Scalable Verification of Stateful Networks

Aurojit Panda, Ori Lahav, Katerina Argyraki, Mooly Sagiv, Scott Shenker

UC Berkeley, TAU, ICSI

Roadmap

- Why consider stateful networks?
- The current state of stateful network verification?
- VMN: Our system for verifying stateful networks.
- Scaling verification.

Why consider *stateful* networks?

Network State Increasingly Common

- 1/3rd of deployed network devices are middleboxes
  - These are typically stateful (e.g., firewalls, caches, etc.)
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  - SNAP: Stateful Network-Wide Abstractions for Packet Processing

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- Later in this conference: stateful programming for P4 switches.
    - SNAP: Stateful Network-Wide Abstractions for Packet Processing
- Bottomline: Stateful is increasingly relevant.

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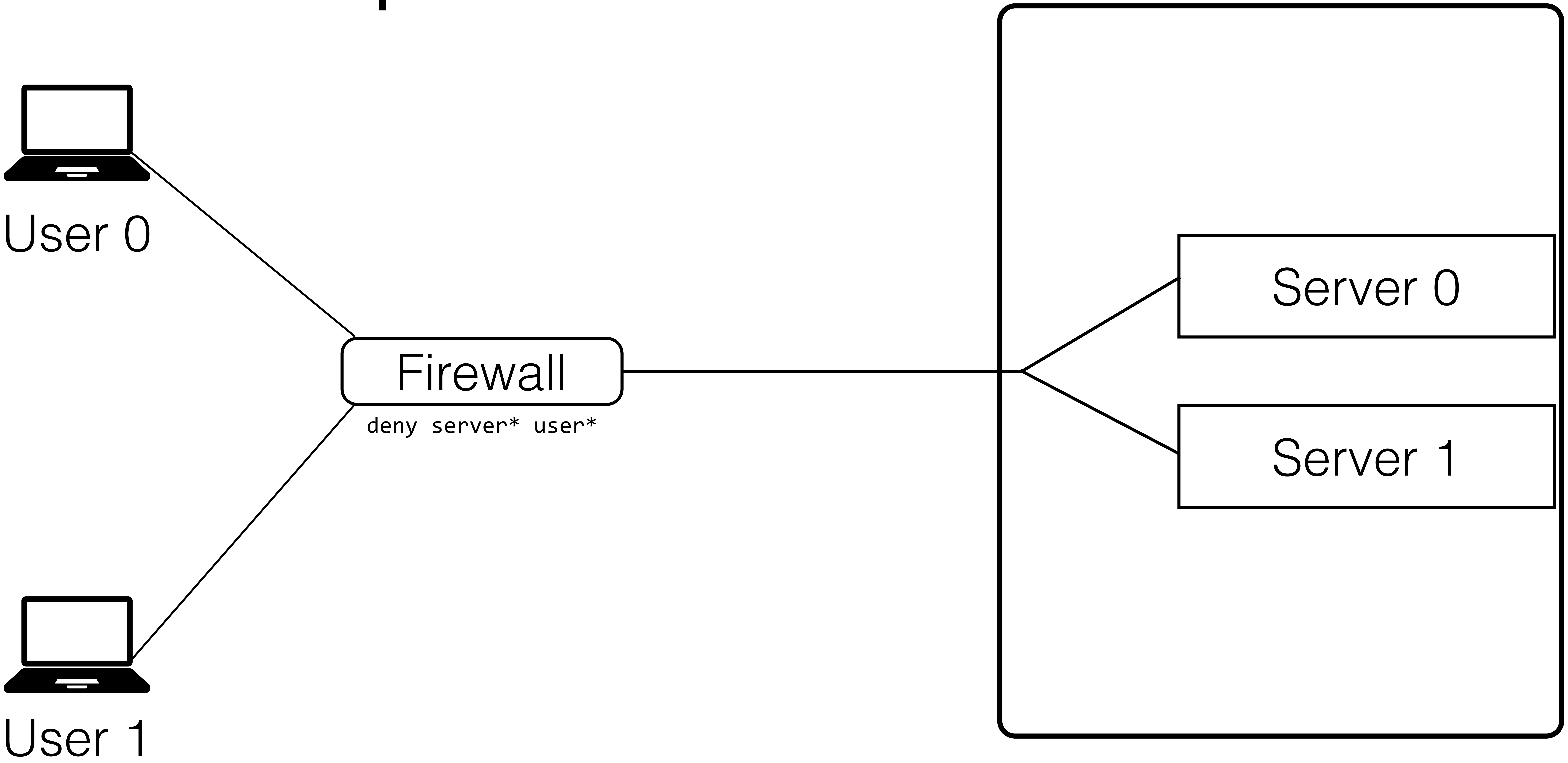
- But statefulness raises some important issues:
  - Invariants include temporal aspects.
  - Storing state can result in spooky action at a distance.

Temporal Invariants



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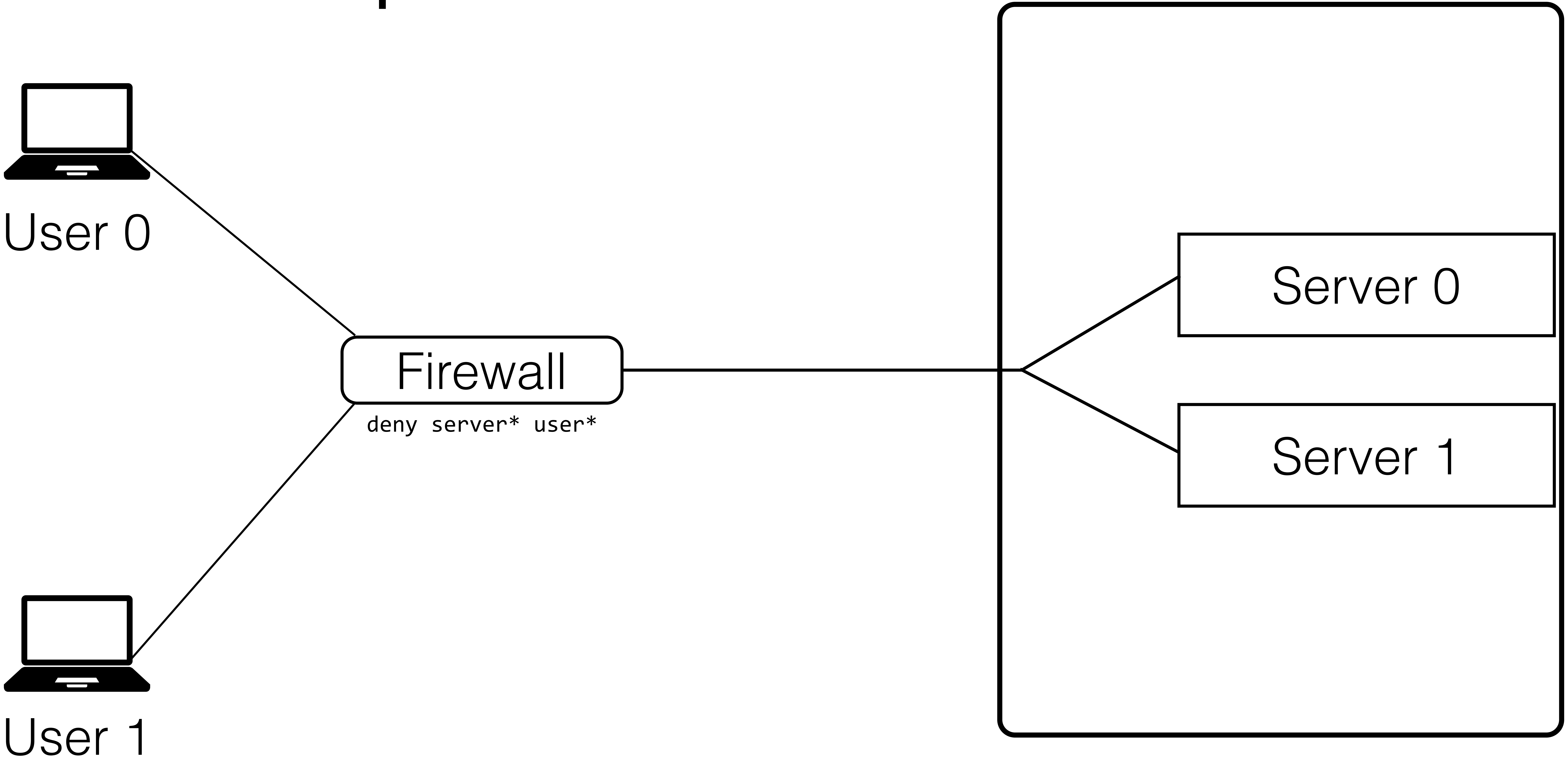

