Safety Verification of Stateful Networks

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Aurojit Panda
Scott Shenker

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האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

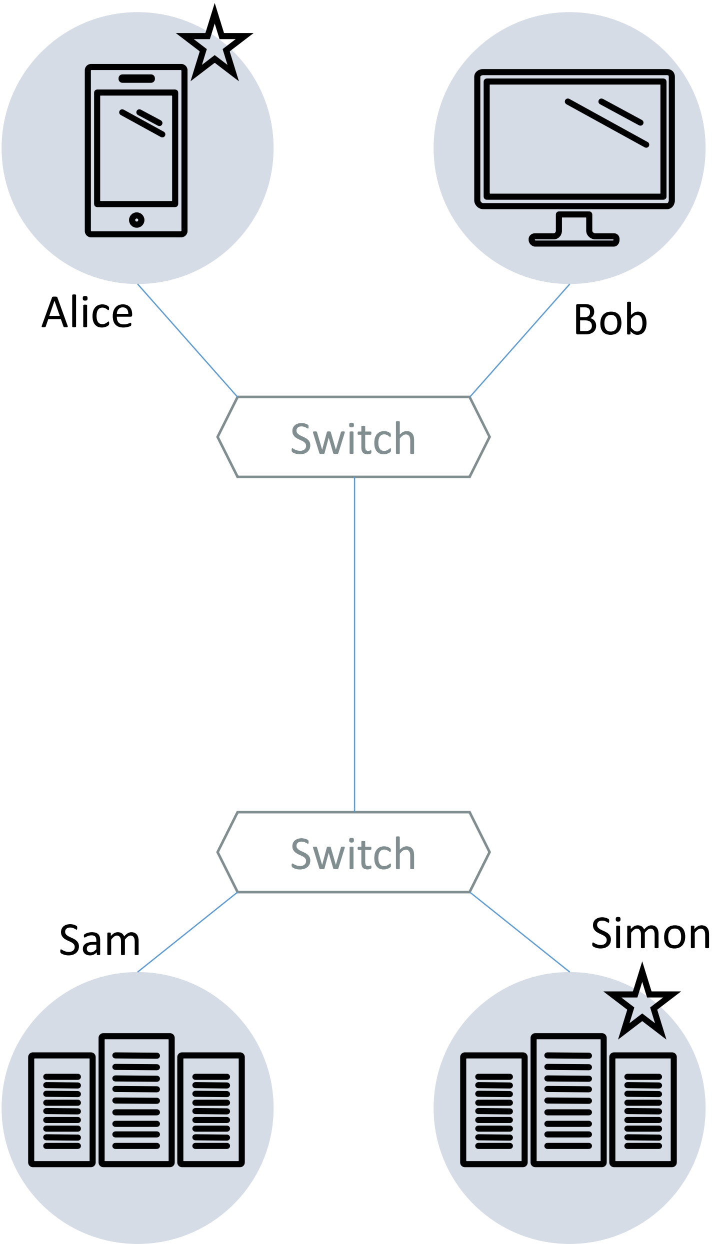
Berkeley
UNIVERSITY OF CALIFORNIA

Network Safety Verification

- Show that something bad cannot happen

- Isolation:
  - A packet of type **t** sent from host **A** never reaches host **B**

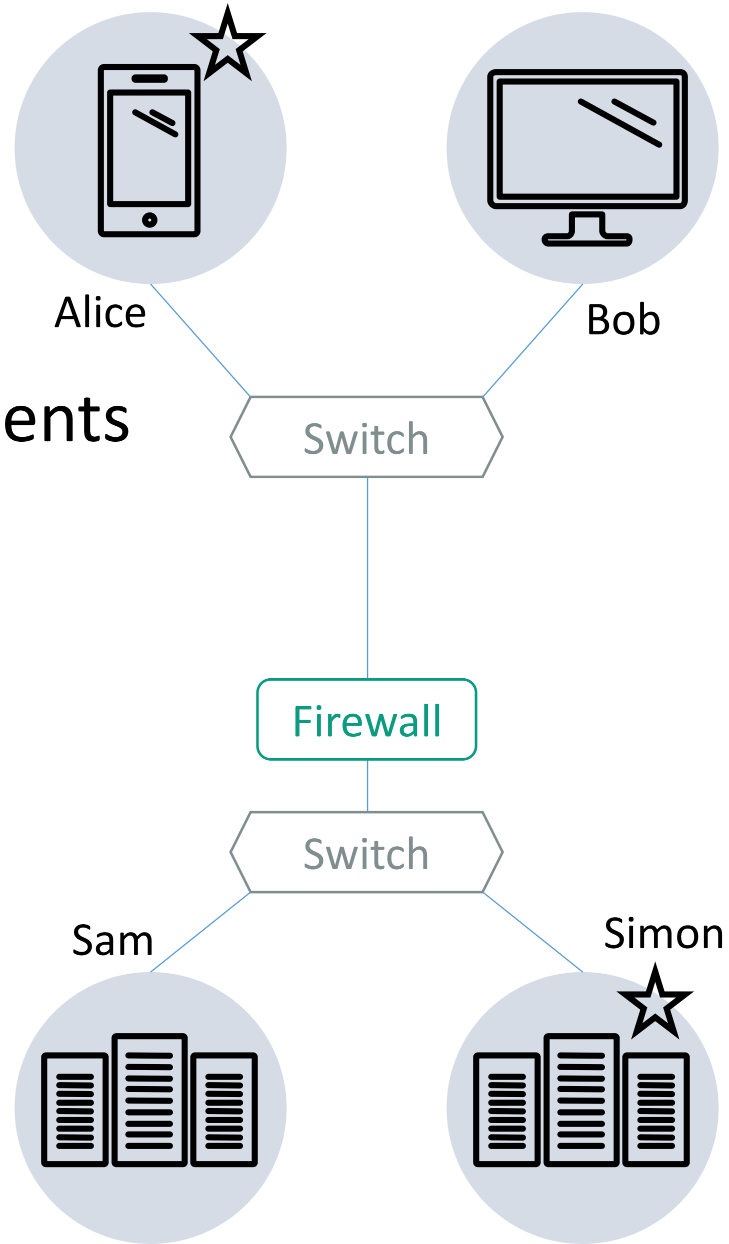
  - E.g., no packets from Simon to Bob



Stateful Networks

Middleboxes: Local functionality enhancements

- Security (firewalls, IDSs,...)
- Performance (caches, load balancers,...)
- New functionality (proxies,...)



