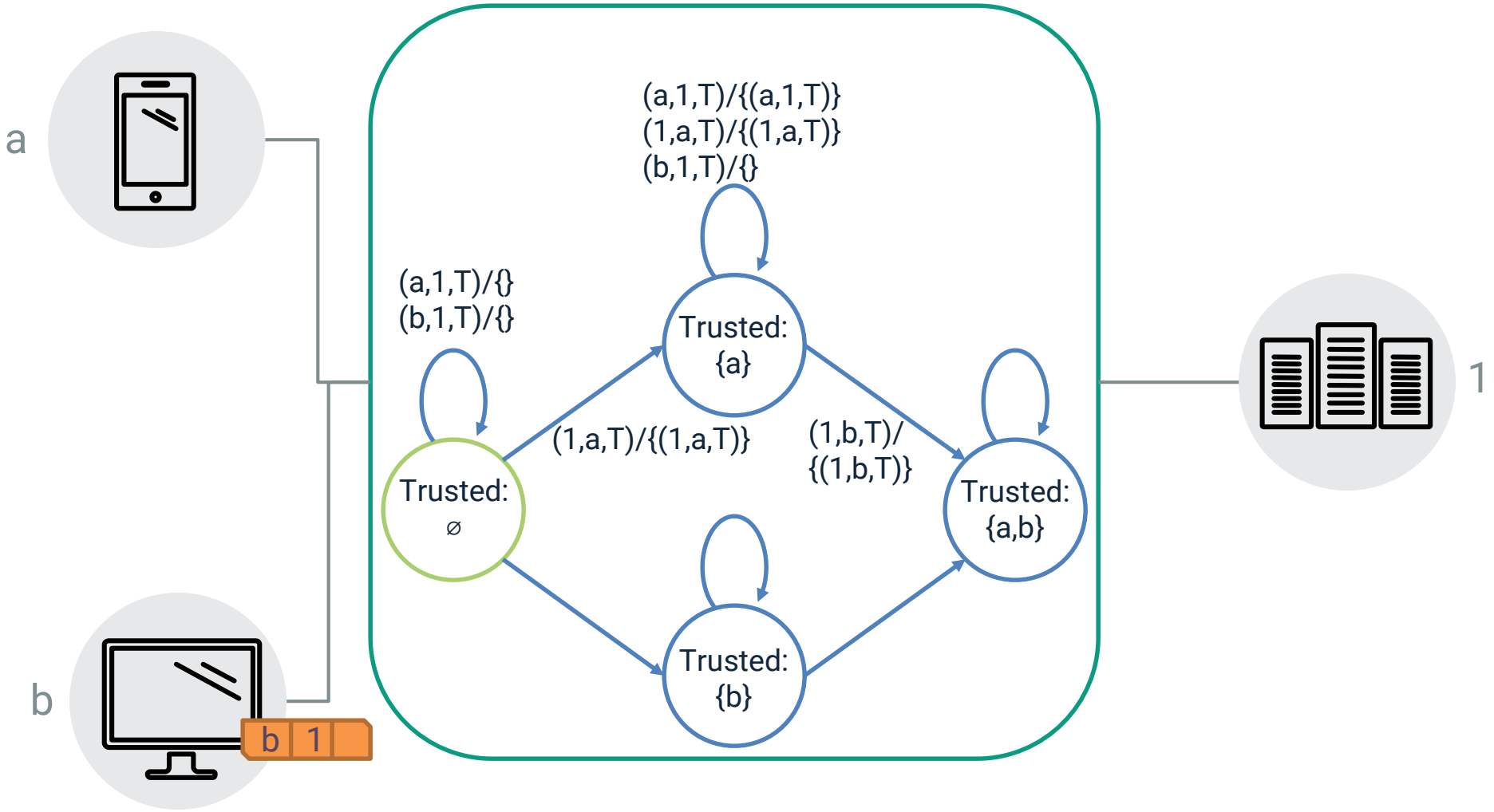

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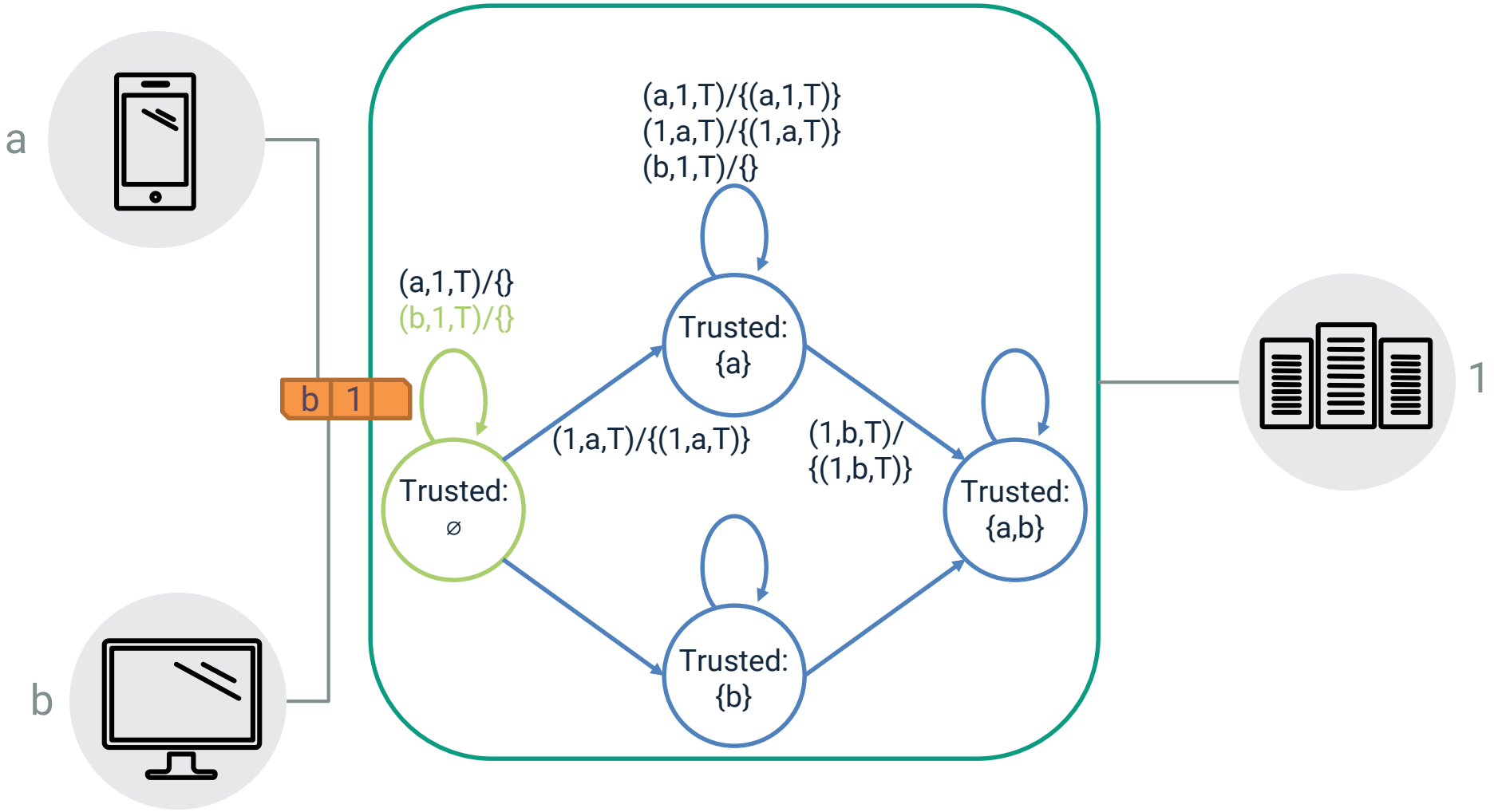

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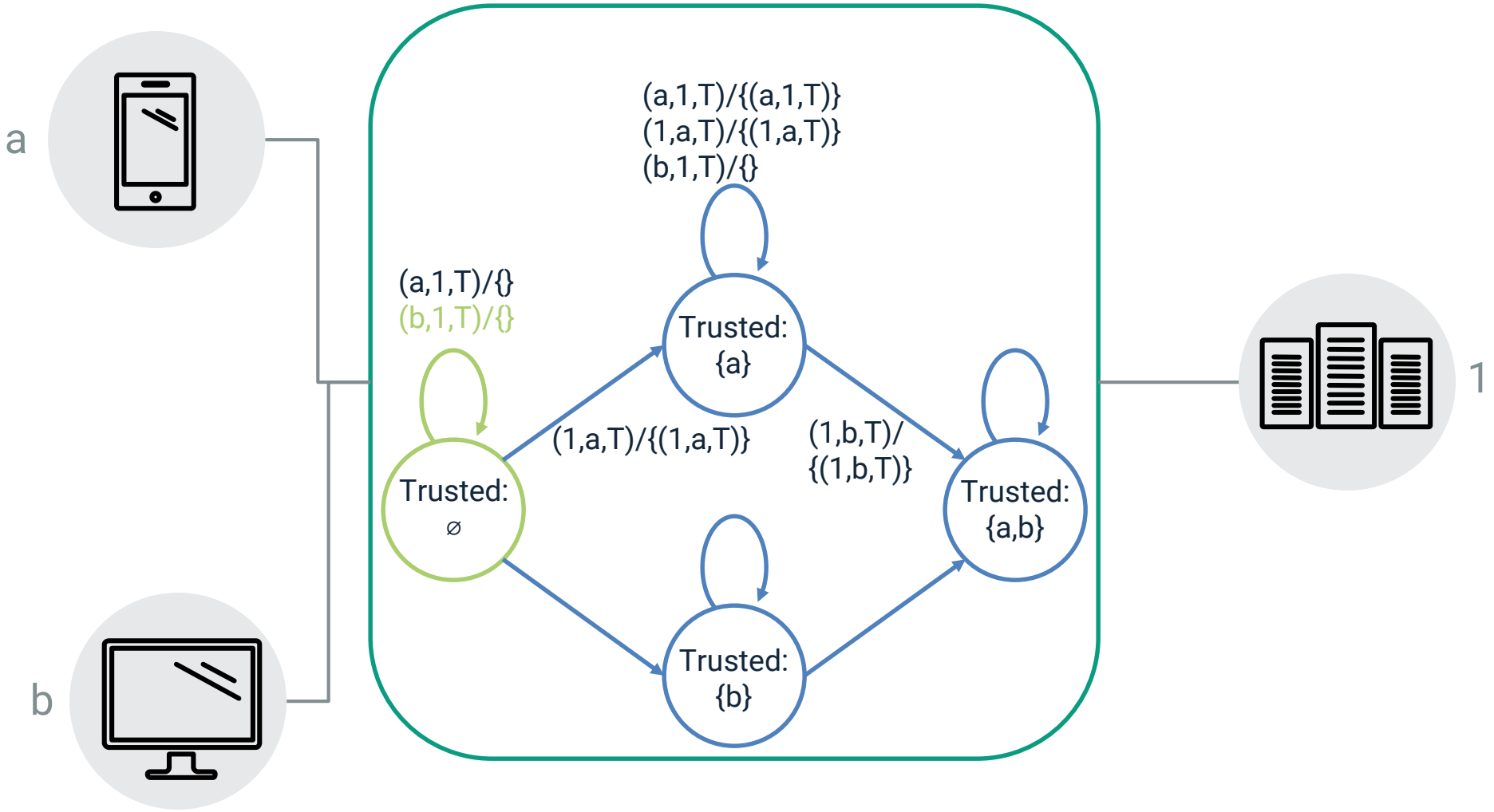