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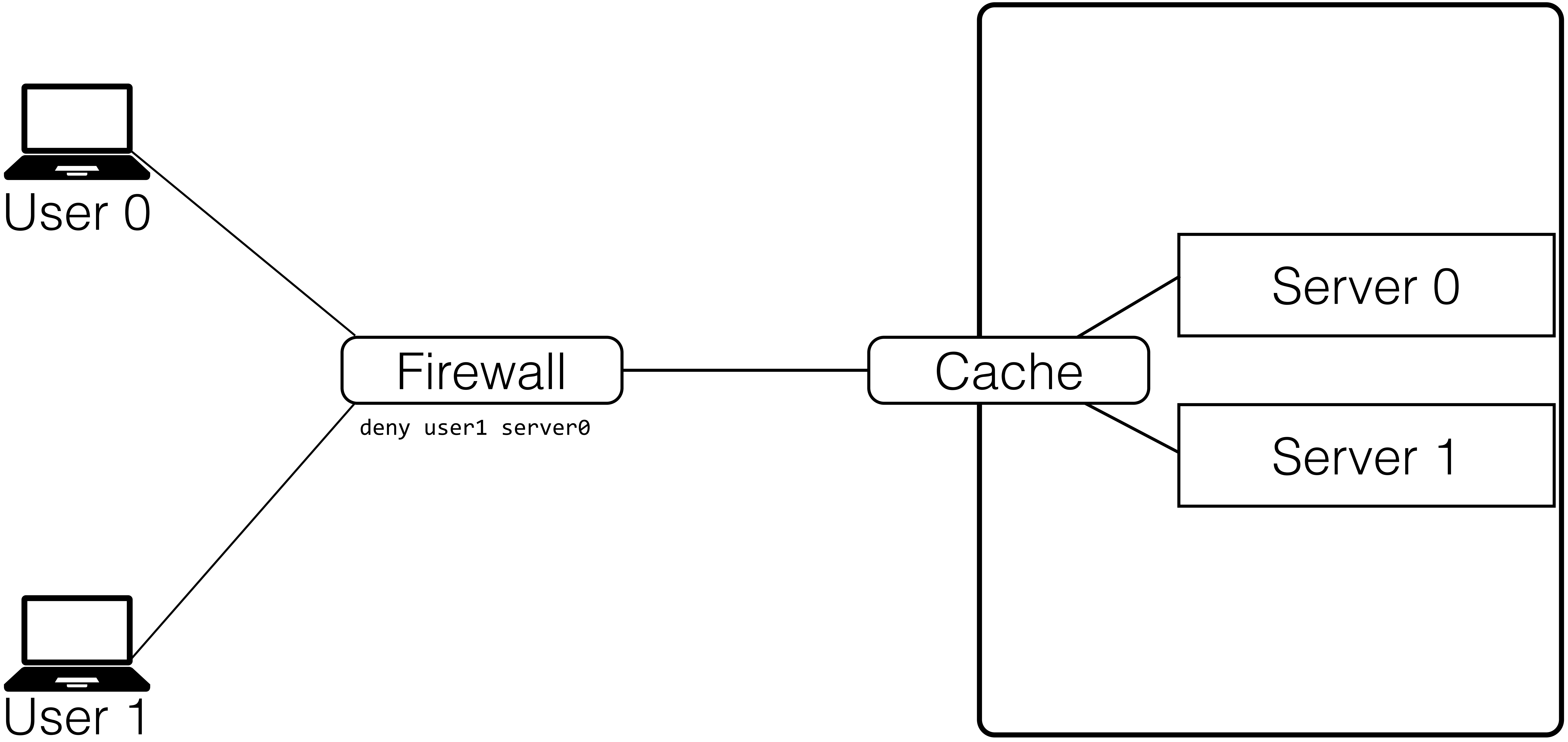
Standard Reachability

Temporal Property

Action at a Distance



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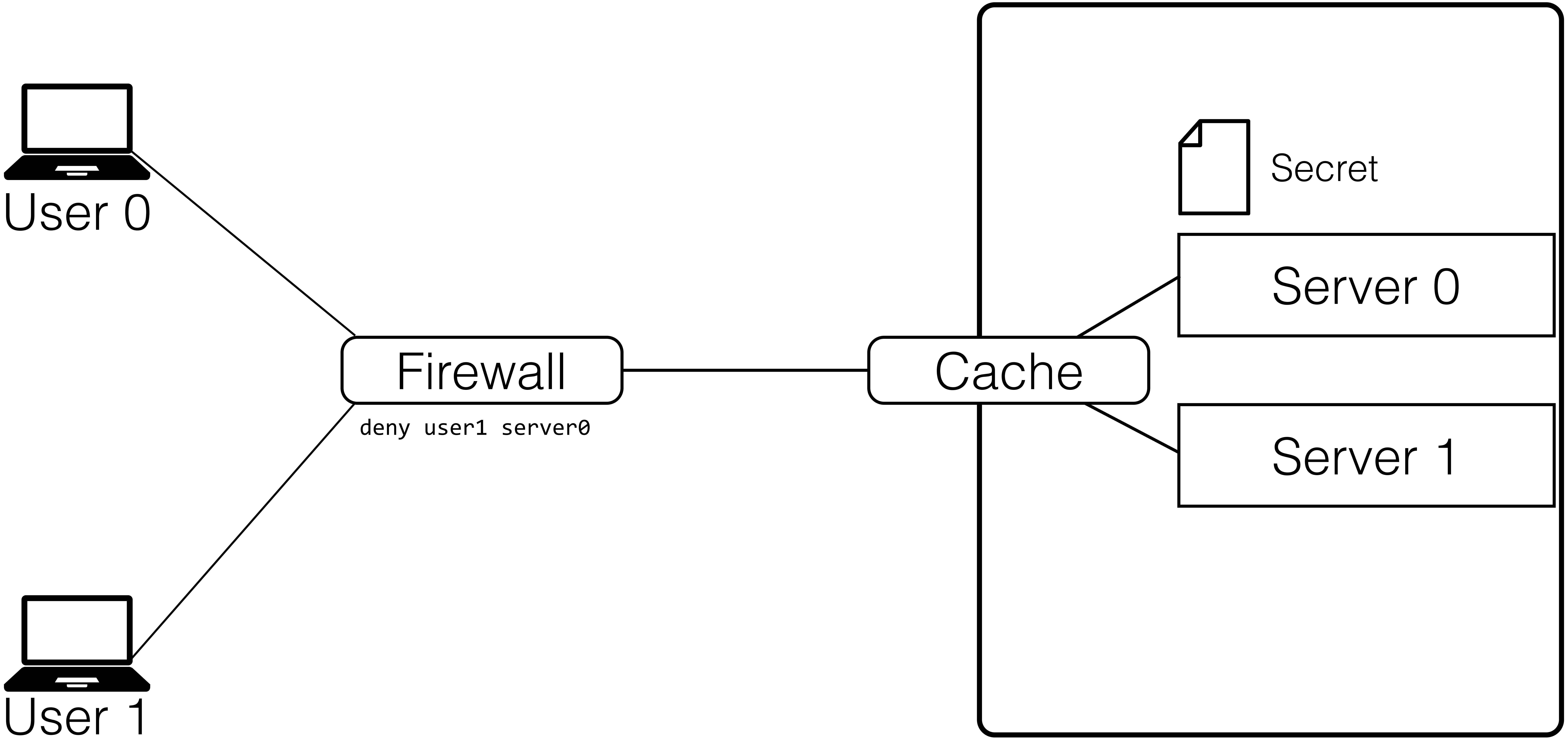

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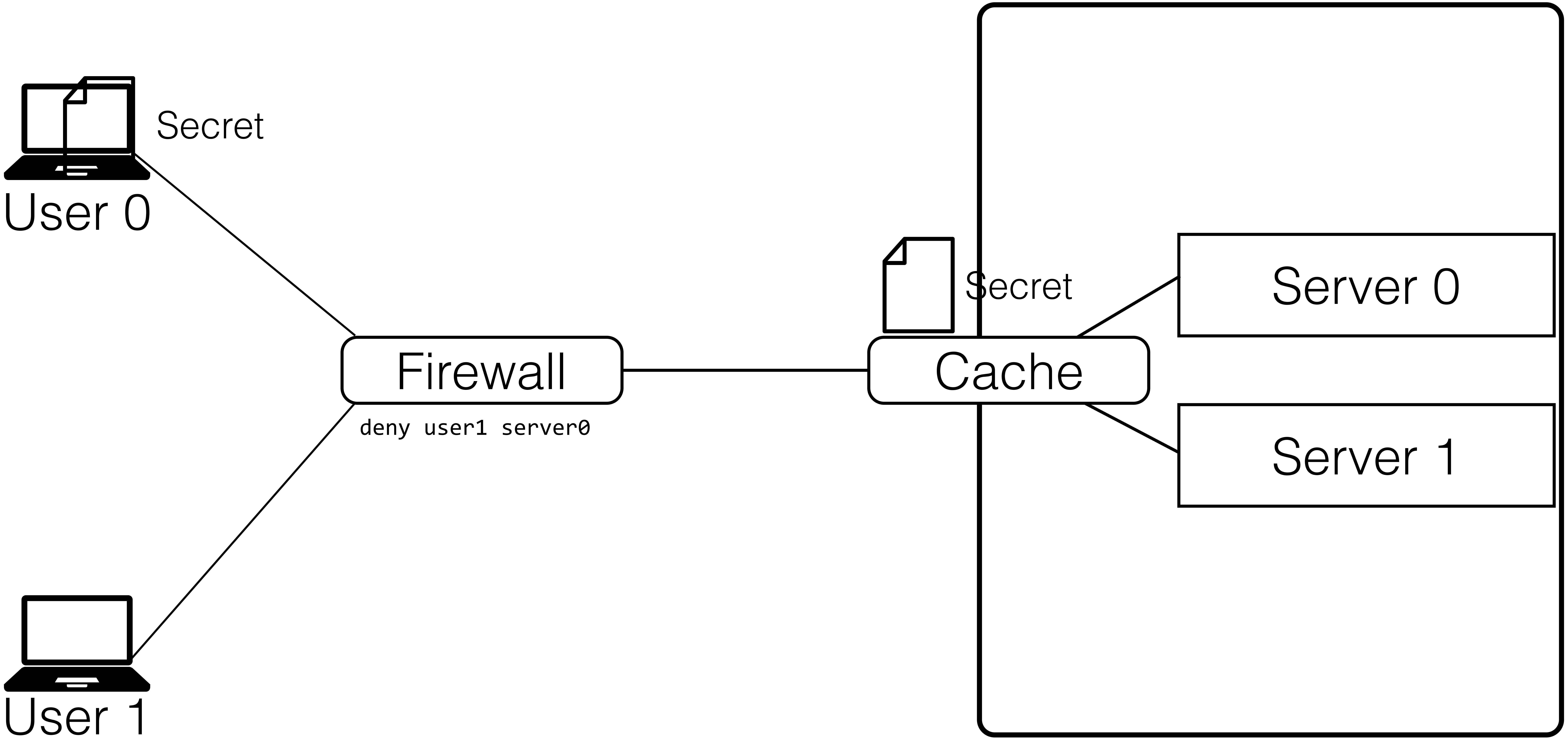