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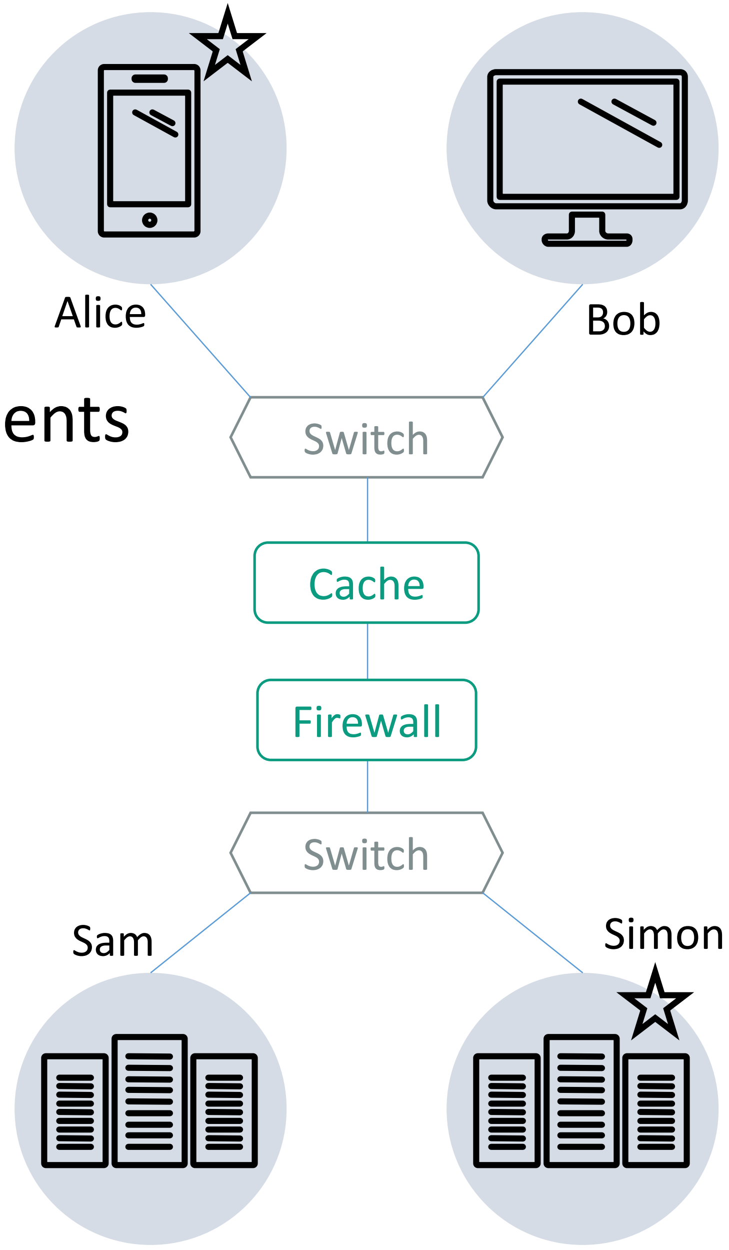


Safety with Middleboxes

- For stateless networks
  - Safety can be checked by tracing the forwarding graph
- Middleboxes make everything harder
  - Rewrite packet headers
  - Behave differently over time – need to reason about history
    - Forwarding of a packet depends on previous packets
    - E.g. cache

Challenges in Stateful Network Verification

- Source code complexity
  - Bro Network Intrusion
    - 101,500 lines of C++, Python, Perl, Awk, Lex, Yacc
  - Snort IDS 220,000 C, …
  - Pfsense 476,438 locs of C,php,scripts,…
- Configuration errors
  - Do the topology and the middlebox configuration satisfy the safety property?
  - Major source of network failures [IMC:RJ13]

[IMC:RJ13] Potharaju R., Jain N. Demystifying the dark side of the middle: a field study of middlebox failures in datacenters. IMC 2013

Our approach for verifying stateful networks

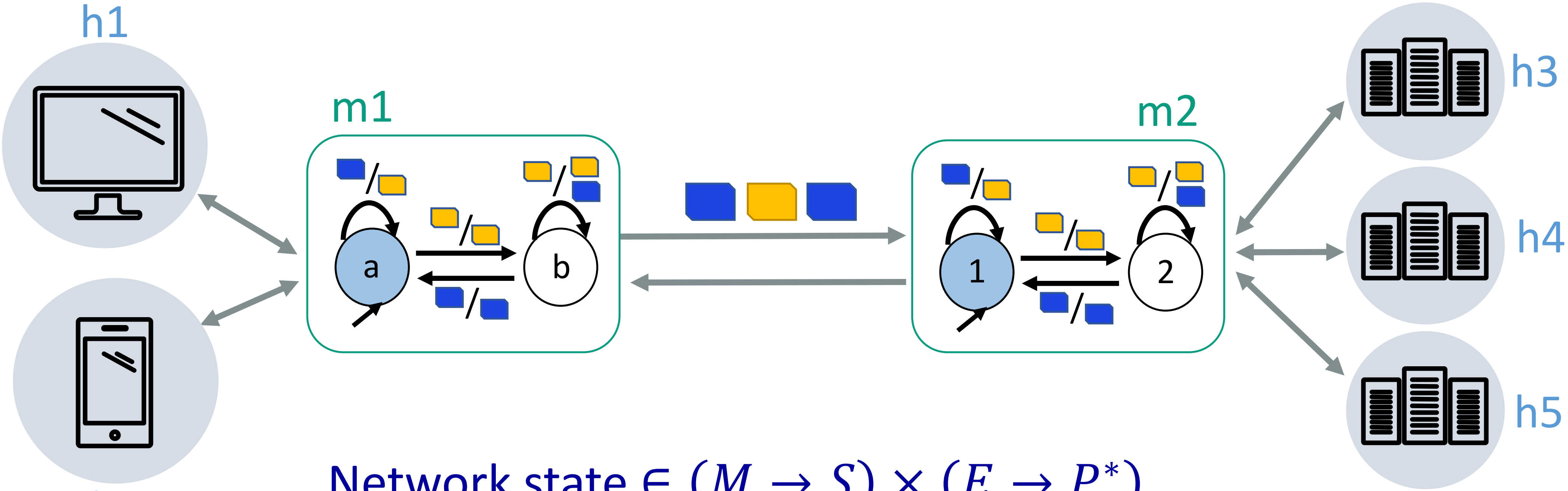
- Abstraction: over-approximate network behavior
  - If isolation is preserved by the over-approximation, the network is safe
  - If violation is detected, may be a false alarm

Abstractions for stateful networks

Abstracting middleboxes as finite state machines (FSM)	No need to analyze the code • Network safety is undecidable
Abstracting the order of packet arrival	Decidability [TACAS’16] • EXPSPACE-complete
Allowing each middlebox to nondeterministically revert to its initial state	Polynomial complexity for isolation • Abstract interpretation

[TACAS’16] Y. Velner, K. Alpernas, A. Panda, A. Rabinovich, M. Sagiv, S. Shenker, S. Shoham: Some Complexity Results for Stateful Network Verification