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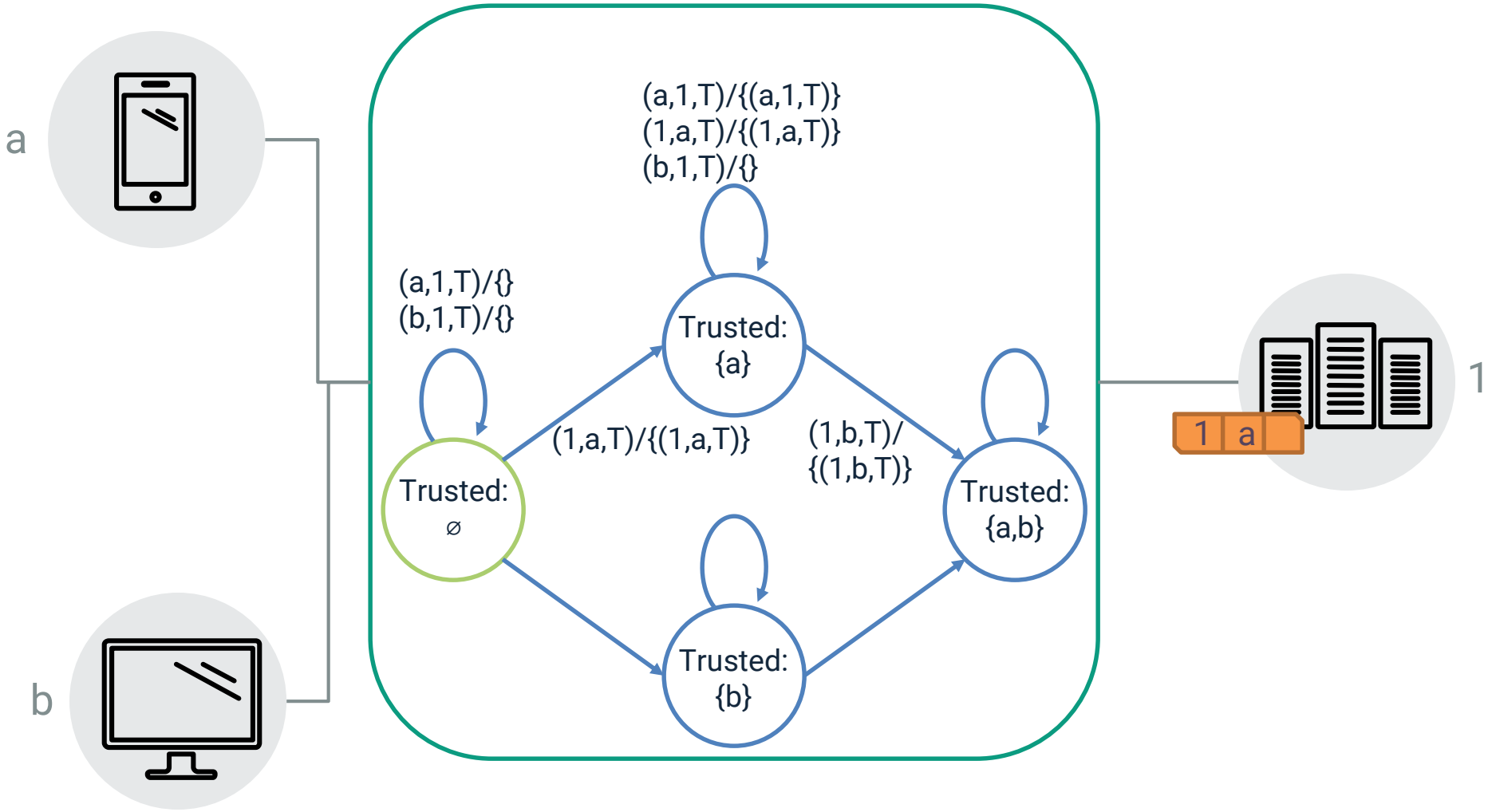

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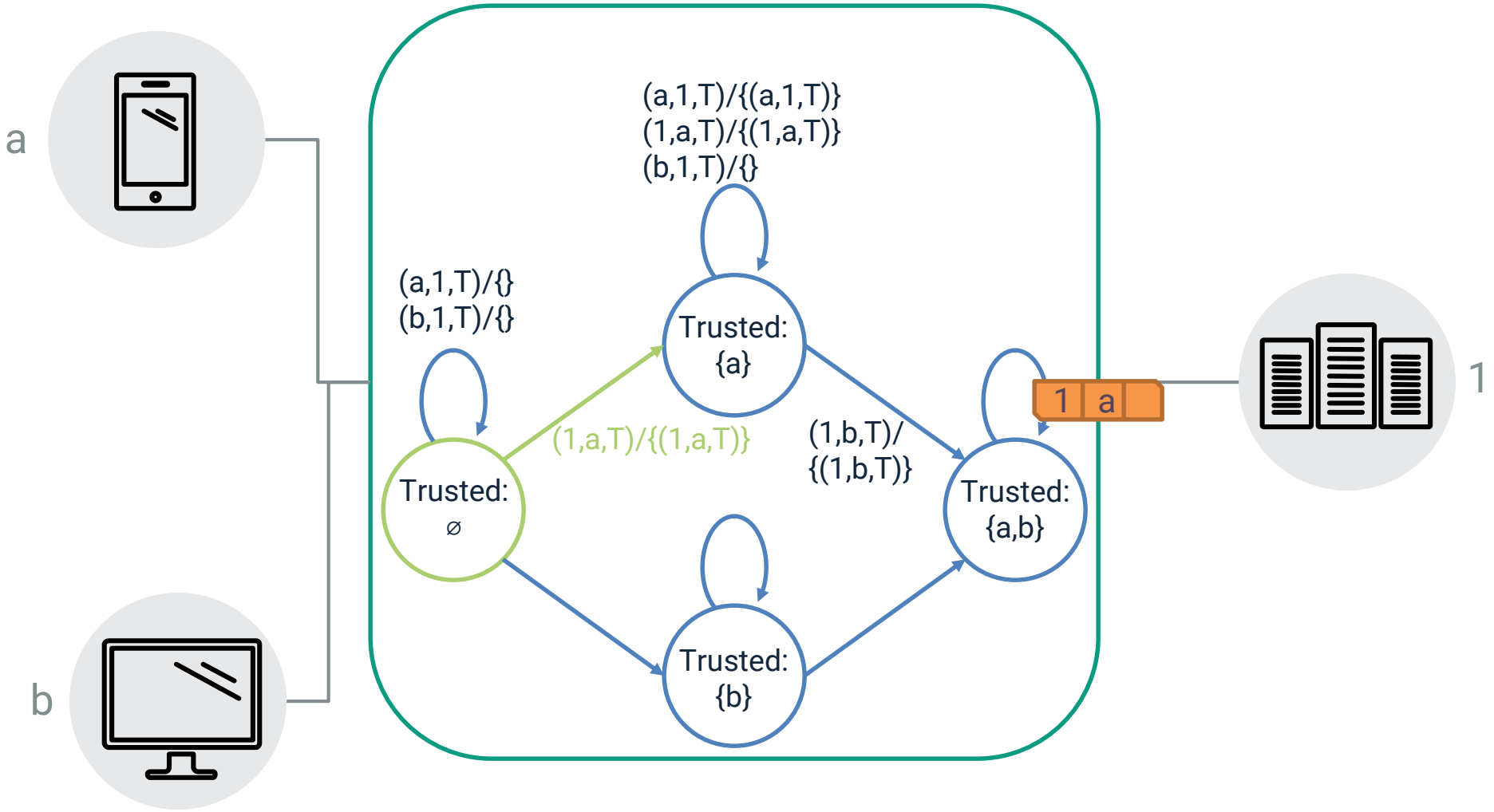

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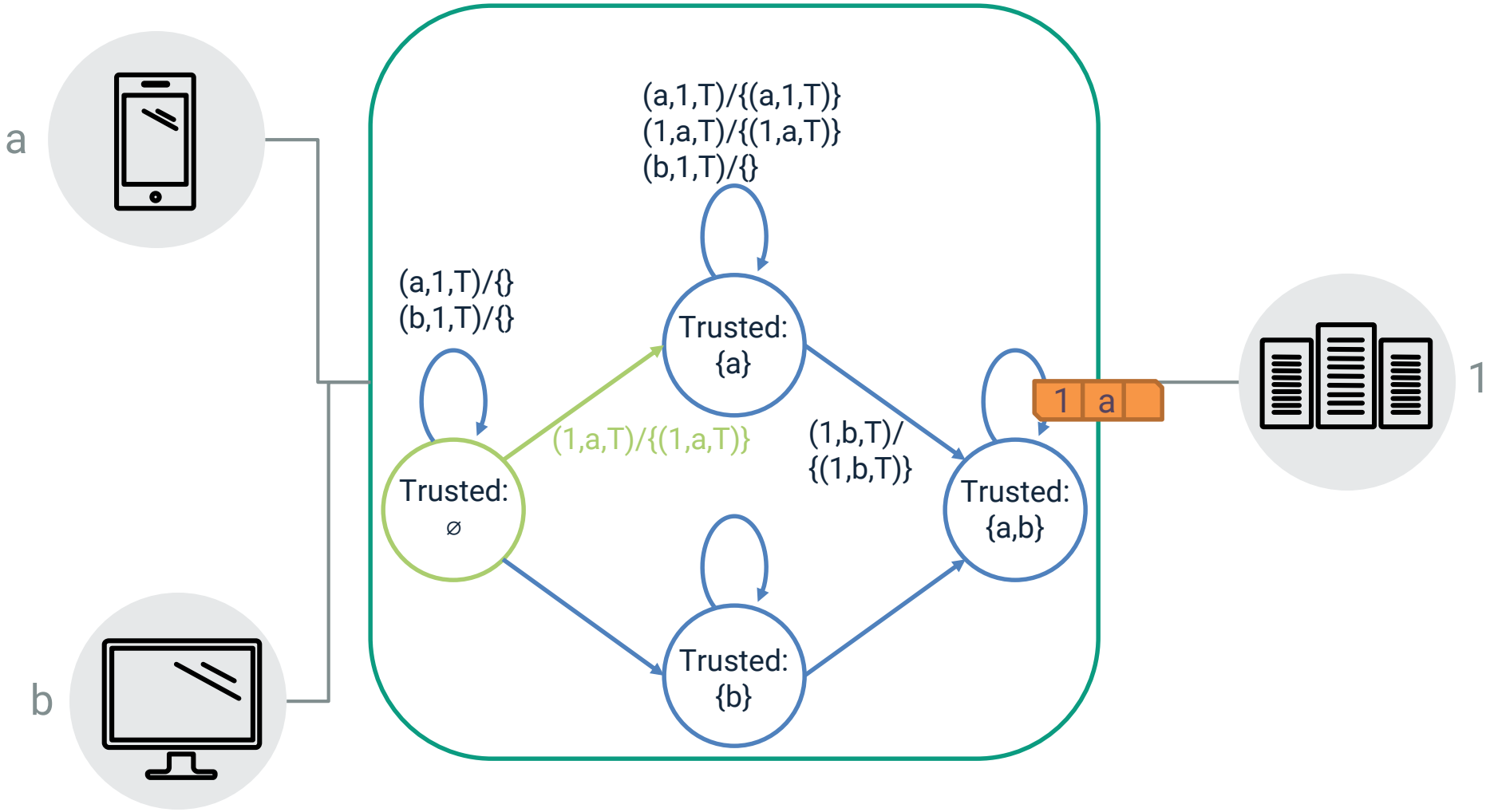