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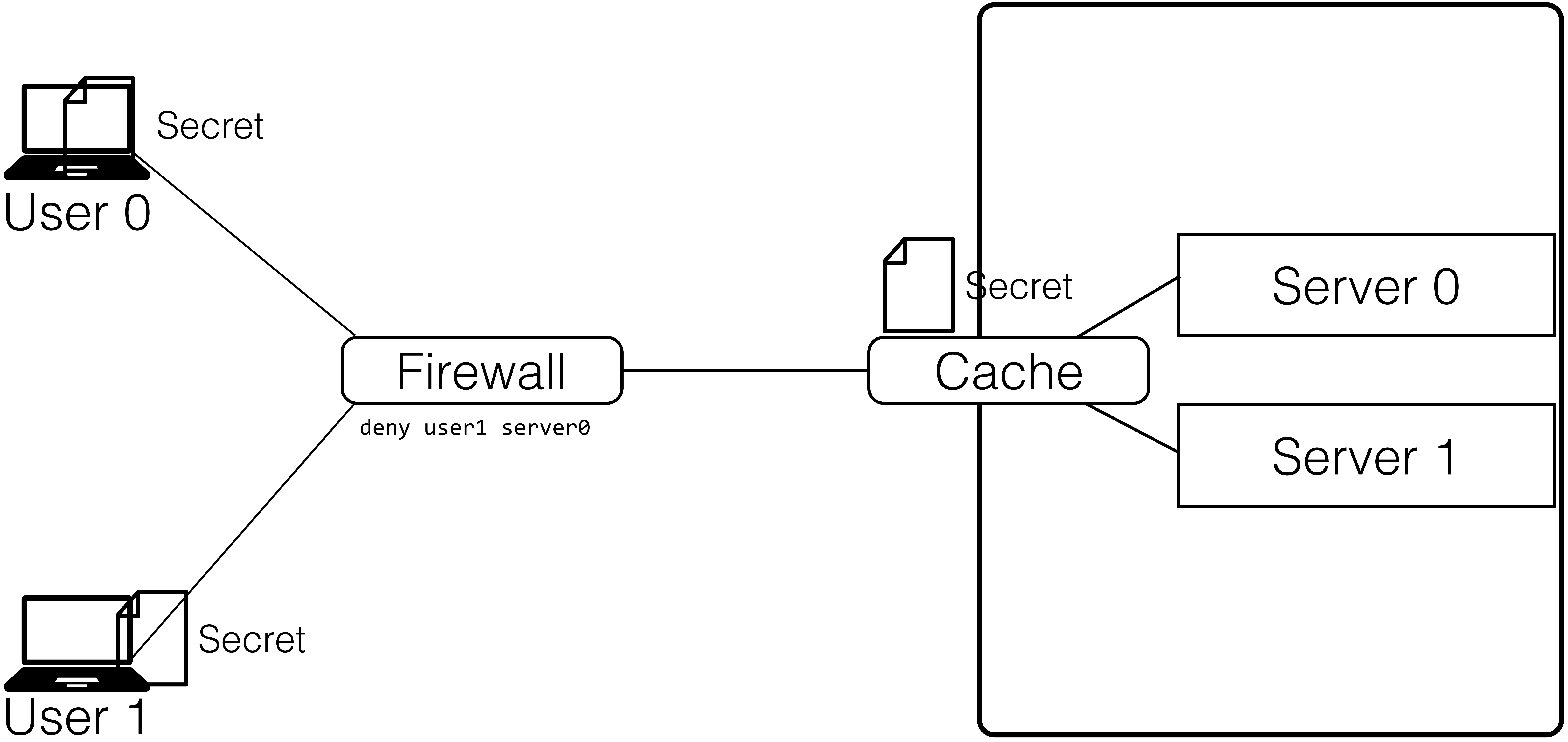

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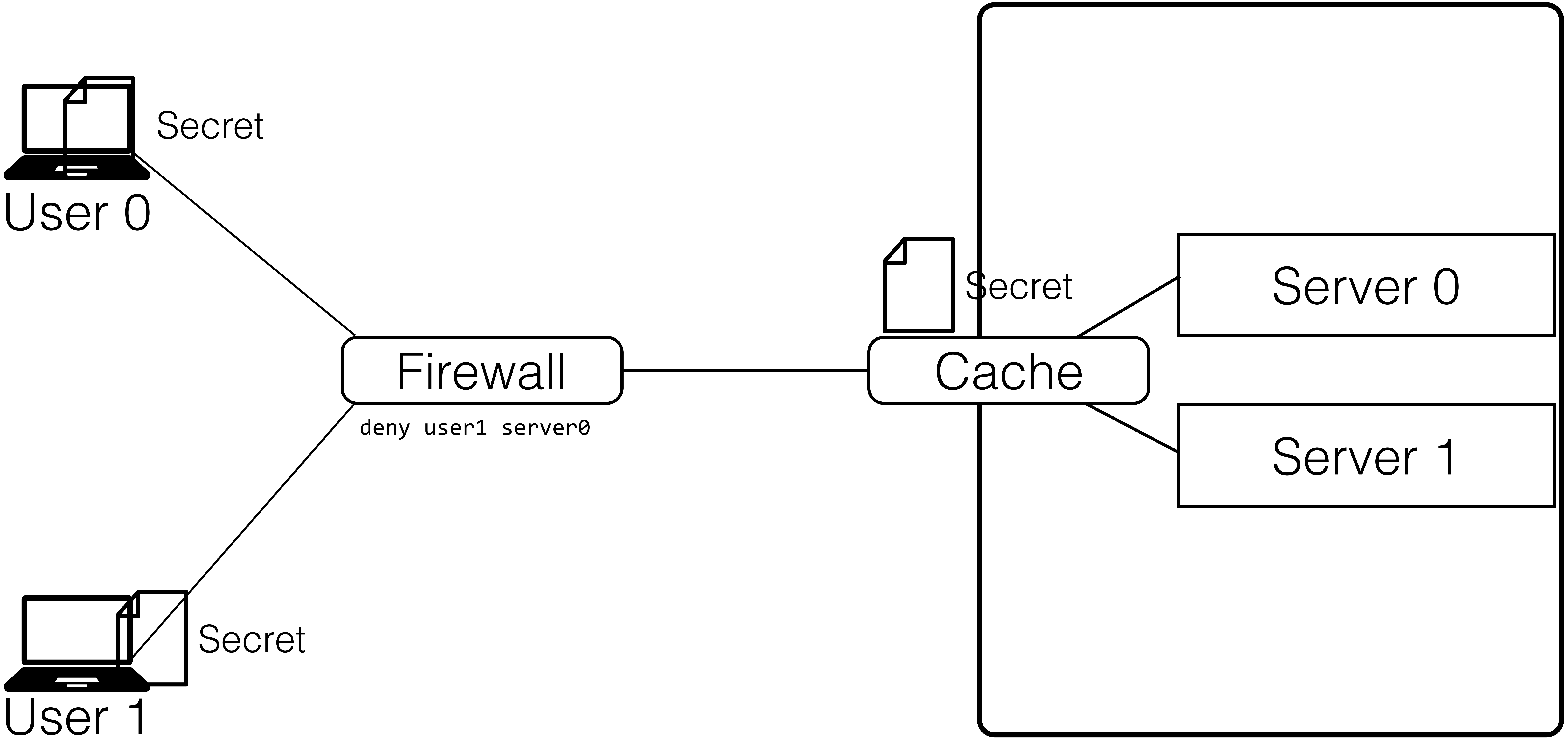

~~User 1 receives no packets from Server 0~~

User 1 receives no data from Server 0

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- Verification for stateful networks

  SymNet: Uses symbolic execution to verify networks with middleboxes.

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VMN: System for **scalable** verification of **stateful networks.**

VMN Flow

Model each middlebox in the network

↓

Build network forwarding model

↓

Logical Invariants

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SMT Solver (Z3 from MSR)

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↓ Example of violation

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  - Configuration is in terms of higher level abstractions
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  - Operators think and configure in terms of these abstractions.
  - Verify invariants written in these terms.