Concrete Network ≈ Communicating FSMs

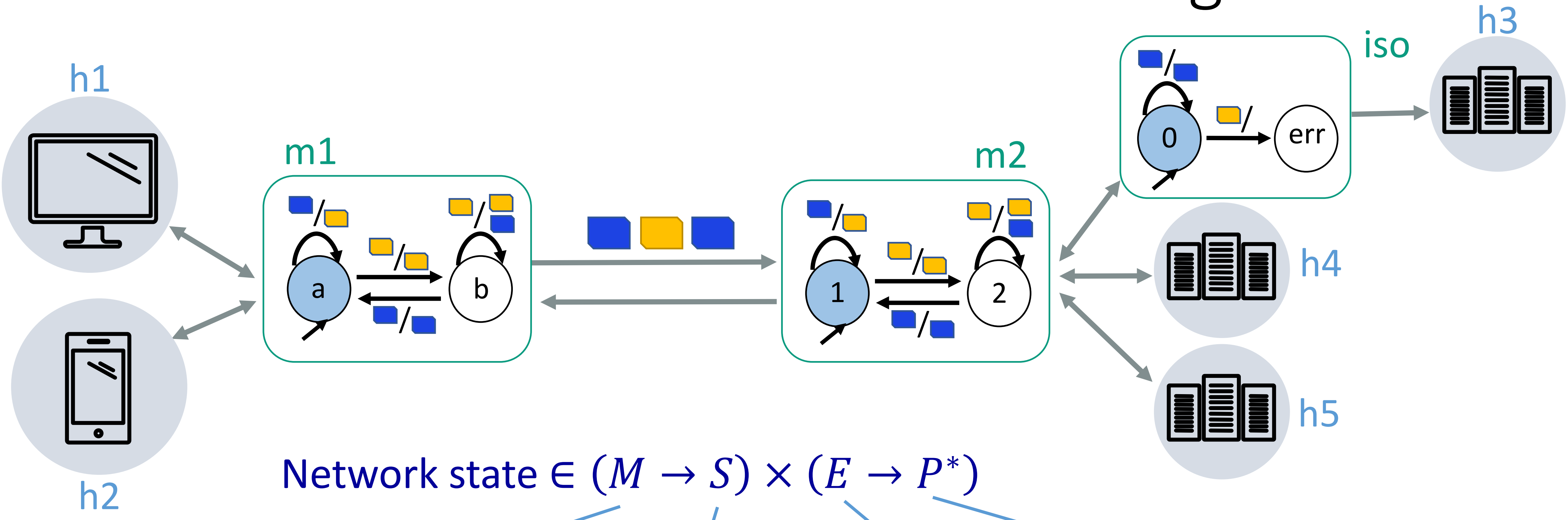


Network state $\in (M \rightarrow S) \times (E \rightarrow P^*)$

mboxes   mbox states   channels   packets $\in$ Hosts $\times$ Hosts $\times$ T

<src, dst, tpe>

Concrete Network ≈ Communicating FSMs



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channels

packets ∈ Hosts × Hosts × T
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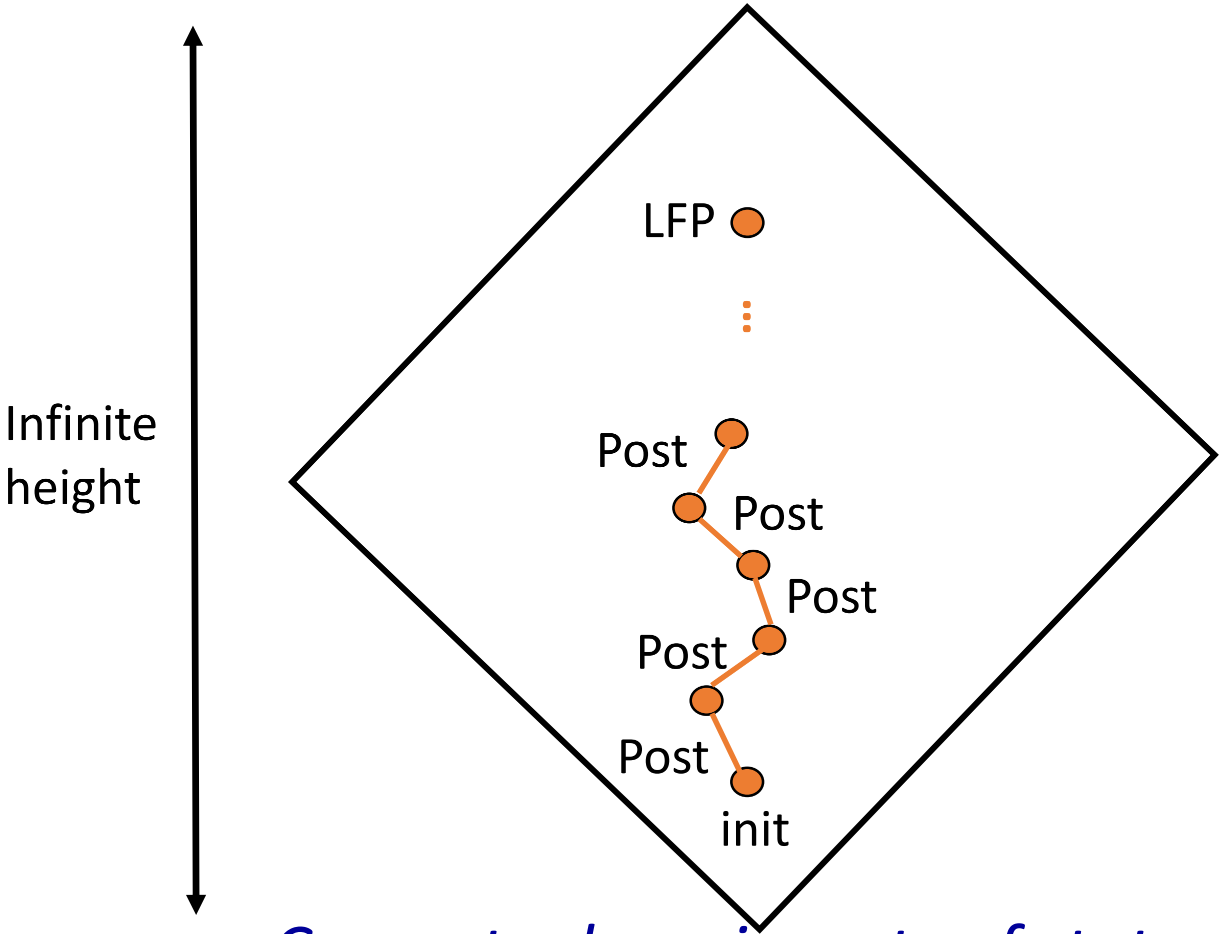
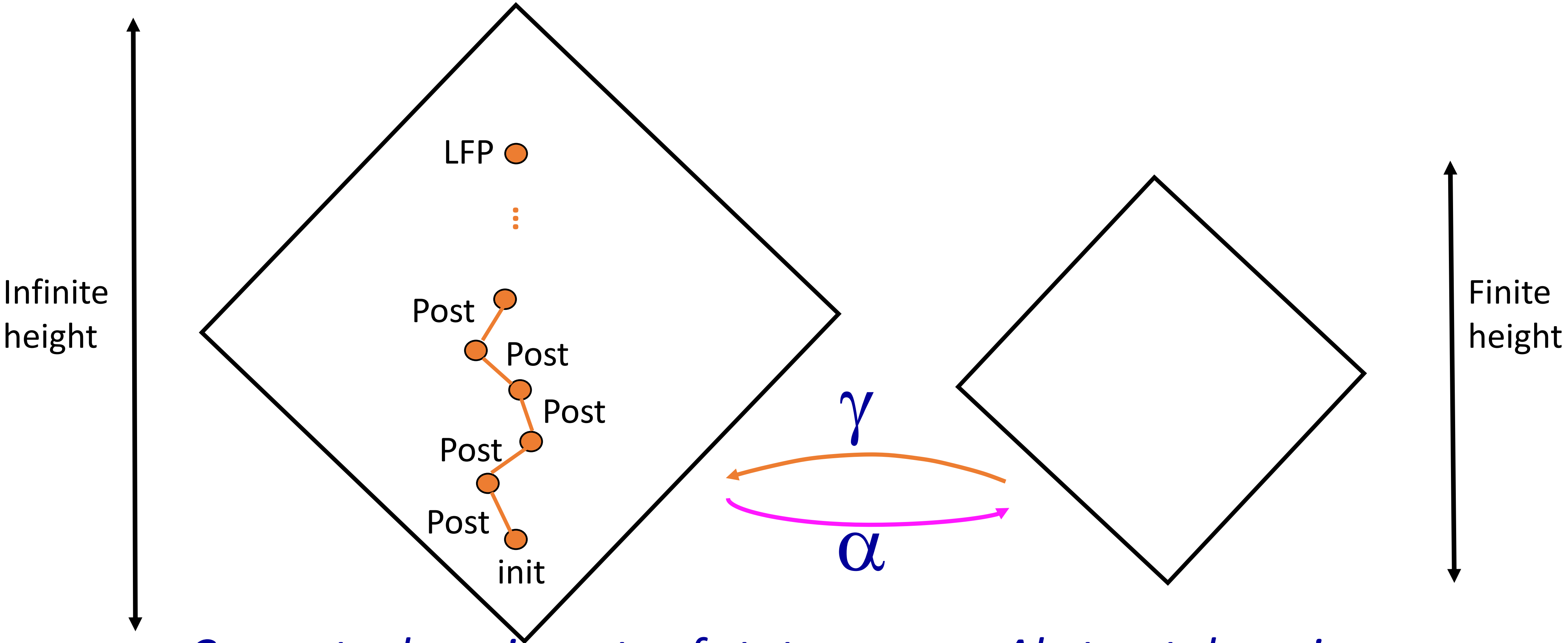
Concrete Interpretation