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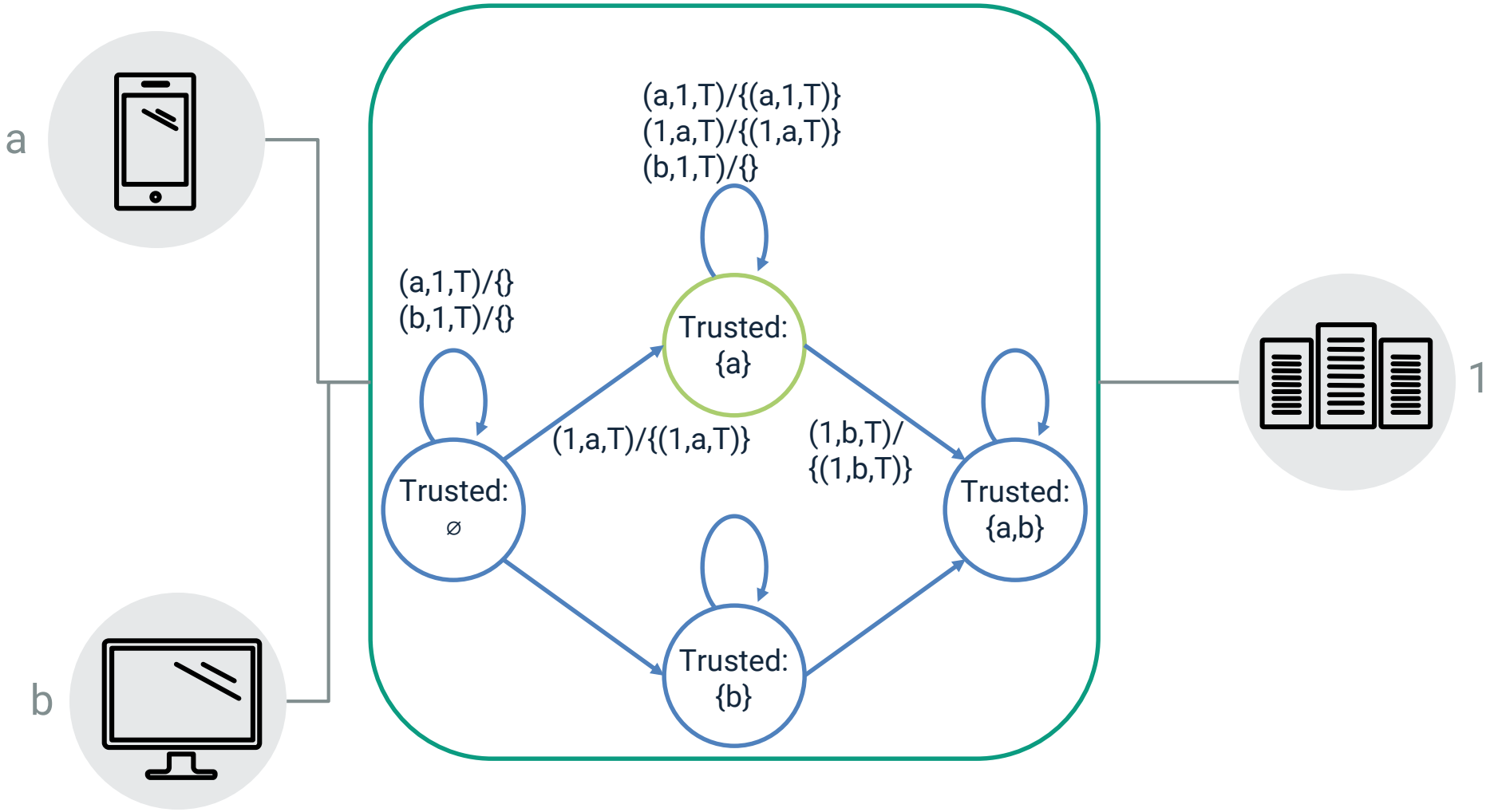

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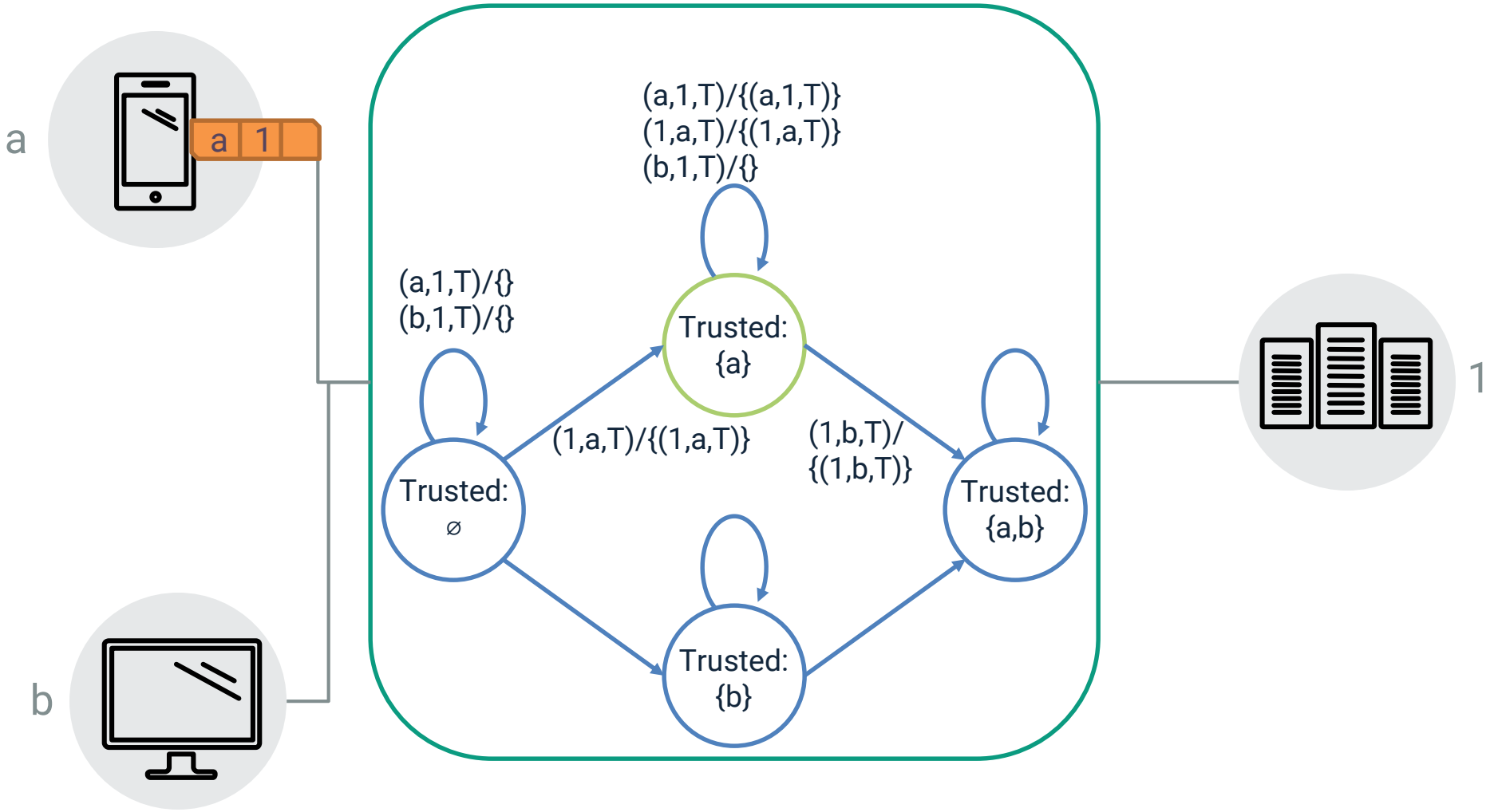

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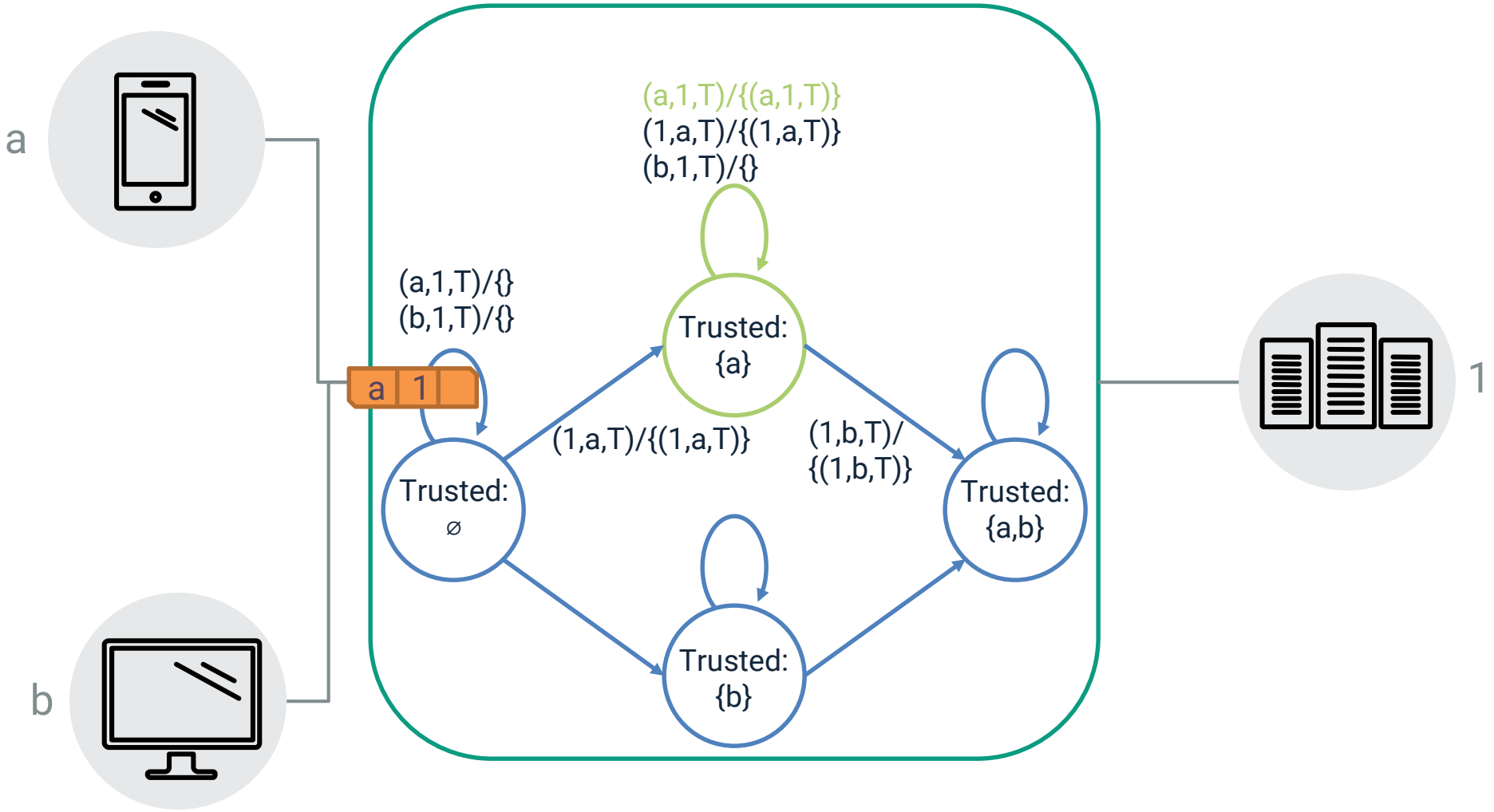