Example Middlebox Configuration

- Drop all packets from connections transmitting infected files.
    - How to define infected files: bit pattern for all worms: not really accurate
    - Also not how operators think about this.

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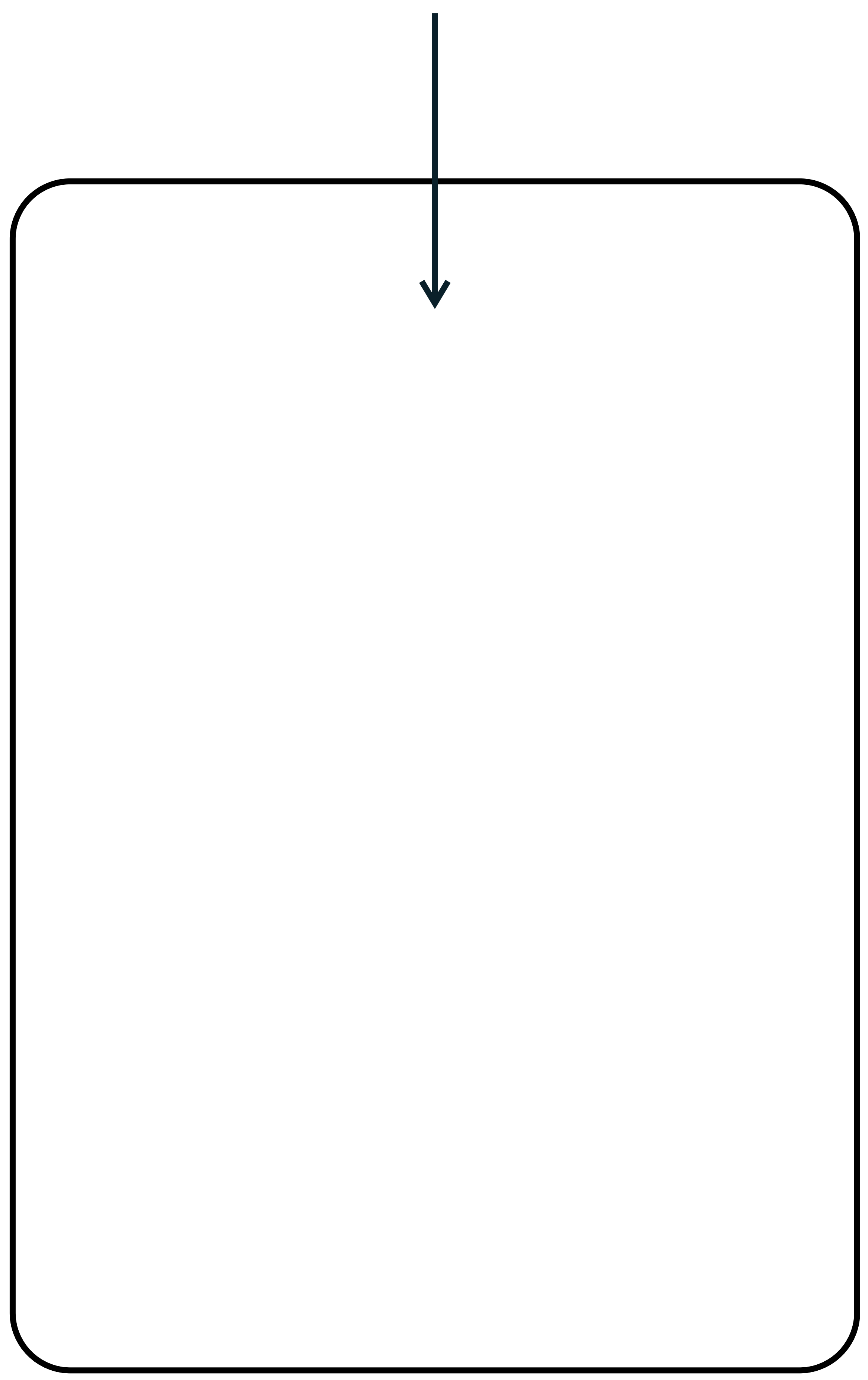
- Model specifies forwarding behavior in terms of these abstractions.
  - Need to know forwarding behavior to reason about reachability.
  - Require that any state that affects forwarding behavior also specified.

Modeling Middleboxes



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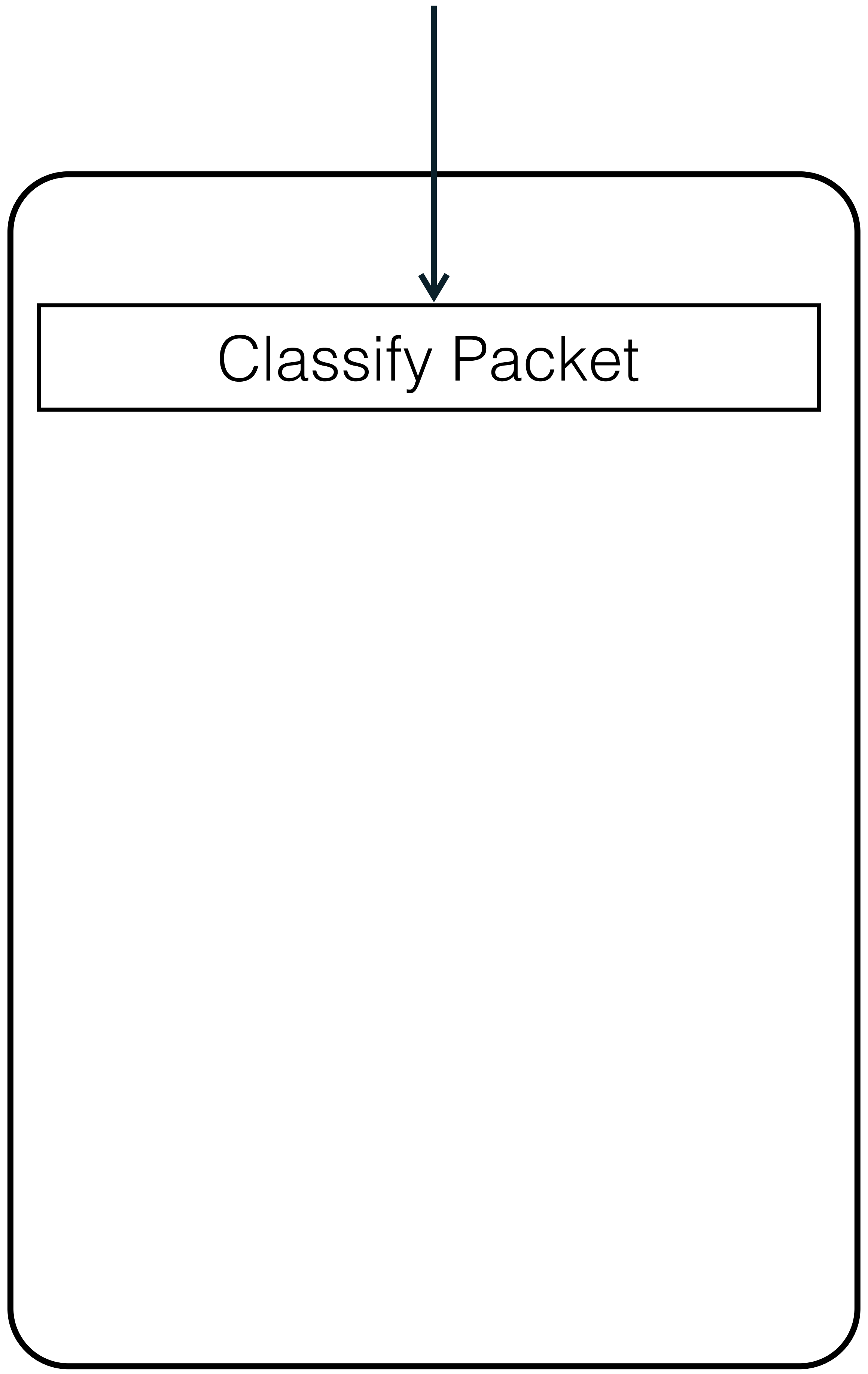

Determines what application sent a packet, etc.
Complex, proprietary processing.