Concrete domain: sets of states

$$C = \mathbb{P}\big((M \to S) \times (E \to P^*)\big)$$

Abstract Interpretation + *Finite* Abstraction



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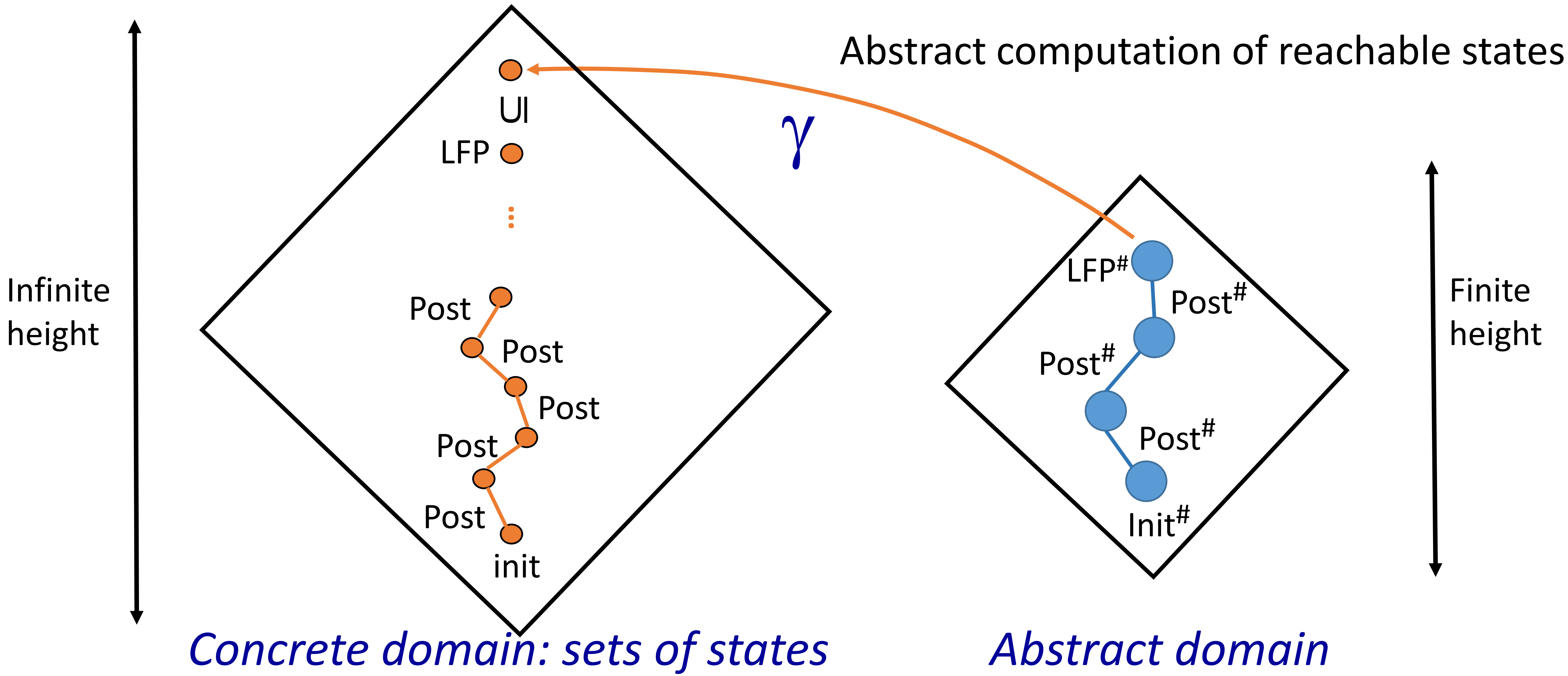

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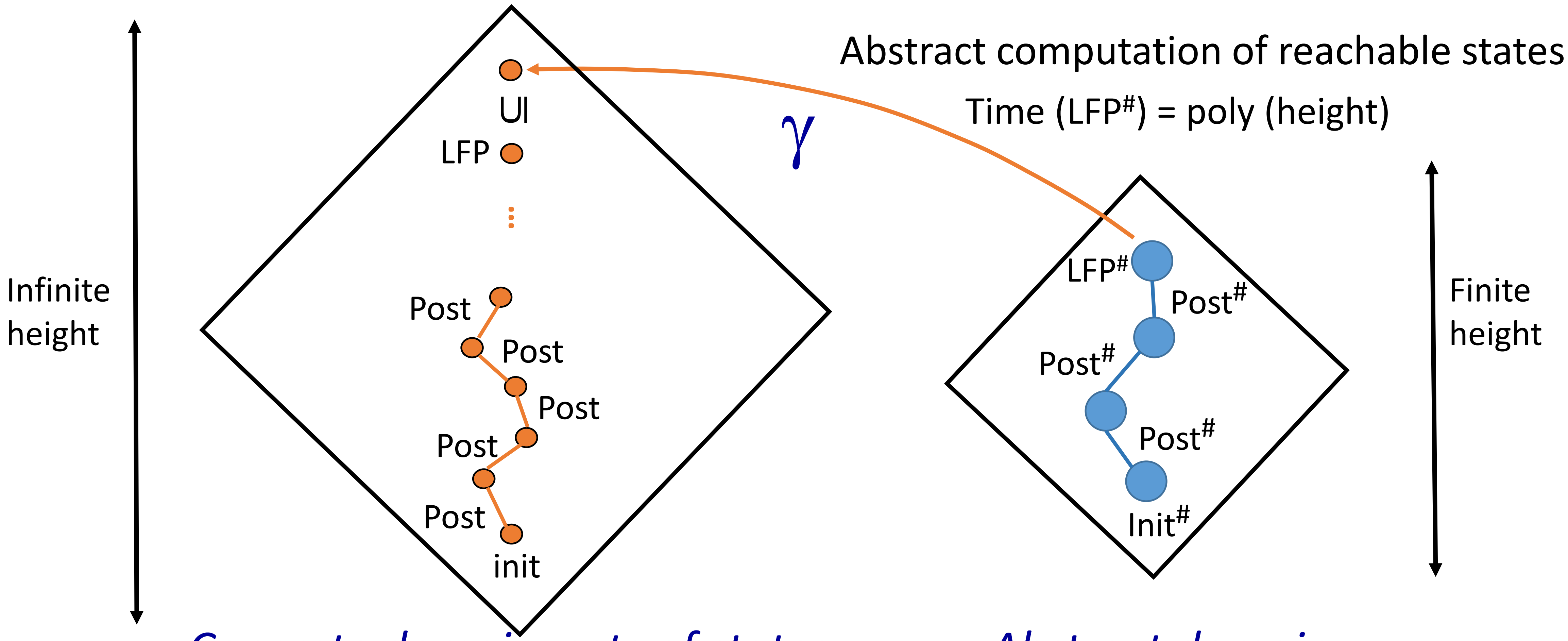