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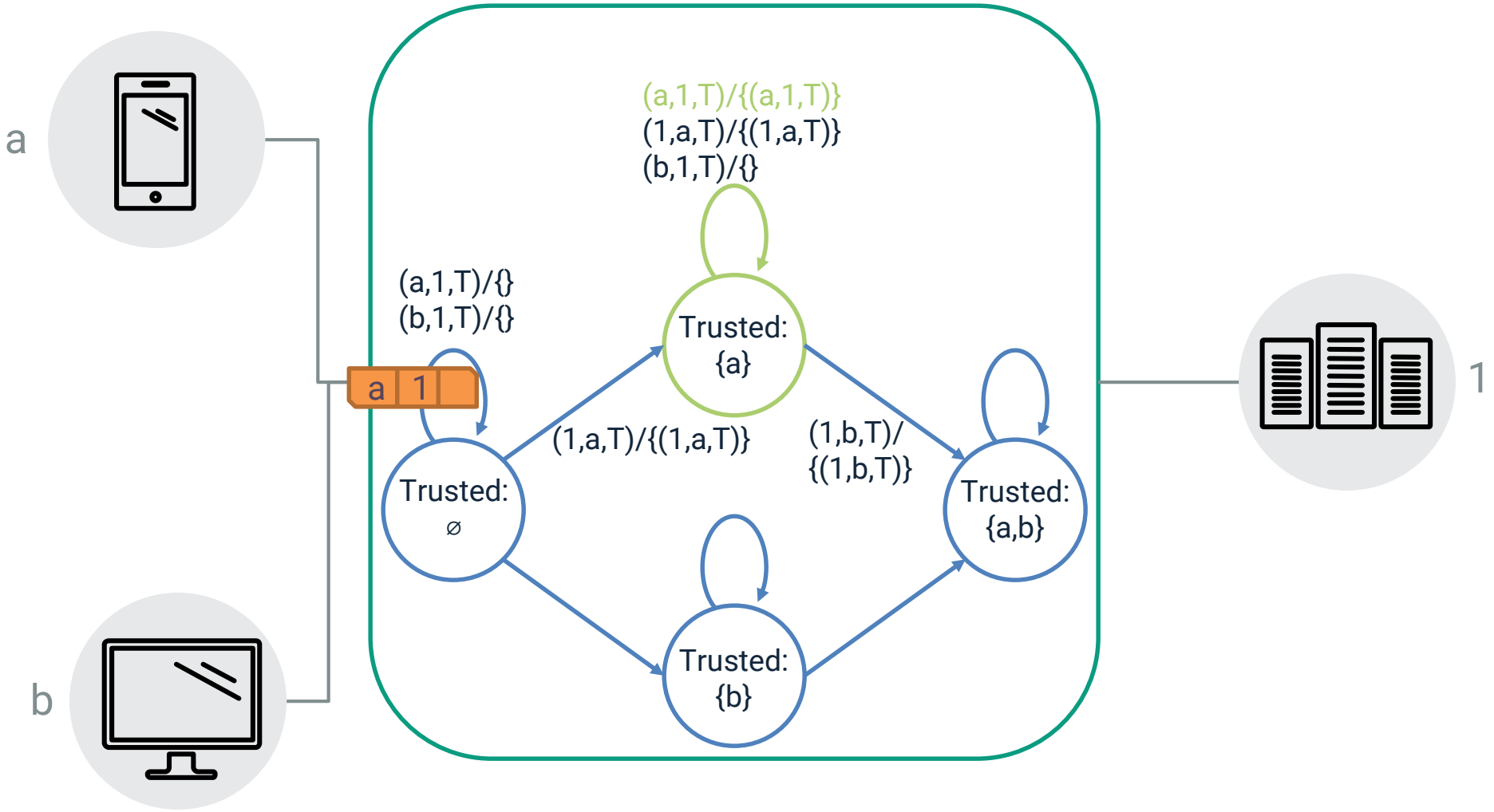
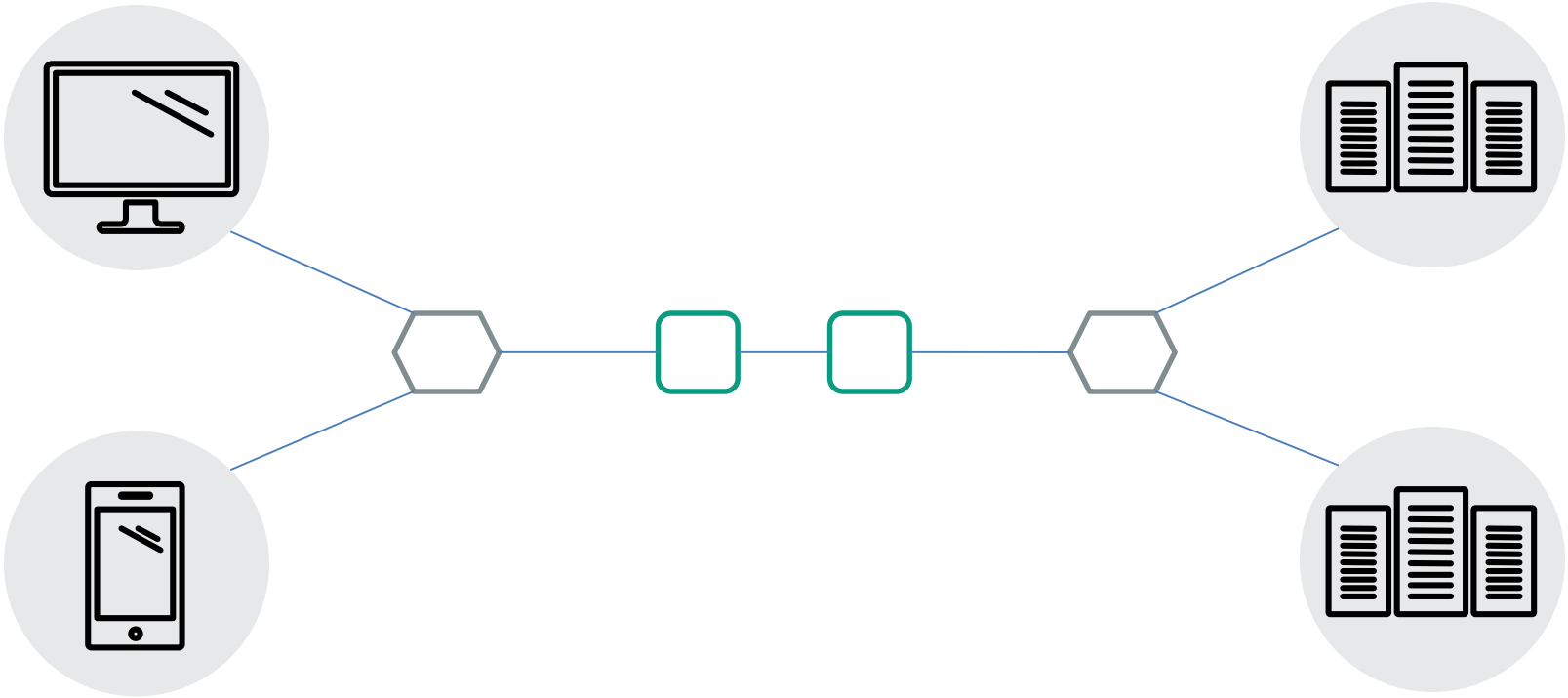


Main Results

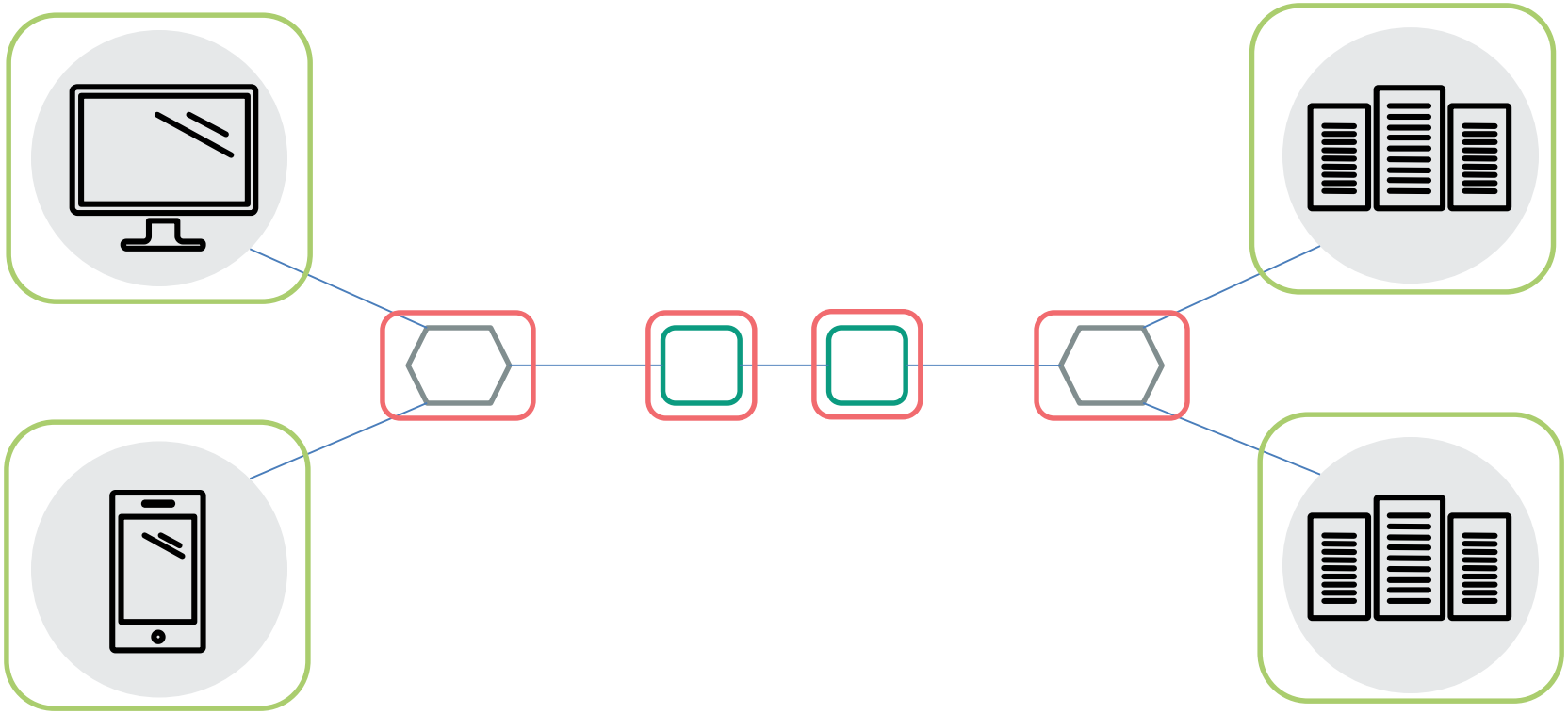
- Classify middleboxes according to the forwarding behaviour
  - Input/Output relation
  - Depends on state (history)
- Tight complexity Results for the different classes
- Compact symbolic representation preserves complexity results
  - Exponential saving in common cases