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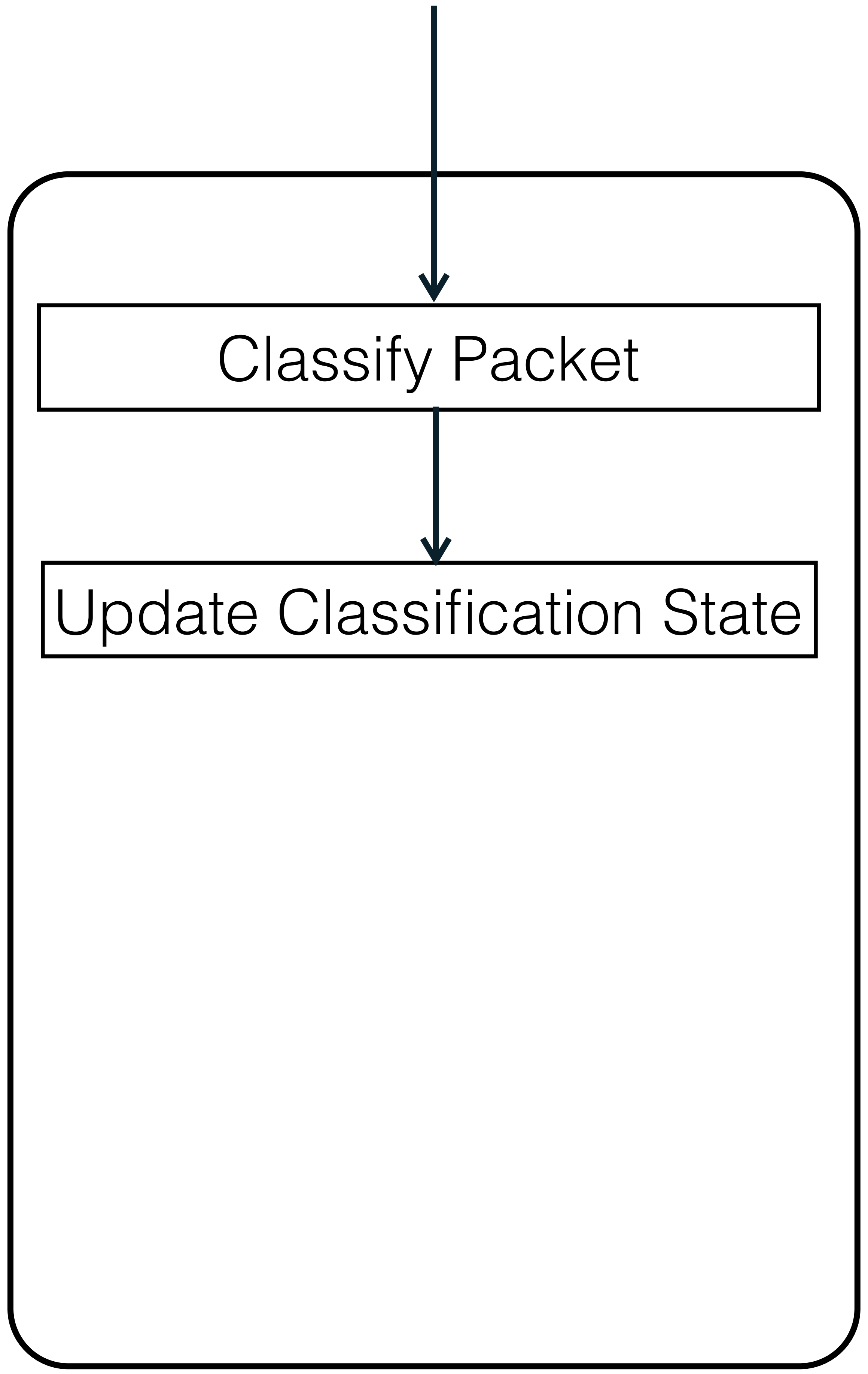

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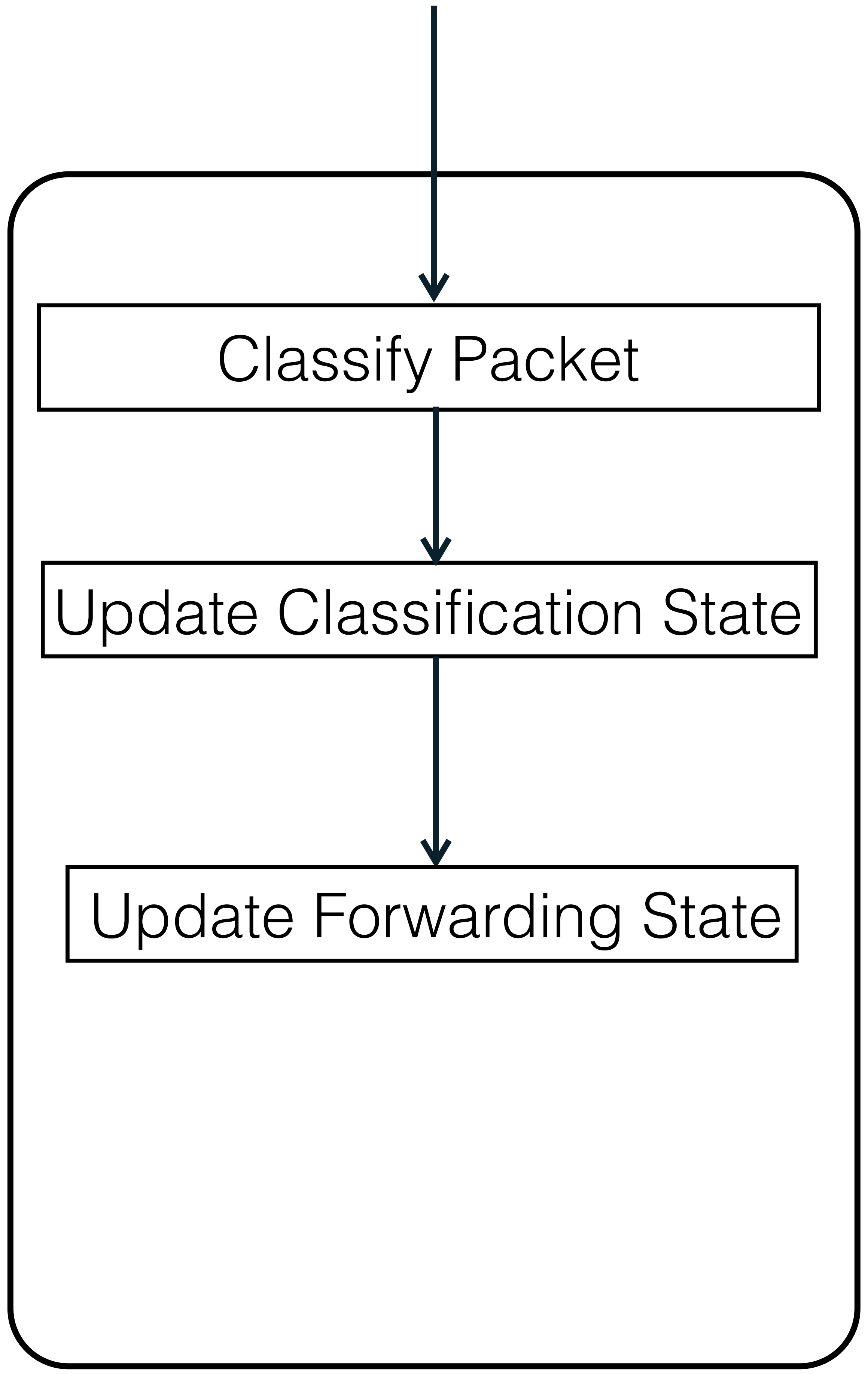

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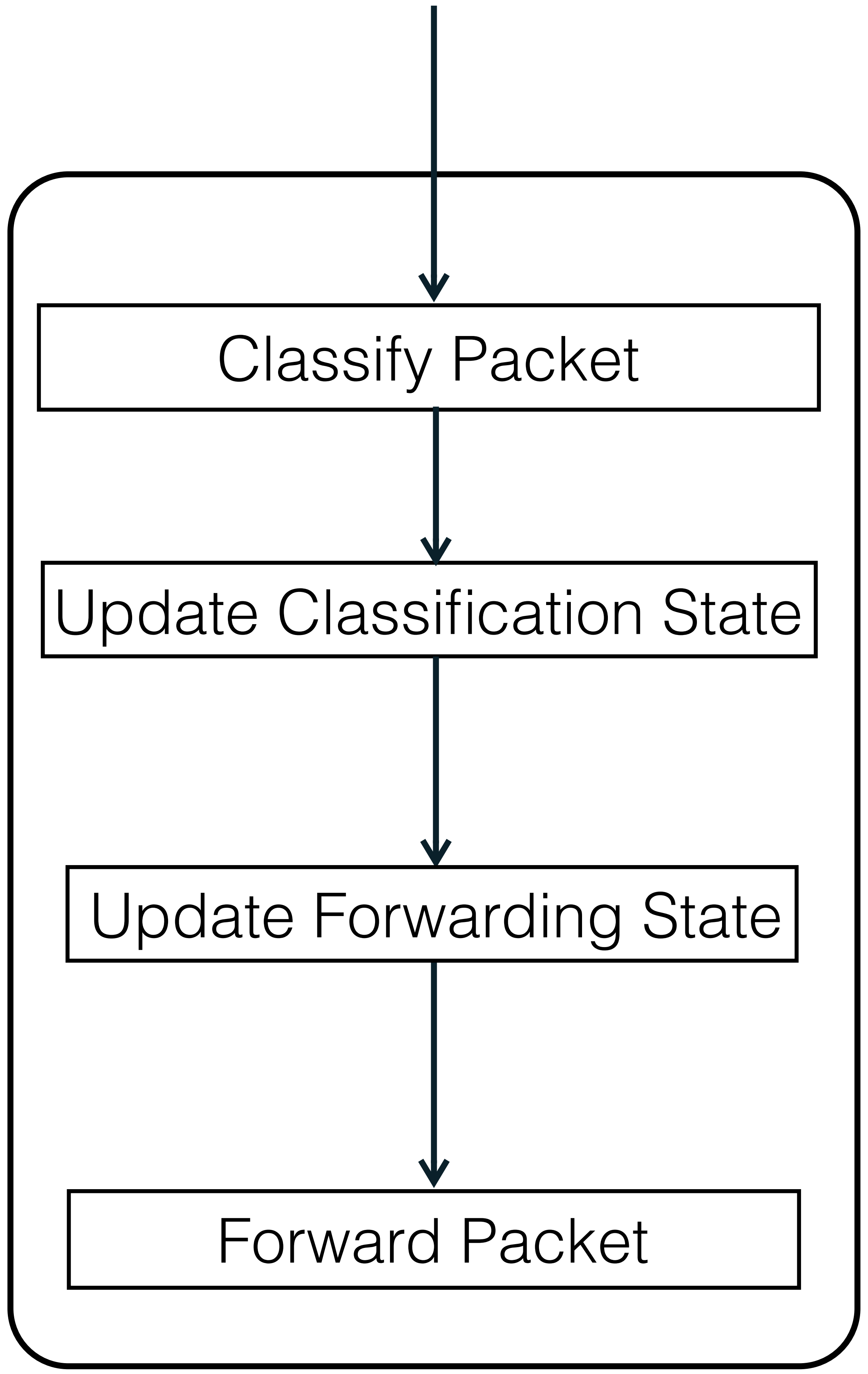