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Network Abstractions

(0) Concrete domain

mboxes   mbox states   channels   packets

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Network Abstractions

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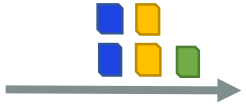
(1) Unordered channels

- Channels as multisets of packets



$$\mathbb{P}\big((M \to S) \times (E \to \underbrace{P \to \mathbb{N})\big)}_{\text{Infinite height}}$$

Network Abstractions

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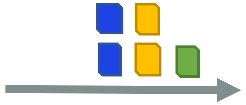

$$\mathbb{P}\big((M \to S) \times (E \to \underbrace{P \to \mathbb{N}}_{\text{Infinite height}})\big)$$

> Safety verification is decidable [TACAS'16]
> - Reduction to/from Petri Net coverability
> - EXPSPACE complexity

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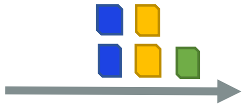

$$\mathbb{P}\big((M \to S) \times (E \to P \to \mathbb{N})\big)$$

(2) Counter abstraction on channels

- Channels as sets of packets

$$\mathbb{P}\big((M \to S) \times (E \to \mathbb{P}(P))\big)$$

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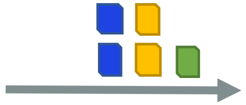

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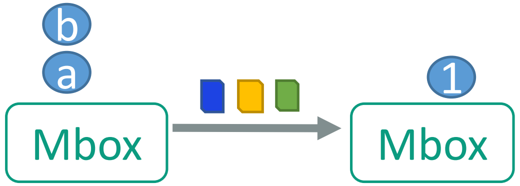
(3) Cartesian Abstraction

- No correlations between mboxes, channels, packets



$$\mathcal{A} = \big(M \to \mathbb{P}(S)\big) \times \big(E \to \mathbb{P}(P)\big)$$

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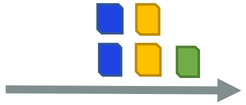

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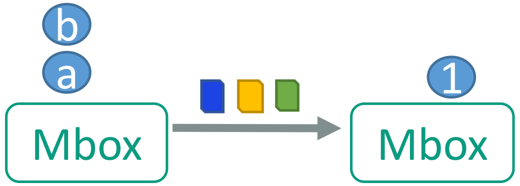

$$\mathcal{A} = \big(M \to \mathbb{P}(S)\big) \times \big(E \to \mathbb{P}(P)\big)$$

Recall: height($\mathbb{P}$(X)) = |X|

Time(LFP$^{\#}$) = poly(|M|, |S|, |E|, |P|)

Network Abstractions

mboxes mbox states channels packets

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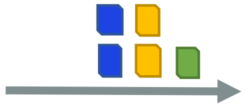

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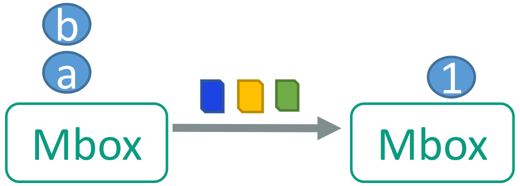
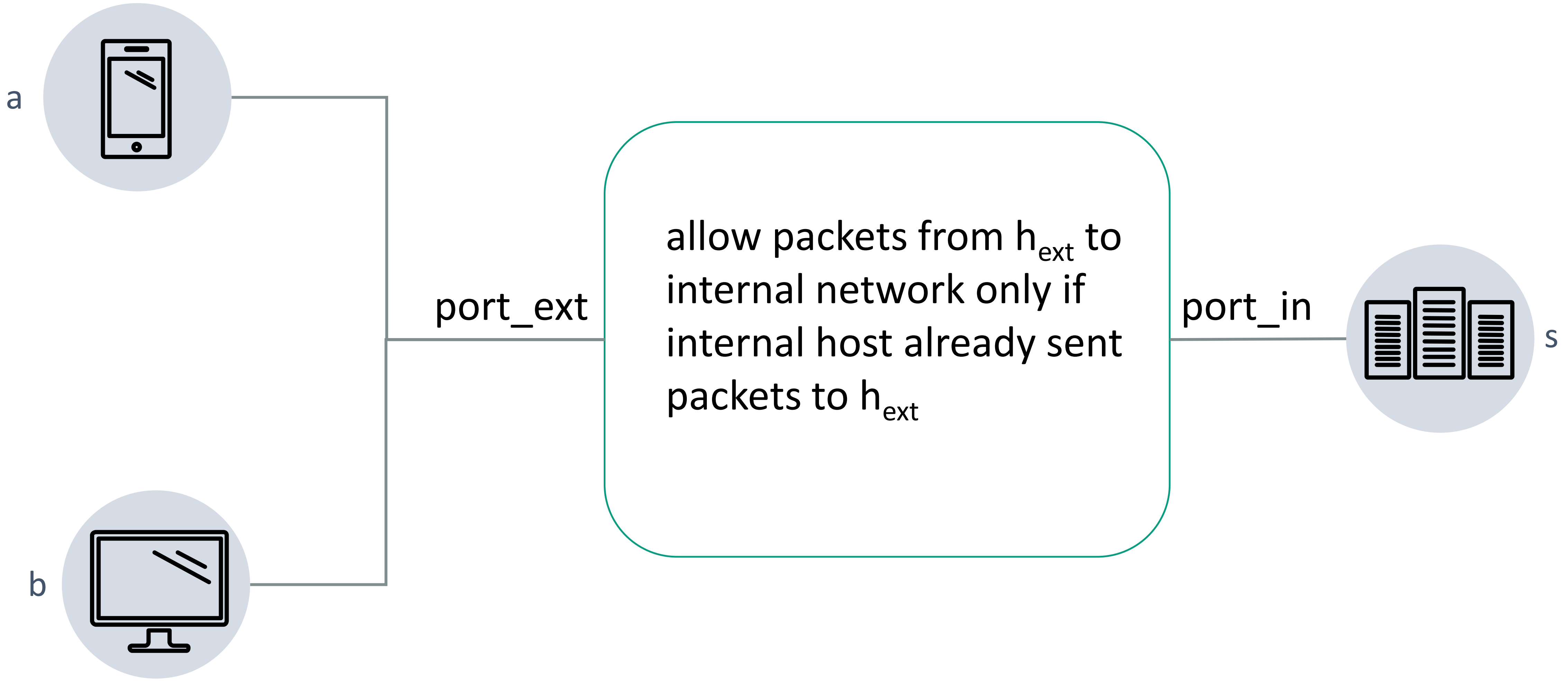


$$\mathcal{A} = \big(M \to \mathbb{P}(S)\big) \times \big(E \to \mathbb{P}(P)\big)$$

Unfortunately
|S| = exp (|Hosts|)

Time(LFP$^{\#}$) = poly(|M|, |S|, |E|, |P|)

Example: Hole-Punching Firewall



Example: Firewall

AMDL: Abstract MBox Def. Lang.