Network Model



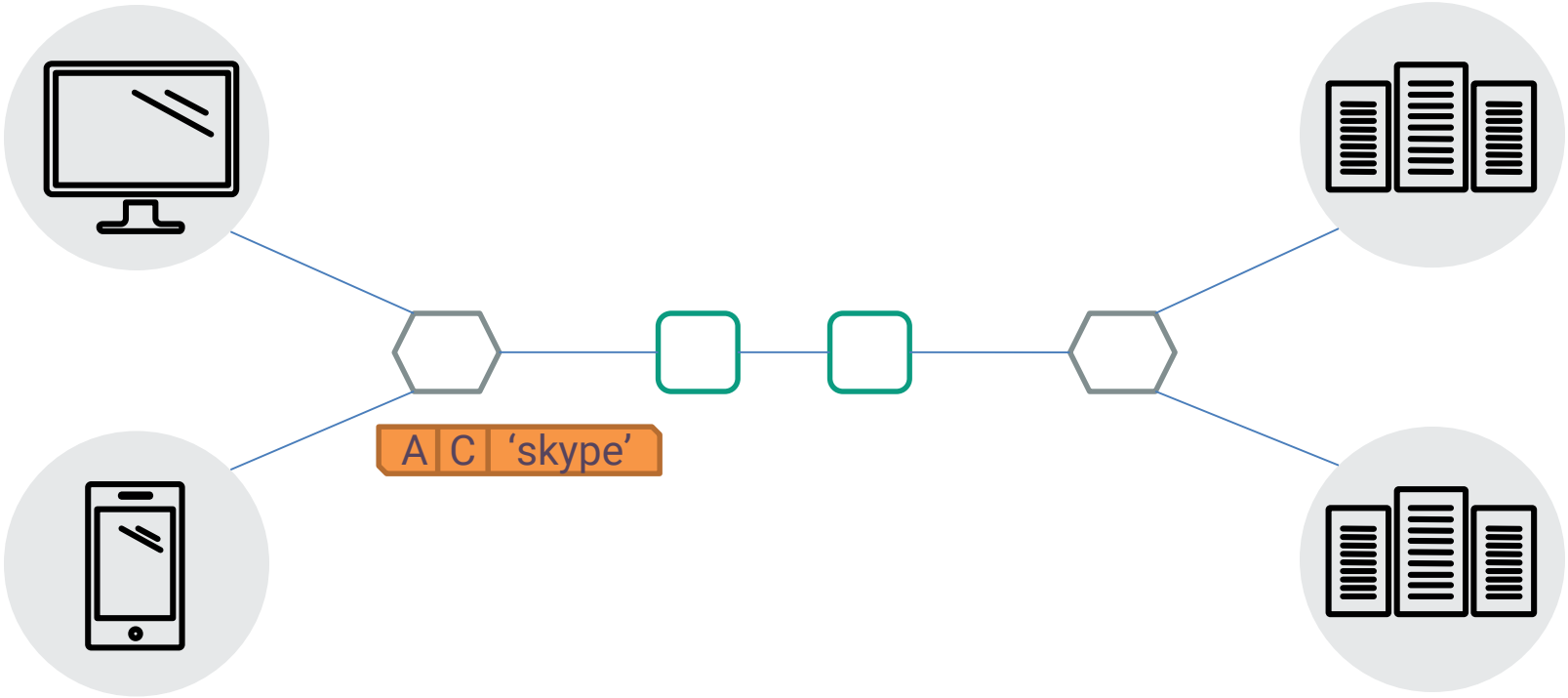
- An undirected graph

Network Model



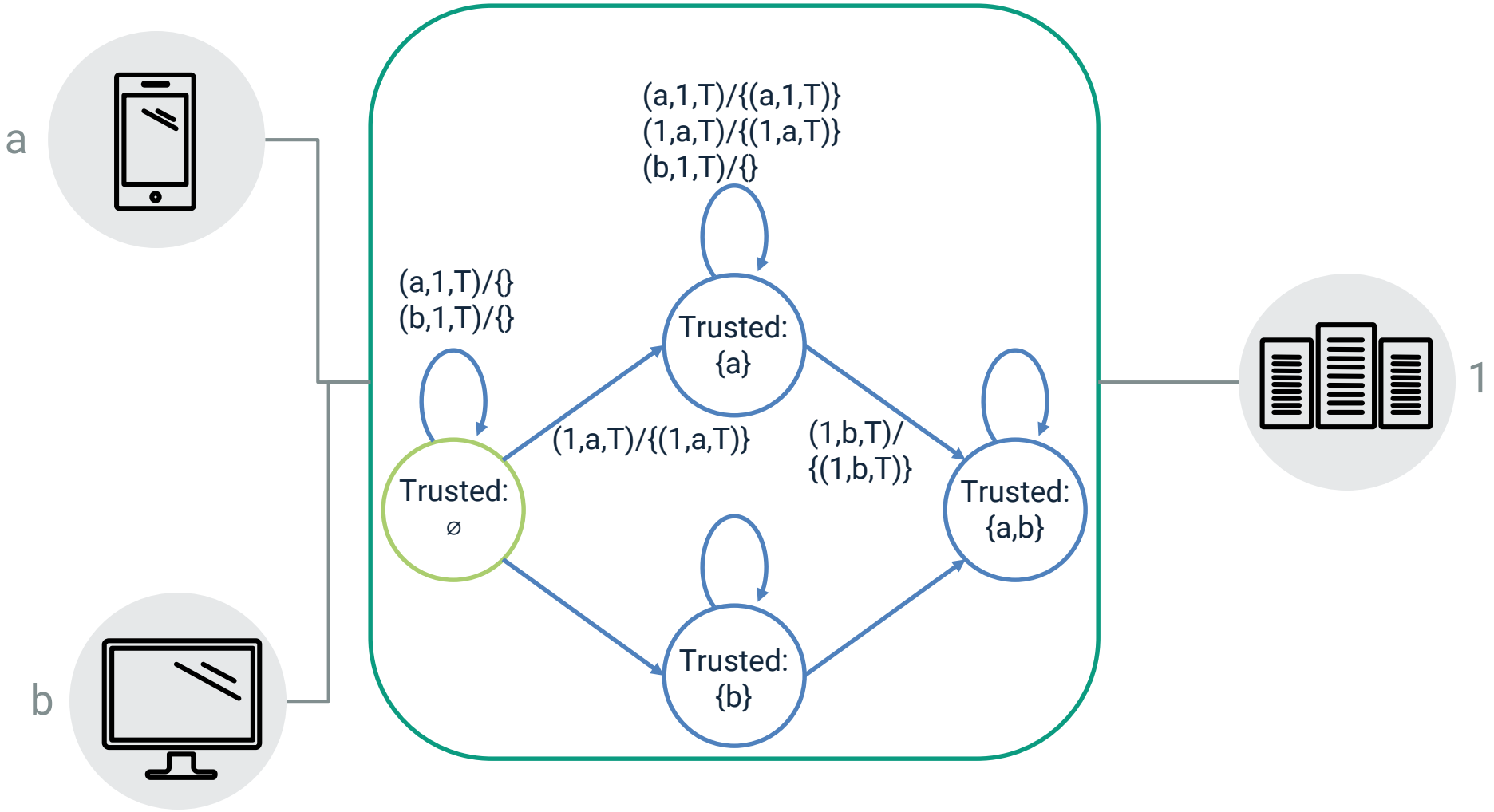
- Vertices are hosts and Middleboxes

Network Model



- Packets are <Source, Destination, Tag> tuples

Transducer Middlebox – Hole Punching Firewall



Symbolic Representation Hole Punching Firewall

```
input(src, dst, tag, prt):
  prt = INTERN ⇒
    // hosts within organization
    trusted.insert dst;
    output {(src, dst, tag, EXTERN)}
  prt = EXTERN ∧ src in trusted ⇒
    // trusted hosts outside organization
    output {(src, dst, tag, INTERN)}
  prt = EXTERN ∧ ¬(src in trusted) ⇒
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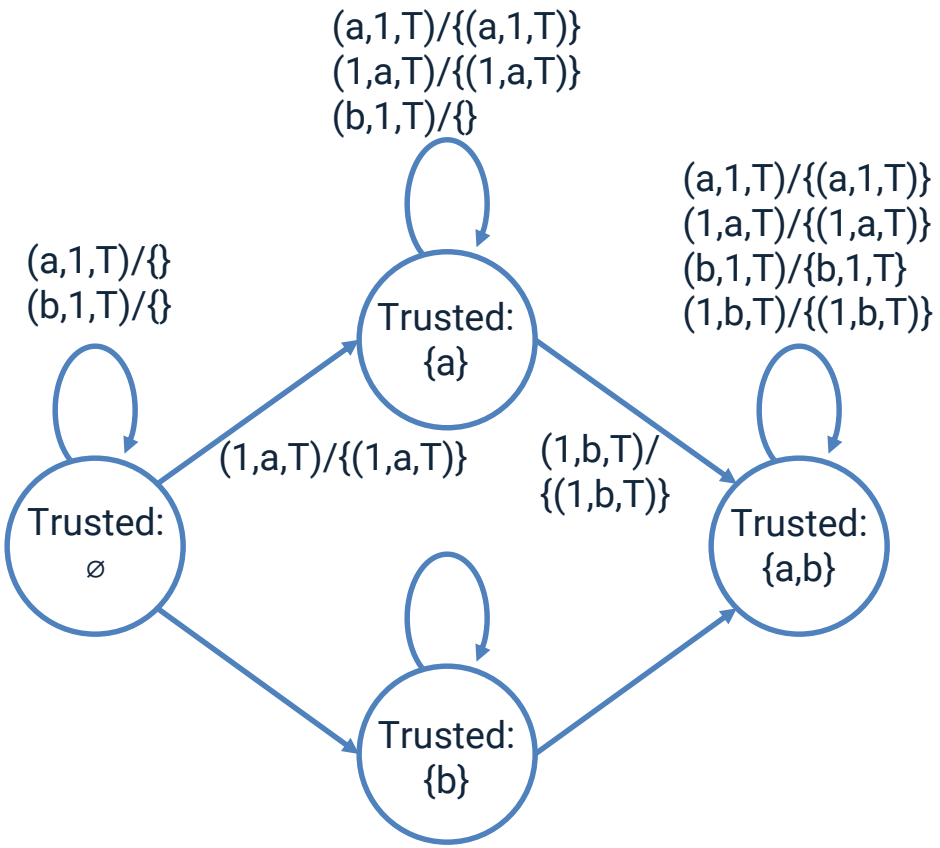
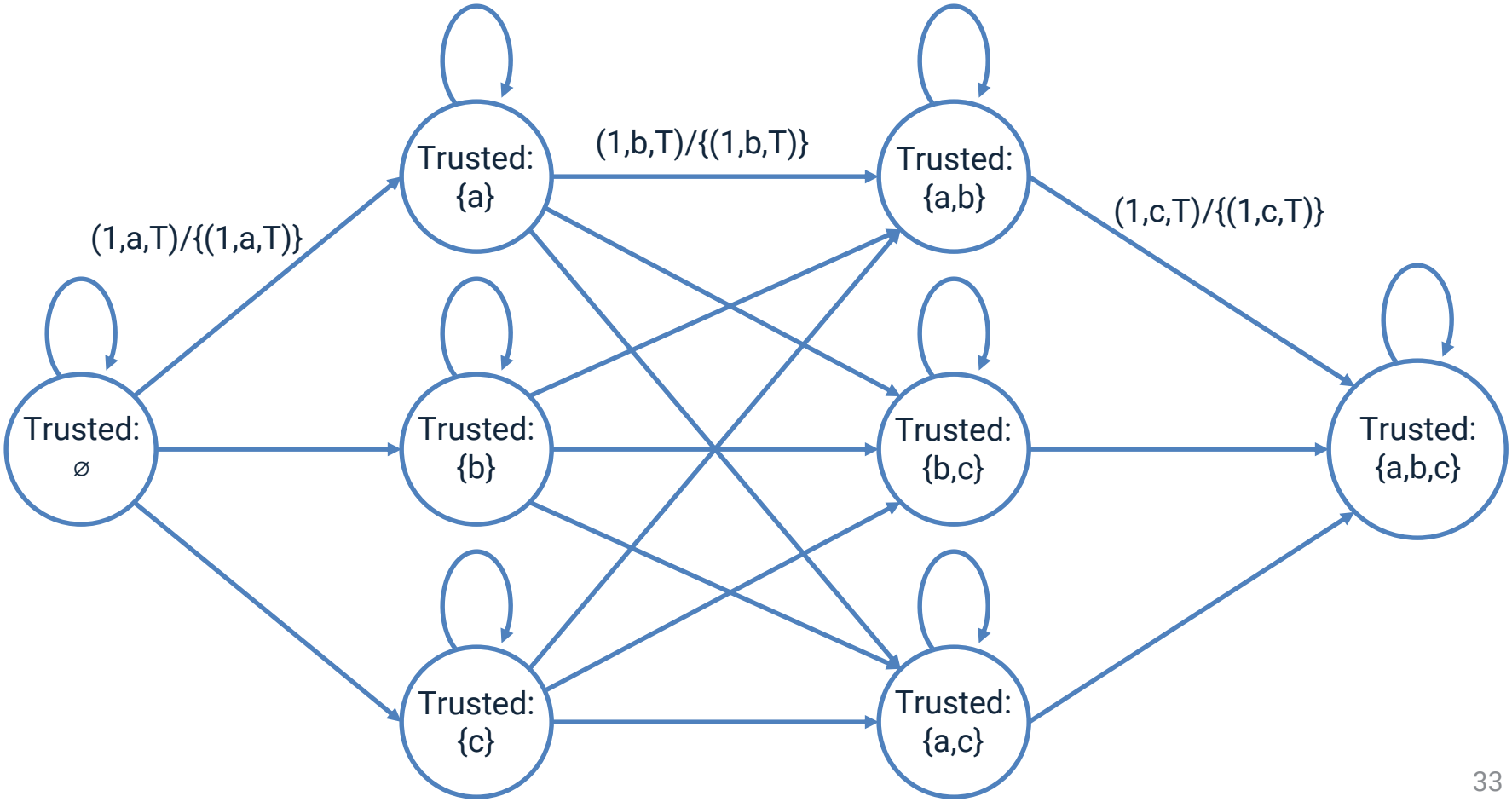
Explicit Representation – Hole Punching Firewall (2 Hosts)



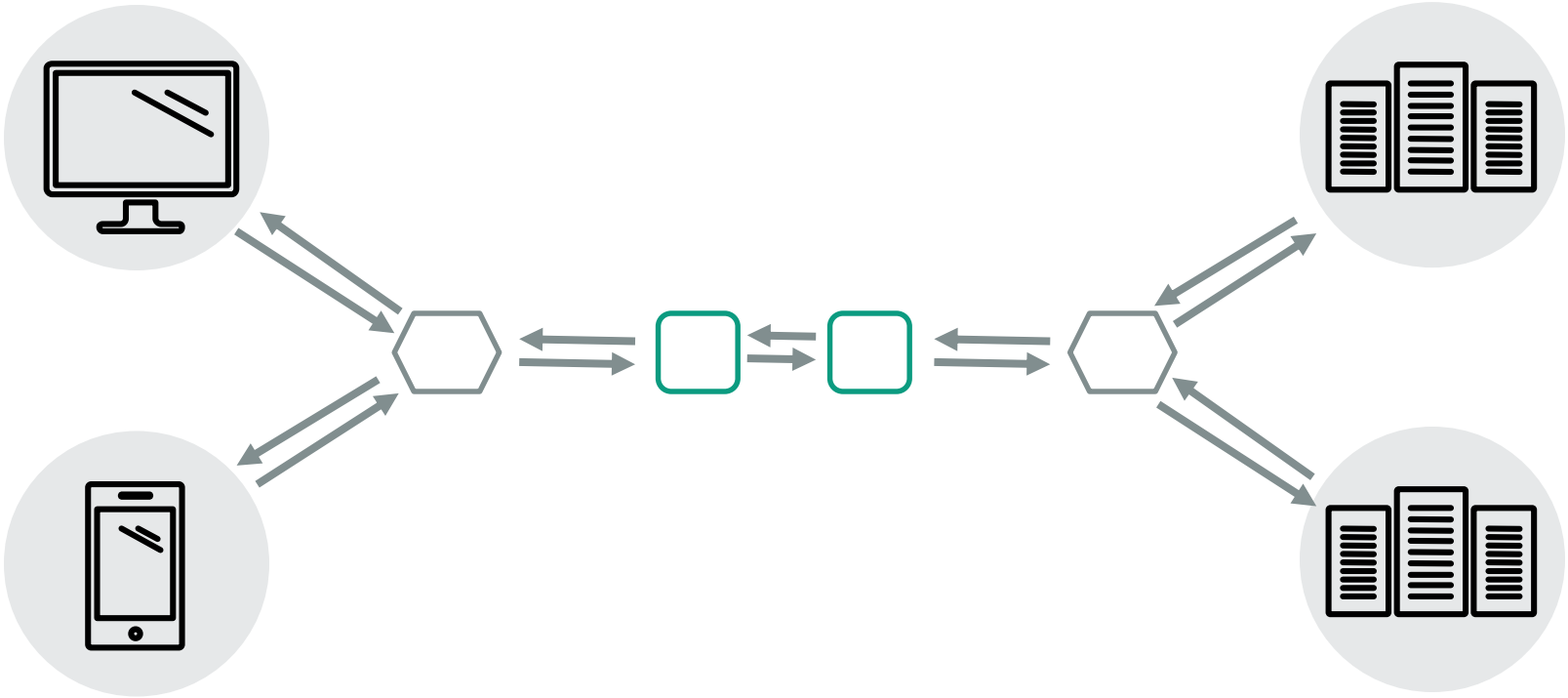
Explicit Representation – Hole Punching Firewall (3 Hosts)



Property Middleboxes - Isolation

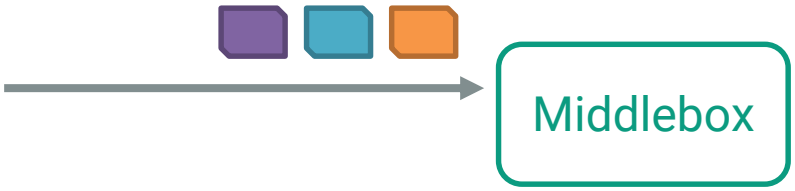
```
input(src, dst, tag, prt):
  prt = HOST ⇒
    // host for which isolation is checked
    output {(src, dst, tag, NET)}
  prt = NET ∧ ¬(src in forbidden) ⇒
    // no isolation violation
    output {(src, dst, tag, HOST)}
  prt = NET ∧ src in forbidden⇒
    // isolation violation