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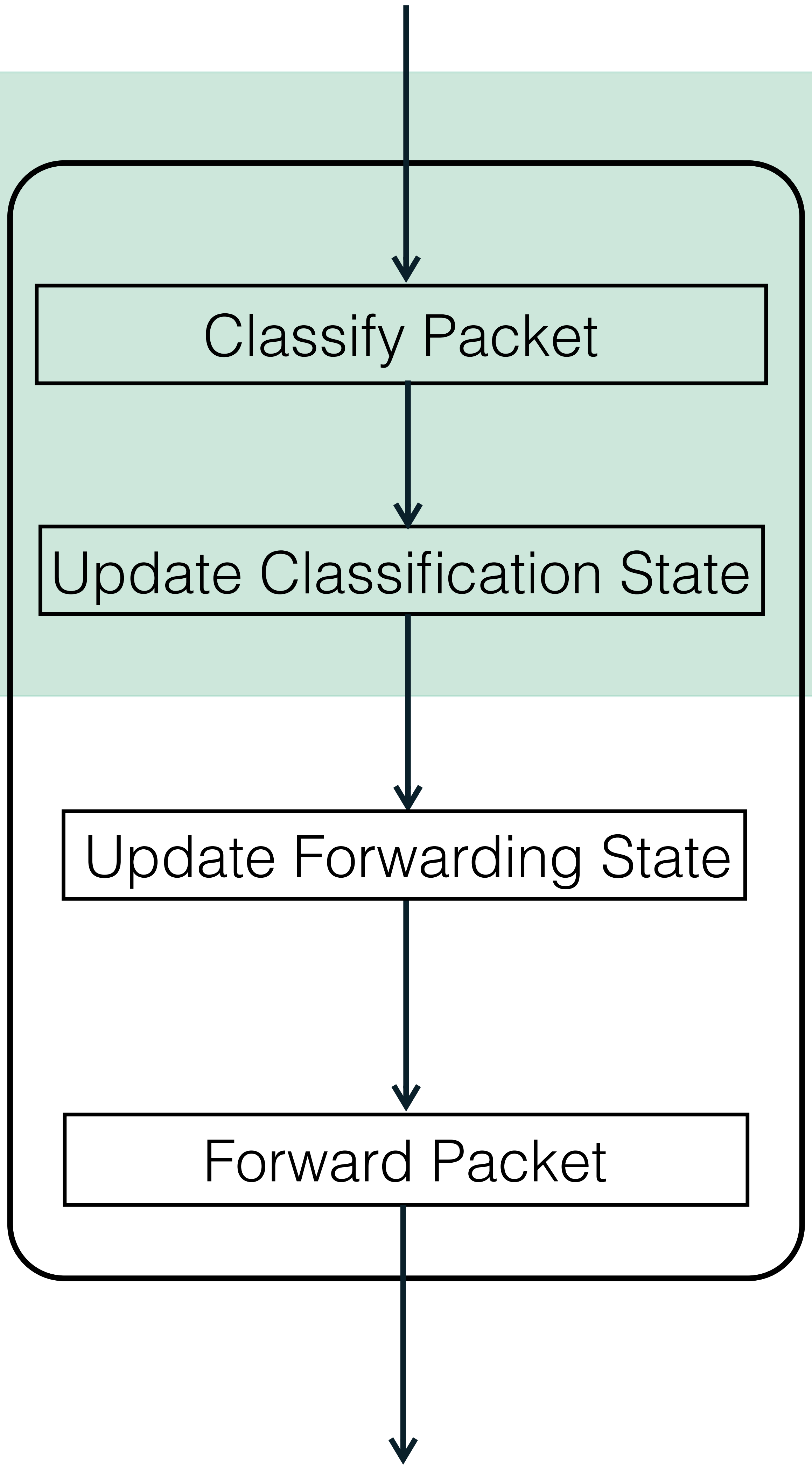

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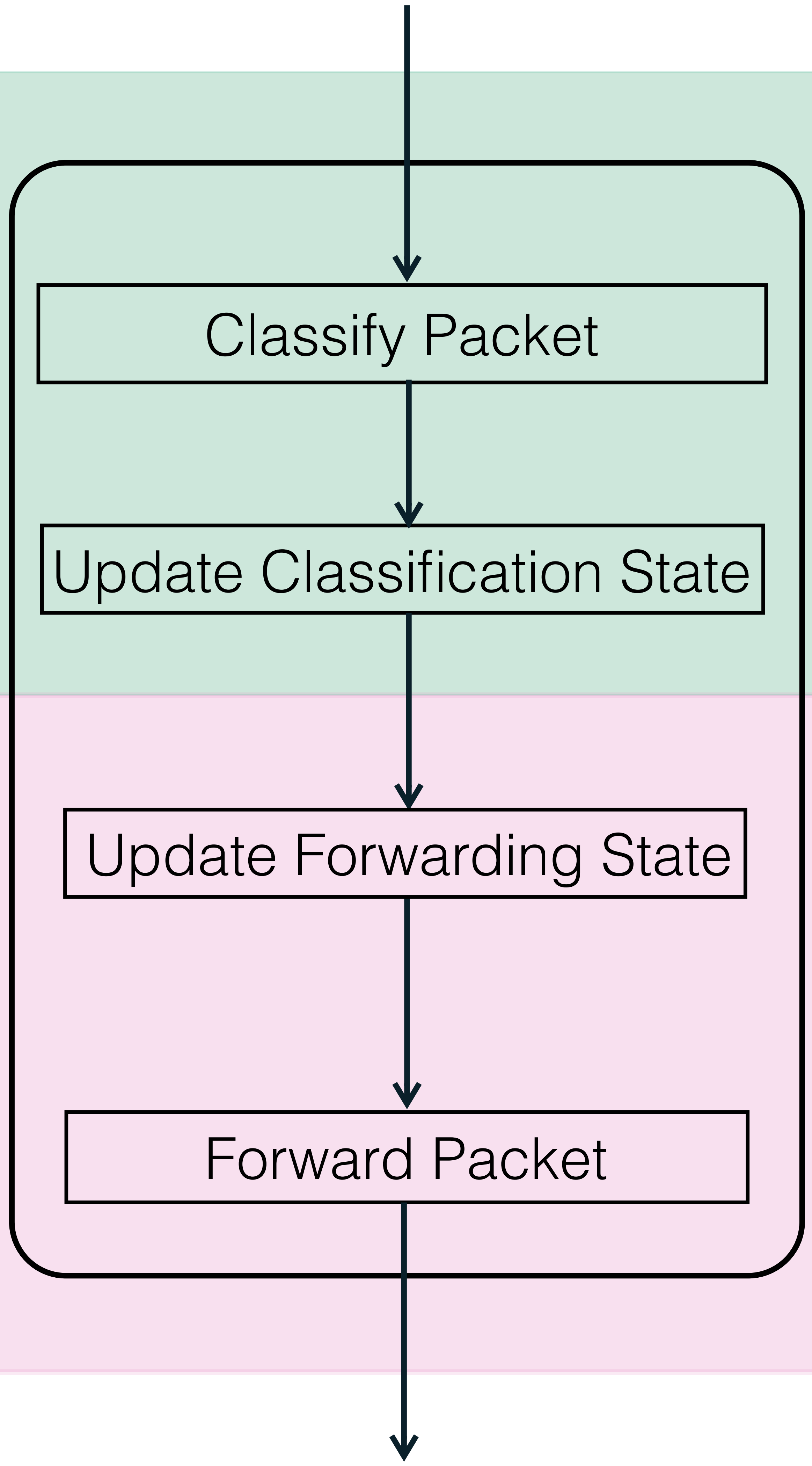

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Forwarding Model: Specify Completely