- Similar to [SIGCOMM'16]

- States ≈ n-ary relations
- Topology agnostic
- Encode FSM compactly
  - For fixed topology finite state

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  port_in ? <src,dst,tpe> =>
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Example: Firewall

AMDL: Abs

- Similar to [S

trusted: $\mathbb{P}(\text{Hosts})$

$|S| = 2^{|\text{Hosts}|}$

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Middlebox-level Abstraction

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- Problem: Middlebox state space exponential in number of hosts
- Solution: apply Cartesian abstraction
  - Ignore some correlations *within* a middlebox state
  - **How to decompose a state into sub-states?**

Packet state

- Alternative (isomorphic) state representation
- Depends on AMDL: the restricted way in which middleboxes query and update their state

Packet state example

(src, dst, type) ↦ `{queries which hold}`

```
(1,_,_) ↦ {}
(2,_,_) ↦ {}
```

```
hole_punching_firewall =      // hosts ∈ {1, 2}
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```

Query name

Query

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```
(1,_,_) ↦ {srcT}
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Query name

Query

Cartesian packet state example

```
(1,_,_) ↦ {} {srcT}
(2,_,_) ↦ {} {srcT}
```

```
hole_punching_firewall =      // hosts ∈ {1, 2}
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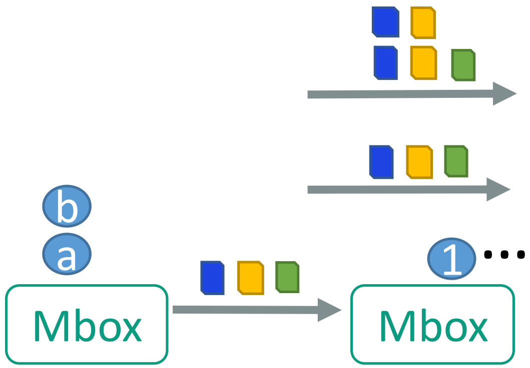
Query

Summary: Network Abstractions

(1) Unordered channels

(2) Counter abstraction on channels

(3) Network-level Cartesian Abstraction



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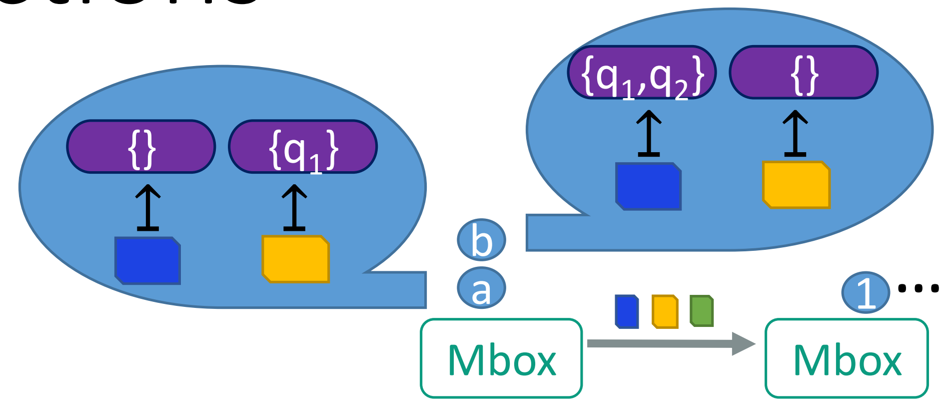

Summary: Network Abstractions

(1) Unordered channels

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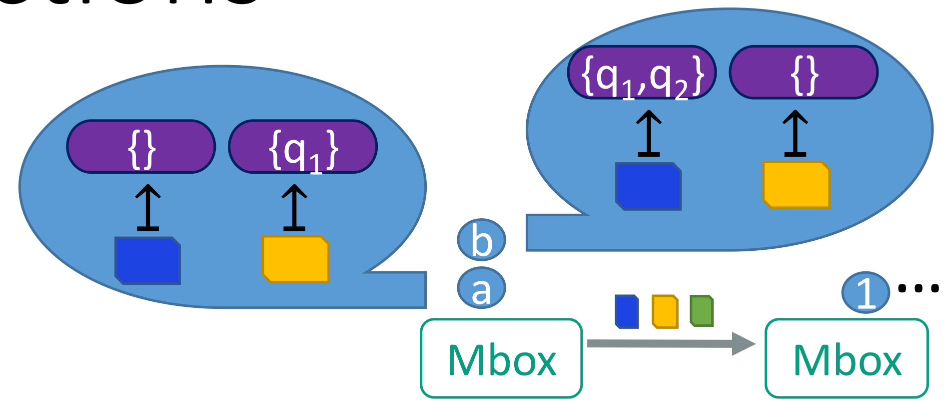
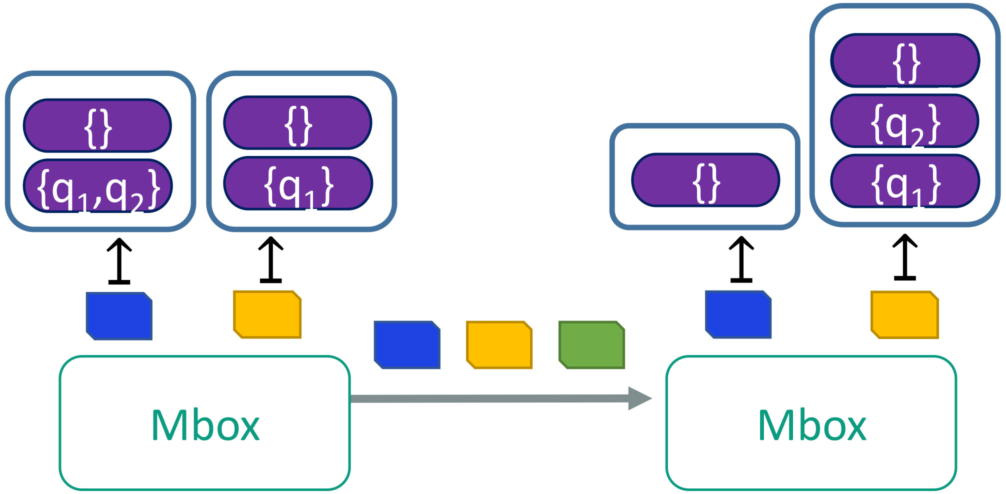
(4) Middlebox-level Cartesian abstraction

- No correlations between packet states
- But **keep** correlations between **queries**

$$\mathcal{A} = \left(M \to P \to \mathbb{P}(\mathbb{P}(Q))\right) \times \left(E \to \mathbb{P}(P)\right)$$

Time($LFP^{\#}$) = poly(|M|, |P|, $2^{|Q|}$, |E|)