    abort
```

Network Semantics



- Each edge admits two directed communication channels

Network Semantics - FIFO



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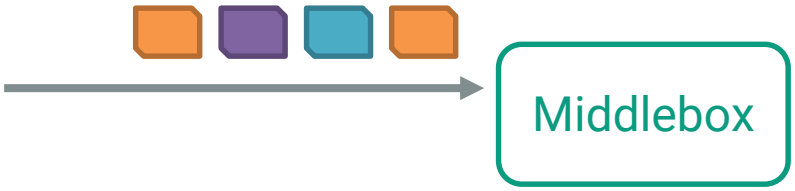

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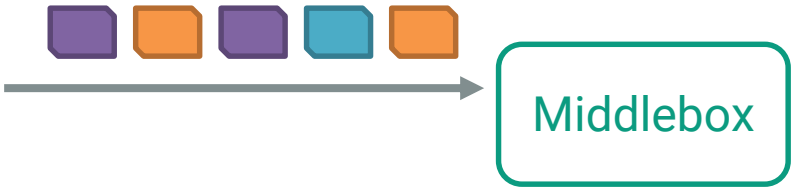

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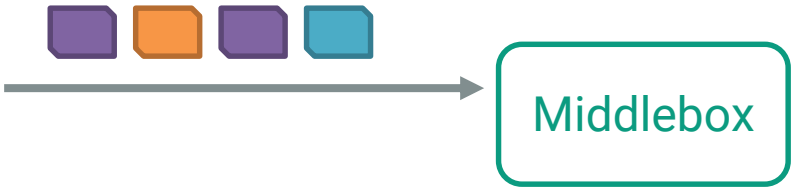
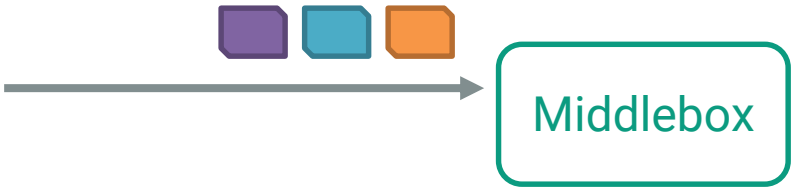


- Network verification is undecidable
  - Can simulate a Turing Machine
  - Even without forwarding loops

[Daniel Brand, and Pitro Zafiropulo. *JACM* '83]

Network Semantics - Unordered



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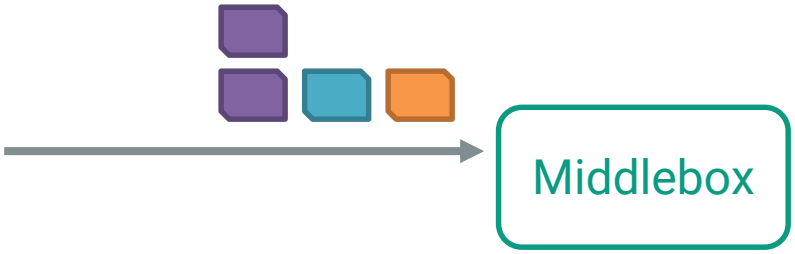

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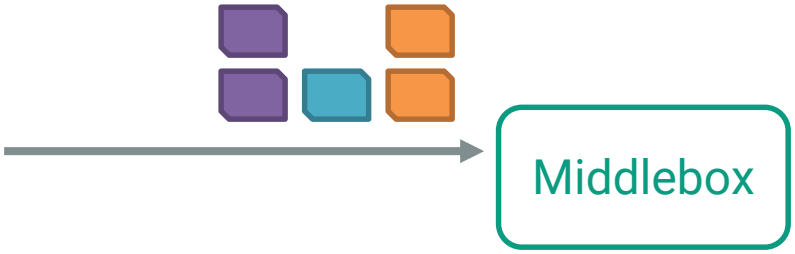

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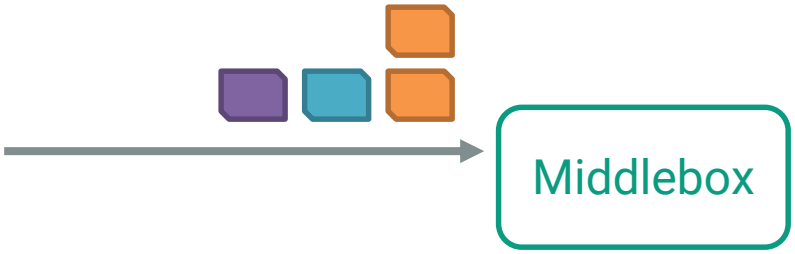


- Now the verification problem is decidable
  - Monotone Transition System

[Abdulla et al. *LICS* '93]
[Finkel, A., Schnoebelen, P. *Theoretical Computer Science* '01]

Verification Complexity

- EXPSPACE-Complete
  - Equivalent to Petri Net coverability
- Can we do better?
- In practice very few middlebox types are used
  - Explore ‘Good’ middleboxes