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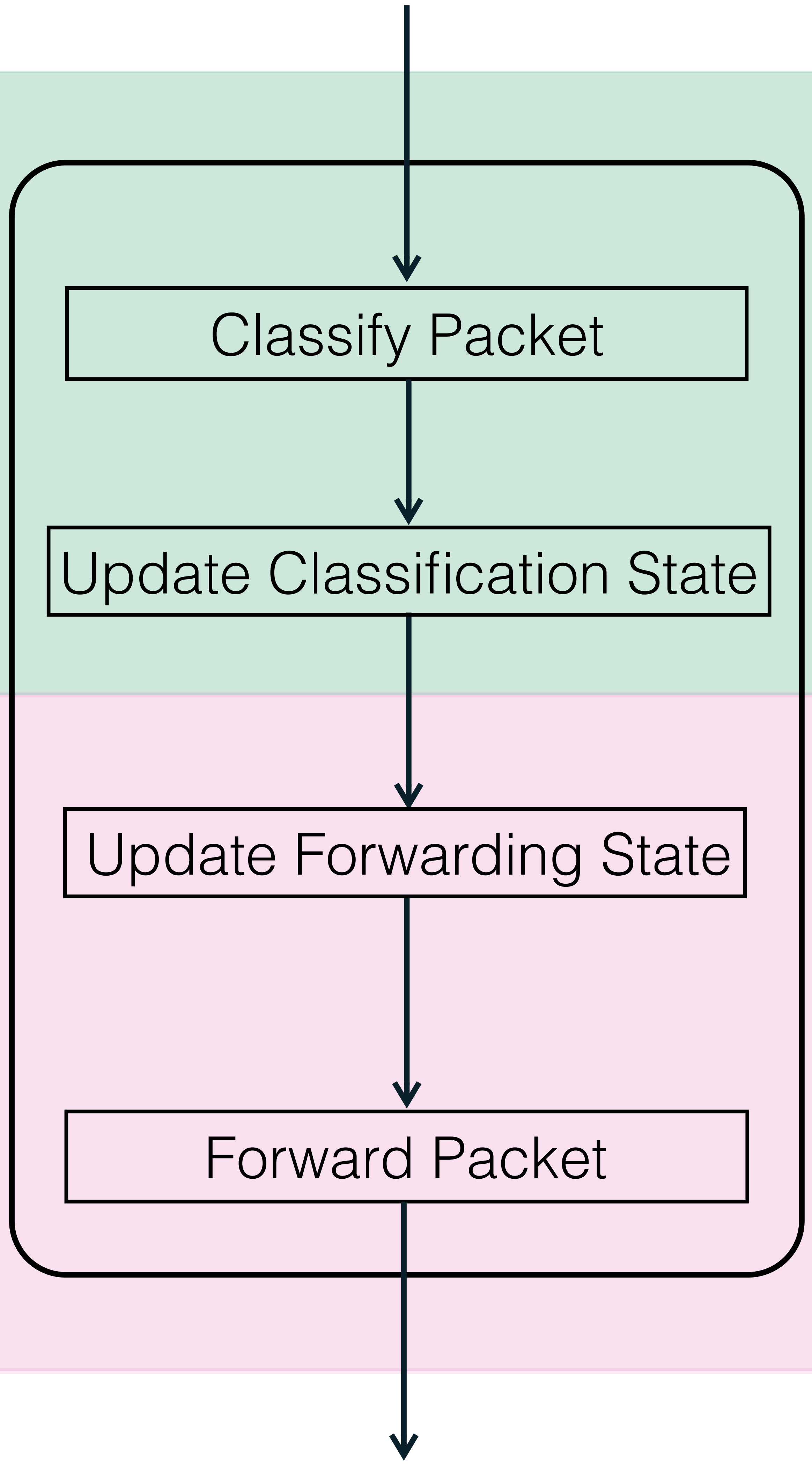

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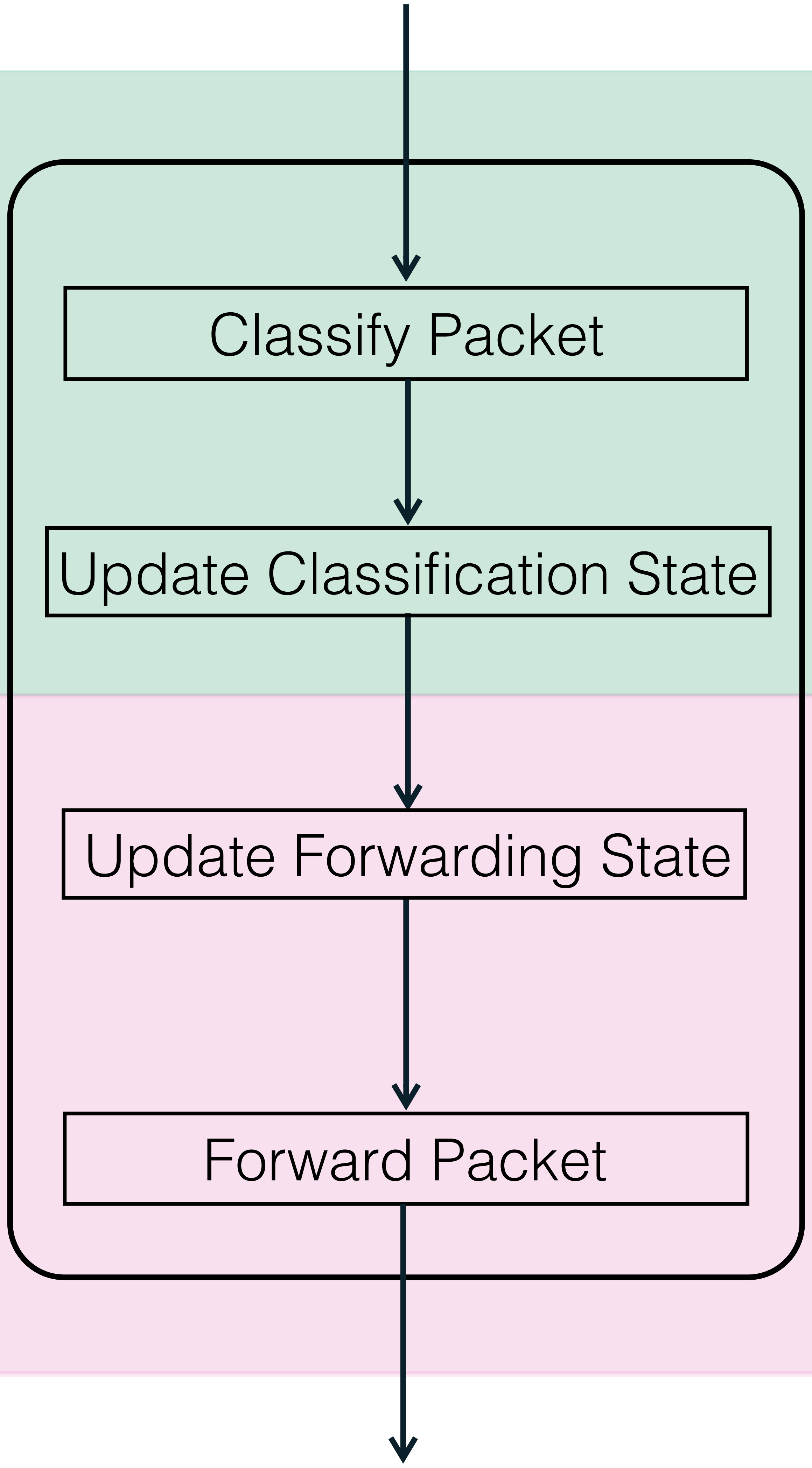

Dependencies
See all packets in connection (flow).

Outputs
Is packet **infected**.

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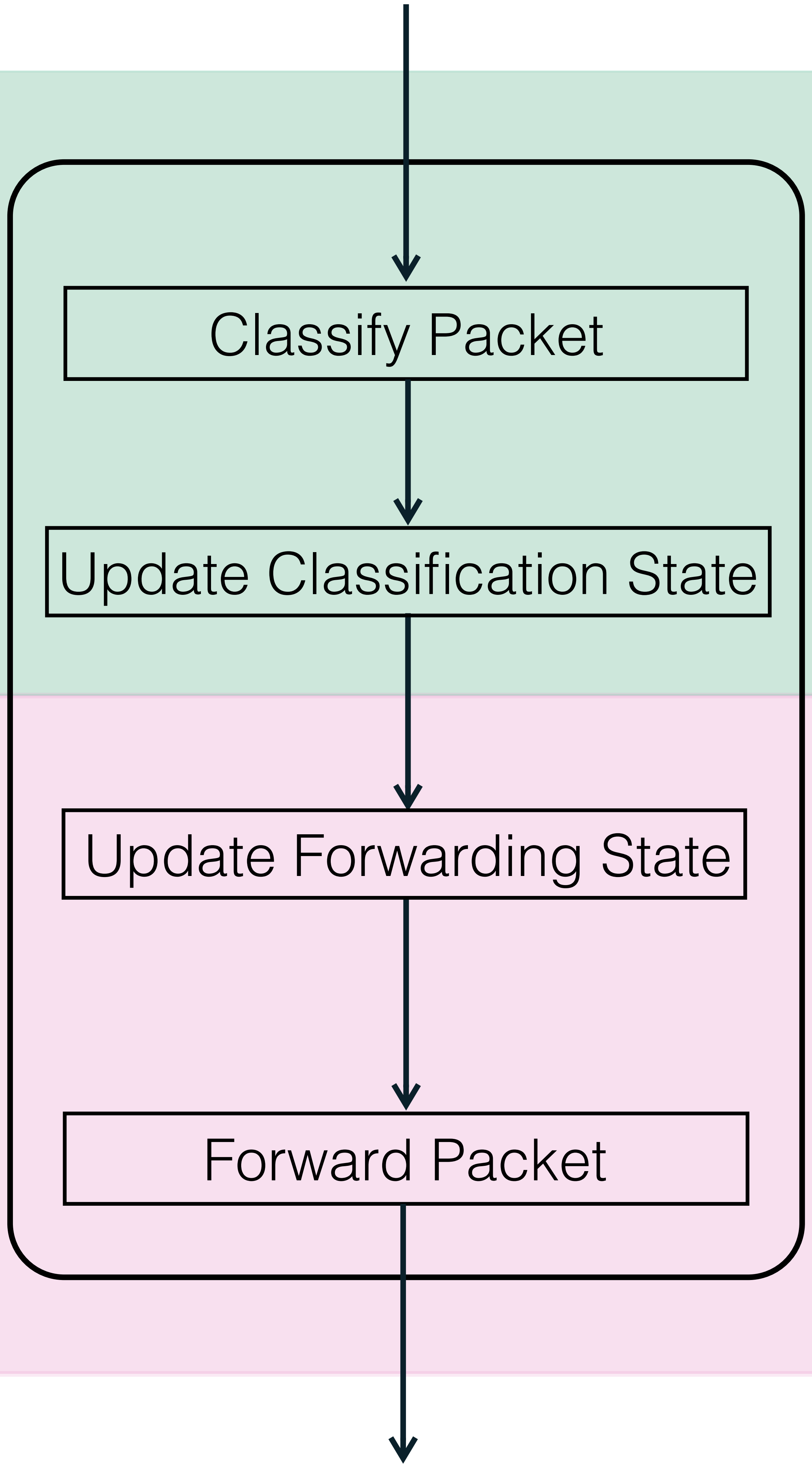