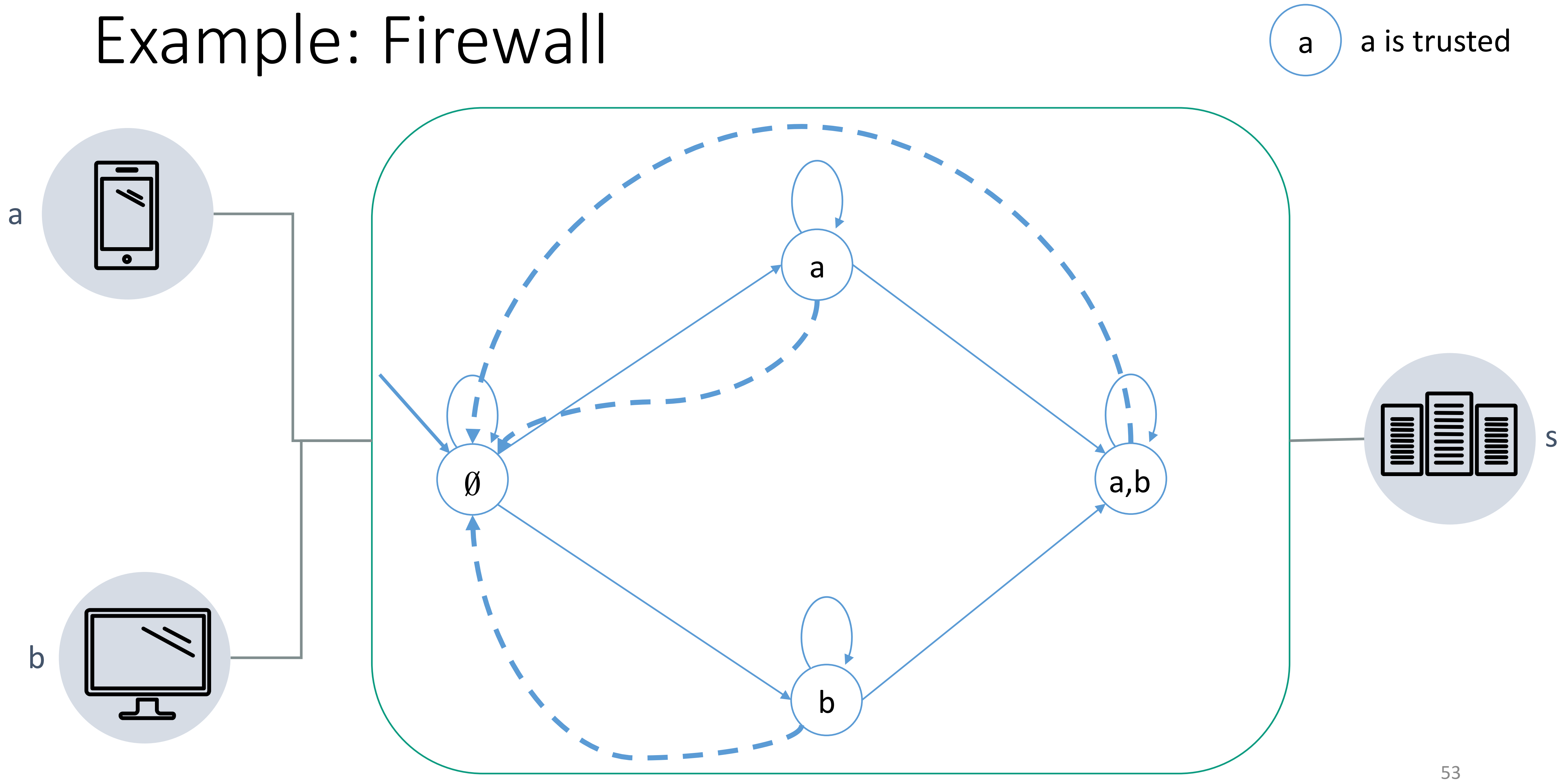
When is this precise?

Reverting Middlebox Abstraction

Cartesian abstraction ≈ Reverting middlebox abstraction

- Let middleboxes independently revert to their initial state

Example: Firewall

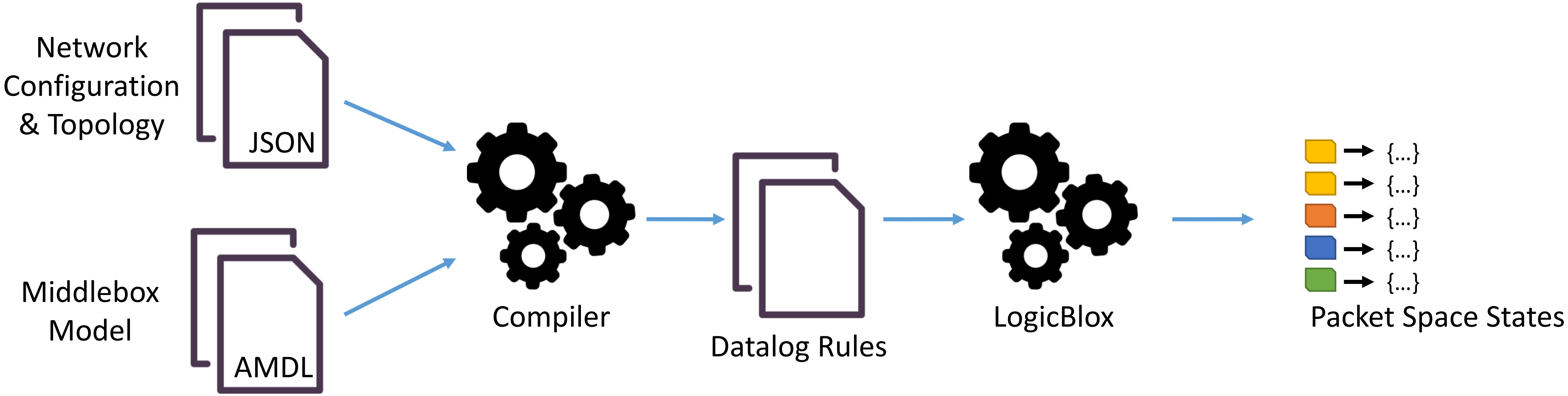


Reverting Middlebox Abstraction

Theorem: If the network is correct in the presence of packet reordering and middlebox reverts then our analysis is precise.

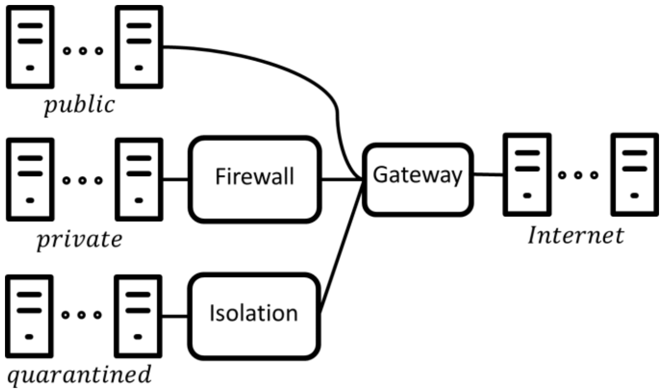
- Common wisdom: Network resets make verification harder
  - Reachability for Petri nets with resets is undecidable
- But: Simplifies the task of automatic verification of networks
  - The analysis is precise for isolation
  - No false alarms