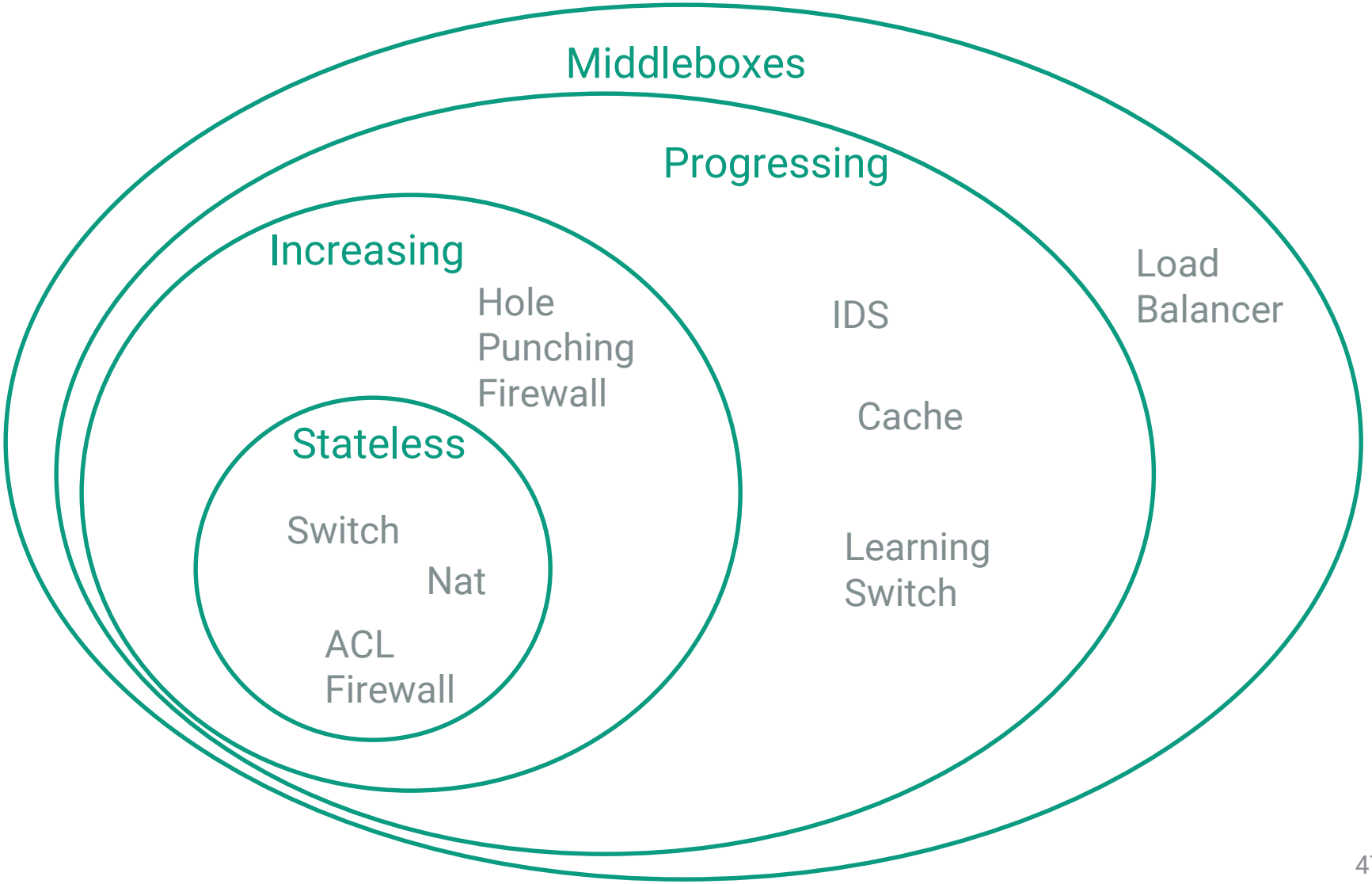
Middlebox Classification

- Middlebox categories
  - Stateless
  - Increasing
  - Progressing
  - Arbitrary
- According to forwarding behaviour
  - Effects of history on the forwarding behaviour

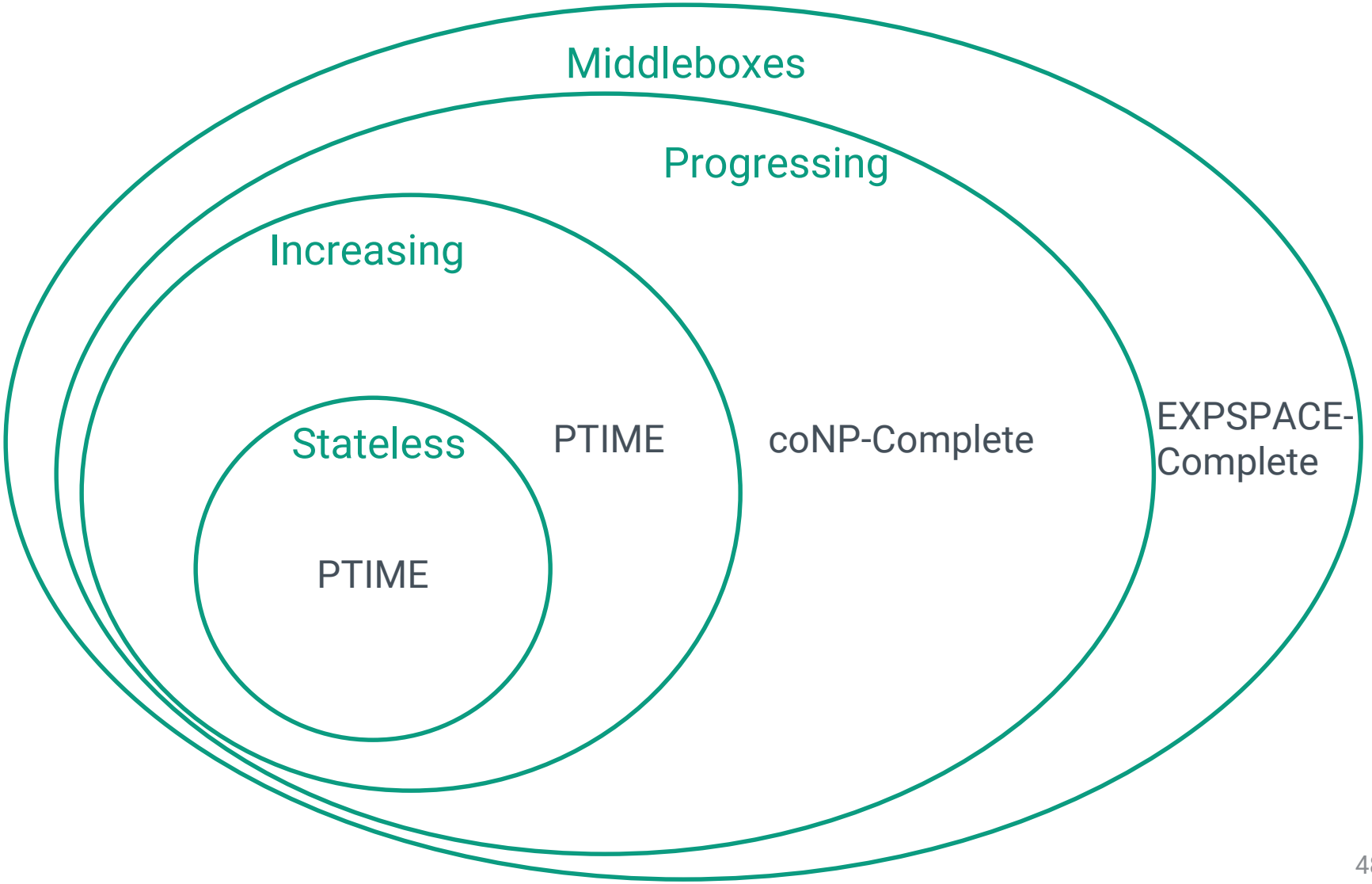
Middlebox Classification

- Equivalently according to syntactic restrictions
- Every class has syntactic limitations it imposes on the symbolic representation
- A middlebox belongs to a class iff there exists a restricted symbolic representation for it

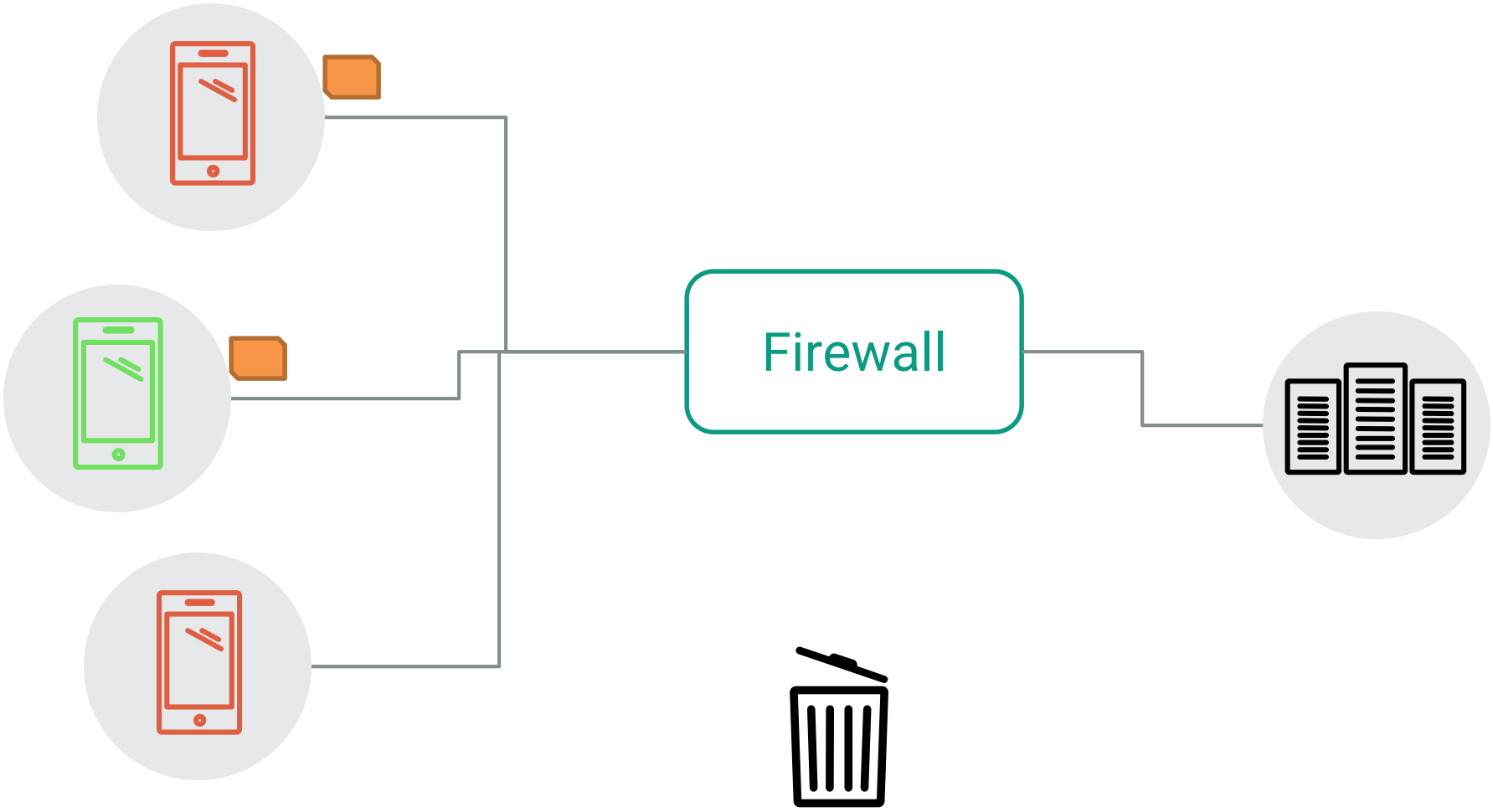
Middlebox Classification



Middlebox Classification



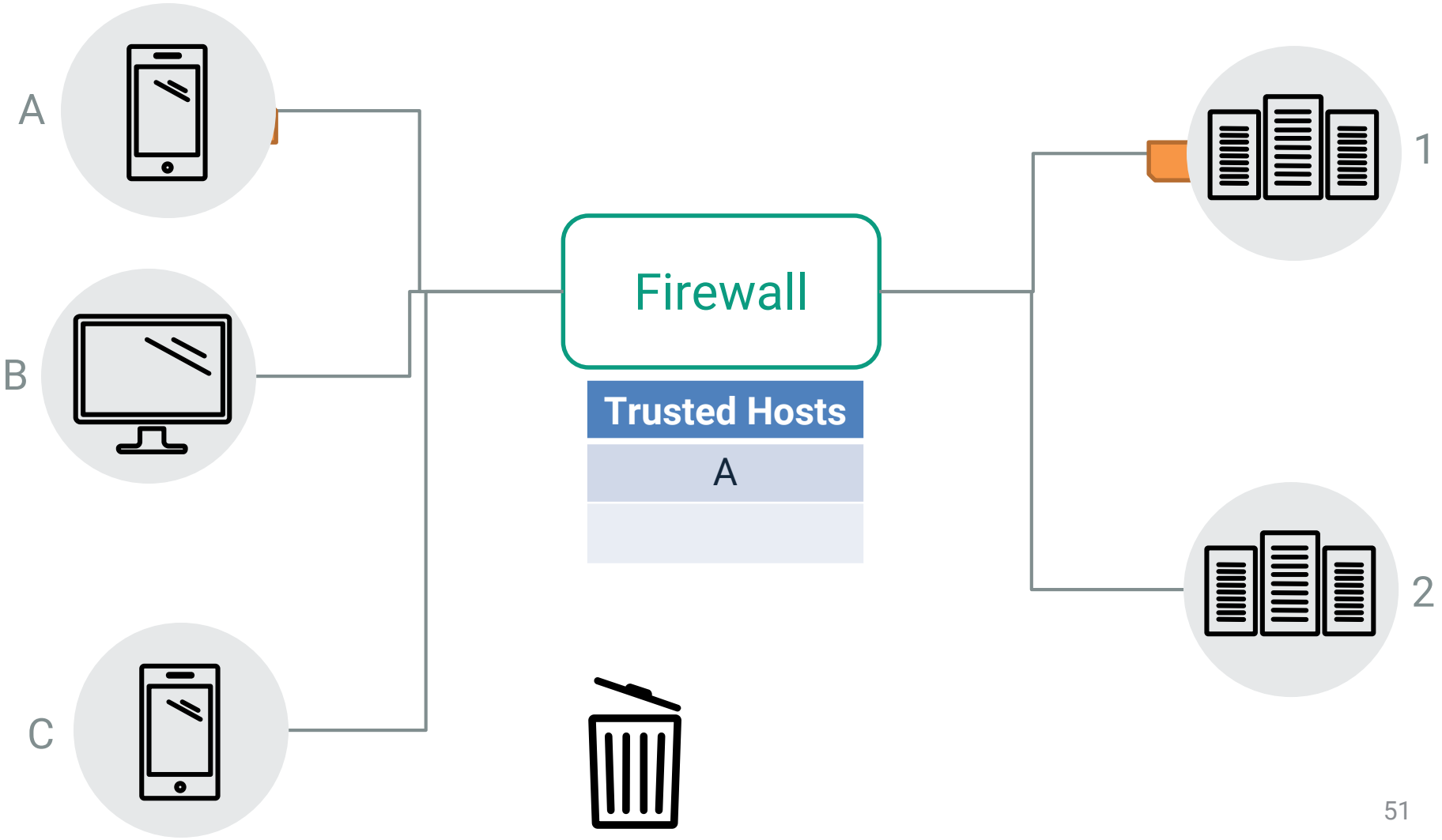
Stateless Middlebox – ACL Firewall



Stateless

- Transducer has only a single state
- Forwarding behaviour is history agnostic
- Syntactic restriction – no changes to the relations

Increasing Middlebox – Hole Punching Firewall



Increasing

- Forwarding behaviour increases over time
- Future instance increases the output
- Syntactic restriction – no negative conditions or removals from relations
  - Monotonic guard ‘truth state’
  - Monotonic middlebox state

Increasing

Theorem:

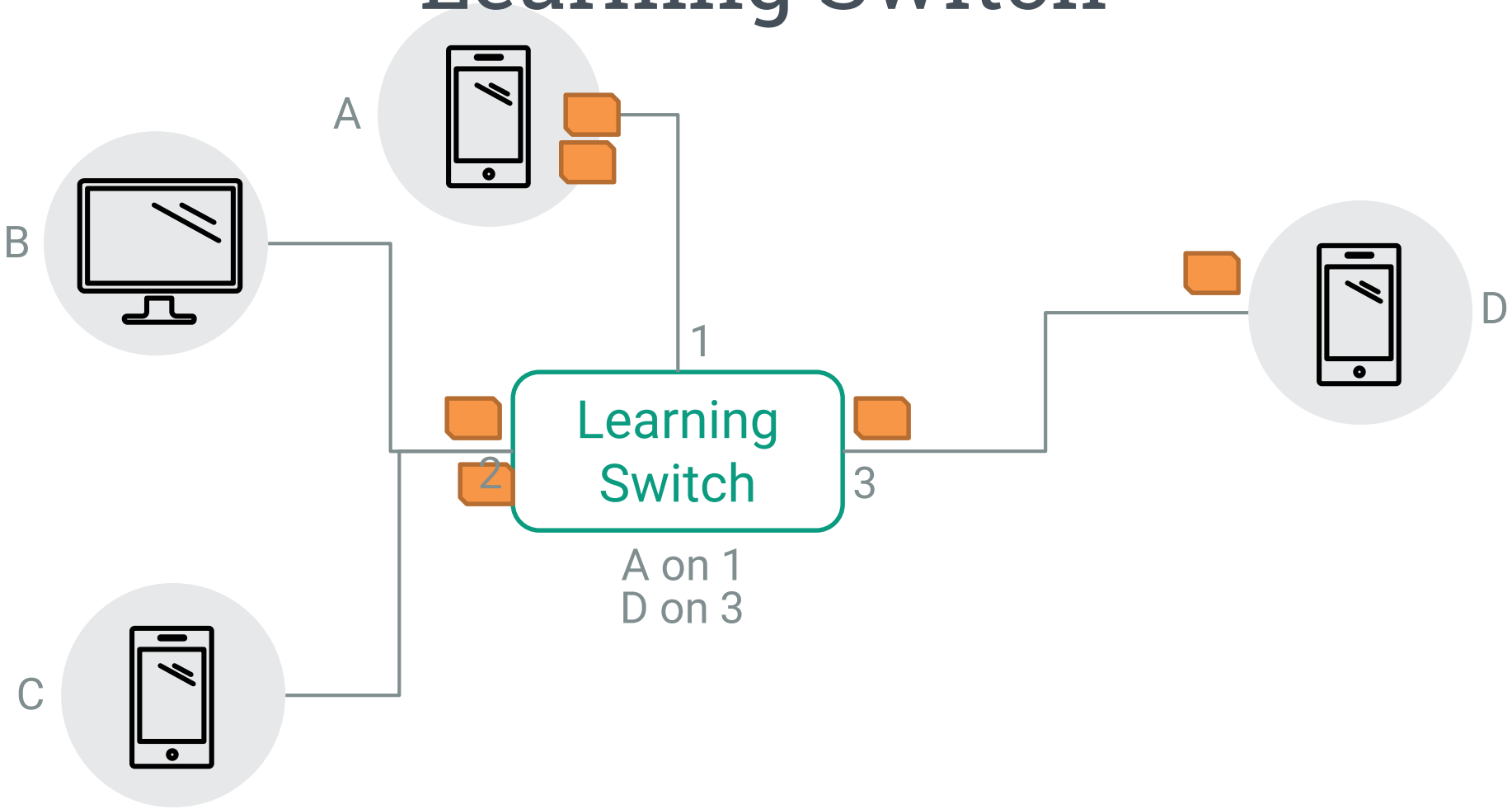
Safety verification of Increasing networks is in

PTIME

Increasing – Proof Sketch

- Any event in the network can happen infinitely many times
  - Middlebox state and forwarding behaviour are monotonic
- No need to consider packet multiplicity
- Reachability search accumulates reachable states

Progressing Middlebox – Learning Switch



Progressing

- Forwarding behaviour ‘progresses’ over time
- The transducer state graph is a DAG
- Syntactic restriction – no removals from relations
  - Monotonic middlebox state

Progressing

Theorem:

Safety verification of Progressing networks is

coNP-Complete

Progressing – Proof Sketch

- Witness for safety violation is of polynomial size
- Middlebox states are monotonic
- A bound on the number of ‘significant’ packets between middlebox state transitions

Complexity Result Summary

Class	Unordered	FIFO
Stateless	PTIME	PTIME
Increasing	PTIME	PTIME
Progressing	coNP-Complete	?
Arbitrary	EXPSPACE	Undecidable

Experimental Results

- Datalog based tool for Increasing networks
  - Good scalability
  - Limited application
- Petri-net based tool for Progressing and Arbitrary networks
  - Poor scalability

Summary

- Classify middleboxes according to the forwarding behaviour
  - Dependence on history
- Tight complexity Results for the different classes
- Compact symbolic representation preserves complexity results
  - Exponential saving in common cases