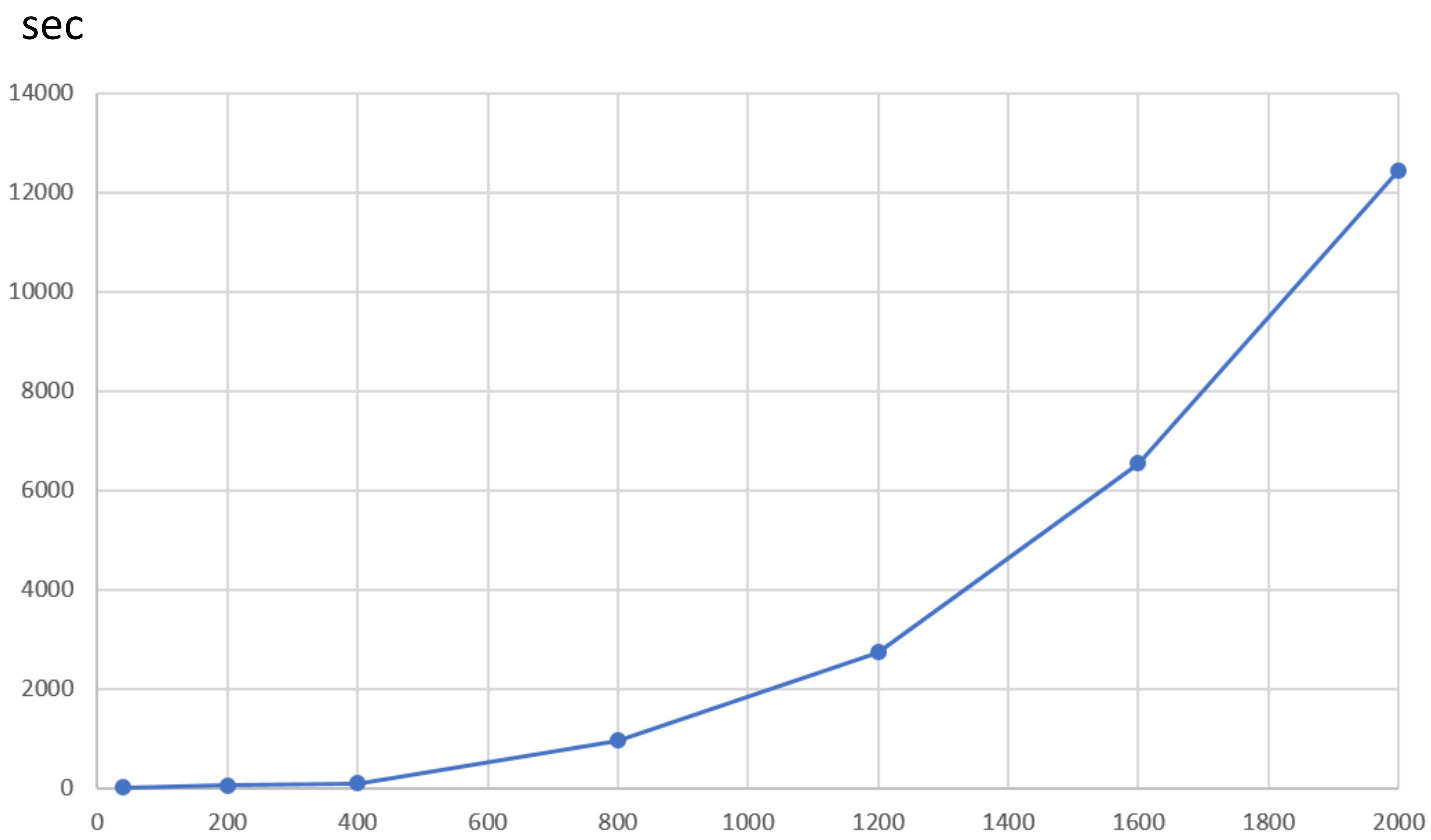
Initial Experimental Results



Scalability Testing - Hosts

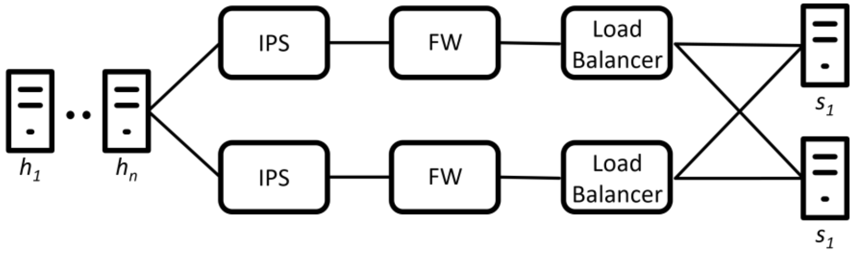
- Enterprise network with 3 subnets
  - Each with a different security policy
- Isolation between *quarantined* and *Internet*

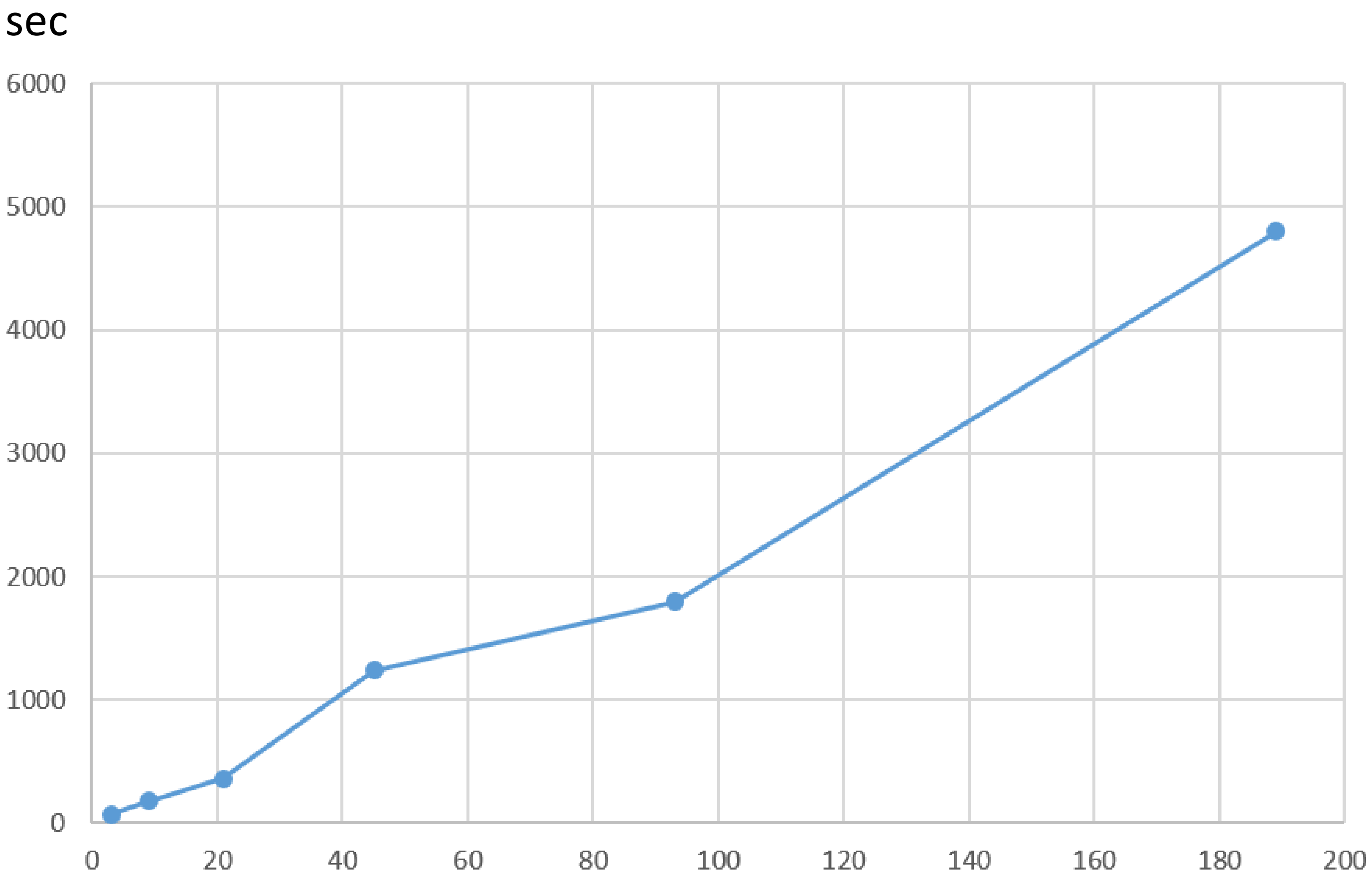




Scalability Testing - Middleboxes

- Servers with parallel middlebox chains
- Scaled the number of chains
- Isolation – packets from h_1 never reach bottom flow





Summary

- Abstract interpretation of stateful networks
    - Unordered + Counter + Cartesian X2
- AMDL – Abstract Middlebox Definition Language
- Packet effect semantics for middelboxes
    - Enables middlebox-level Cartesian abstraction
- Precise for unordered channels + reverting middleboxes

Further Work

- Correlated middlebox states
- Temporal properties
- Parameterized case

Seeking students and postdocs

erc Supervised Verification of Infinite-State Systems