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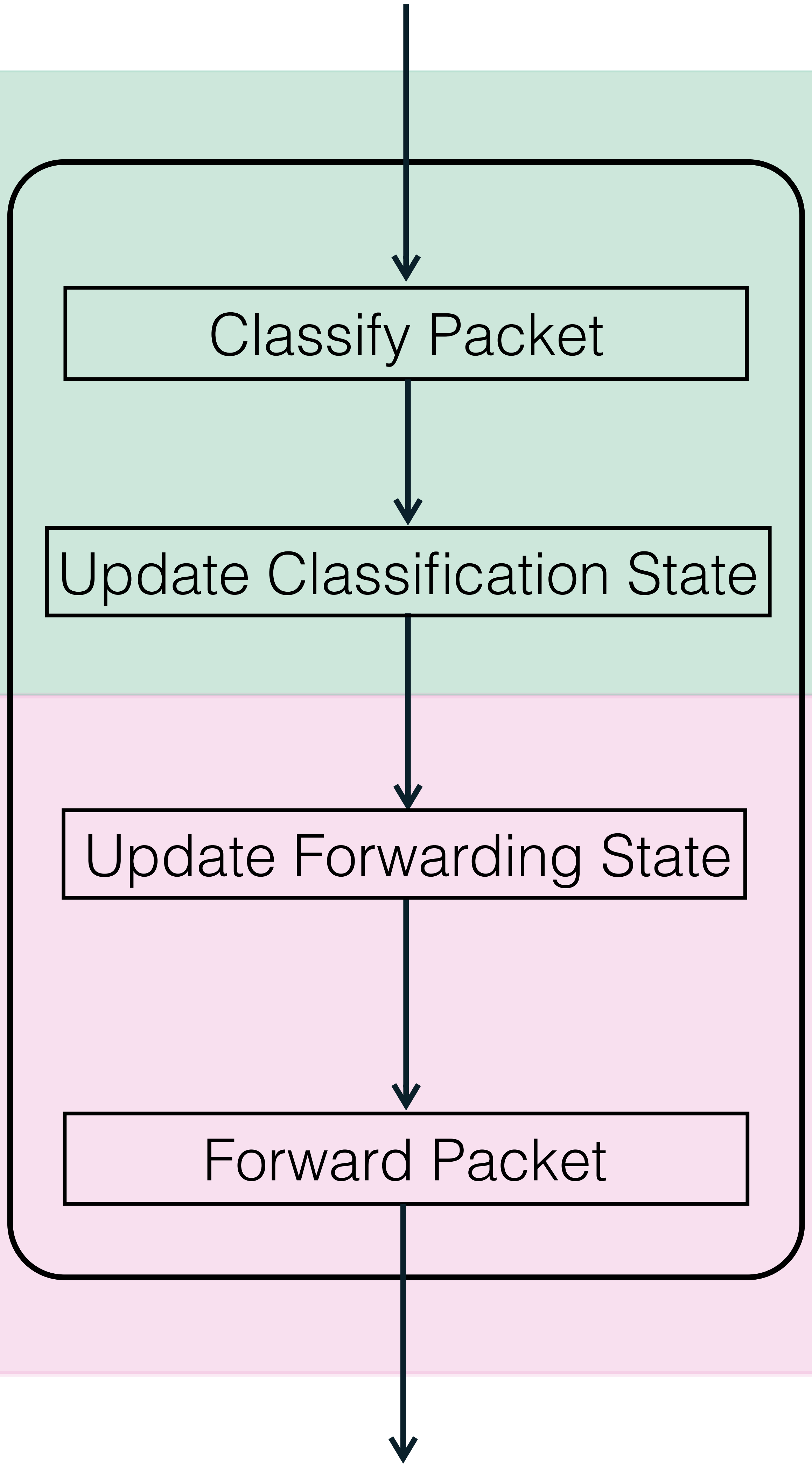

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if (**infected**) {
    infected_connections.add(packet.flow)
}

if (**packet.flow** not in **infected_connections**) {
    forward (packet);
}

Modeling Middleboxes

$$
\begin{aligned}
\boldsymbol{infected\_connection}(flow(p)) \\
\implies (\blacklozenge rcv(\boldsymbol{n}, p')\land \\
flow(p') = flow(p)\land \\
infected(p))
\end{aligned}
$$

$$
\begin{aligned}
snd(\boldsymbol{n}, p) \implies \\
(\blacklozenge rcv(\boldsymbol{n}, p)\land \\
\neg \boldsymbol{infected\_connection}(flow(p)))
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$$

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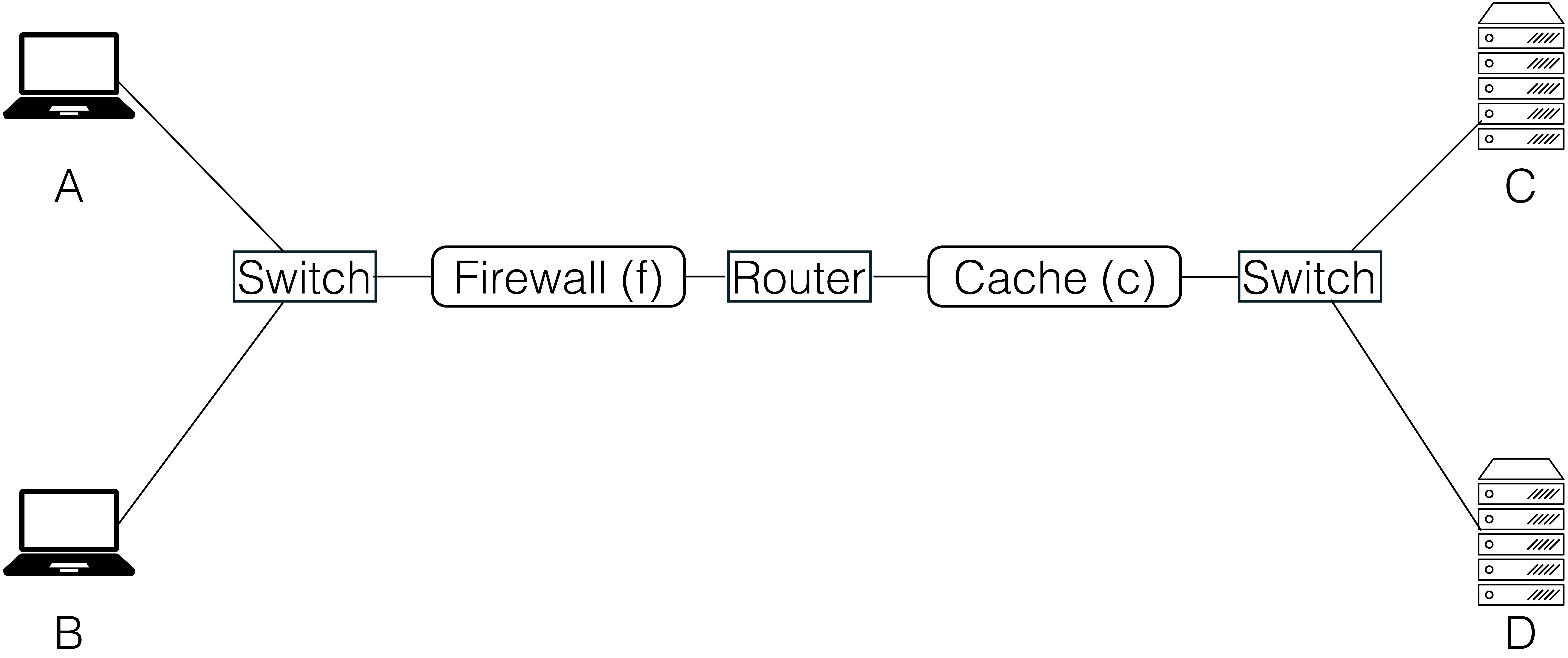
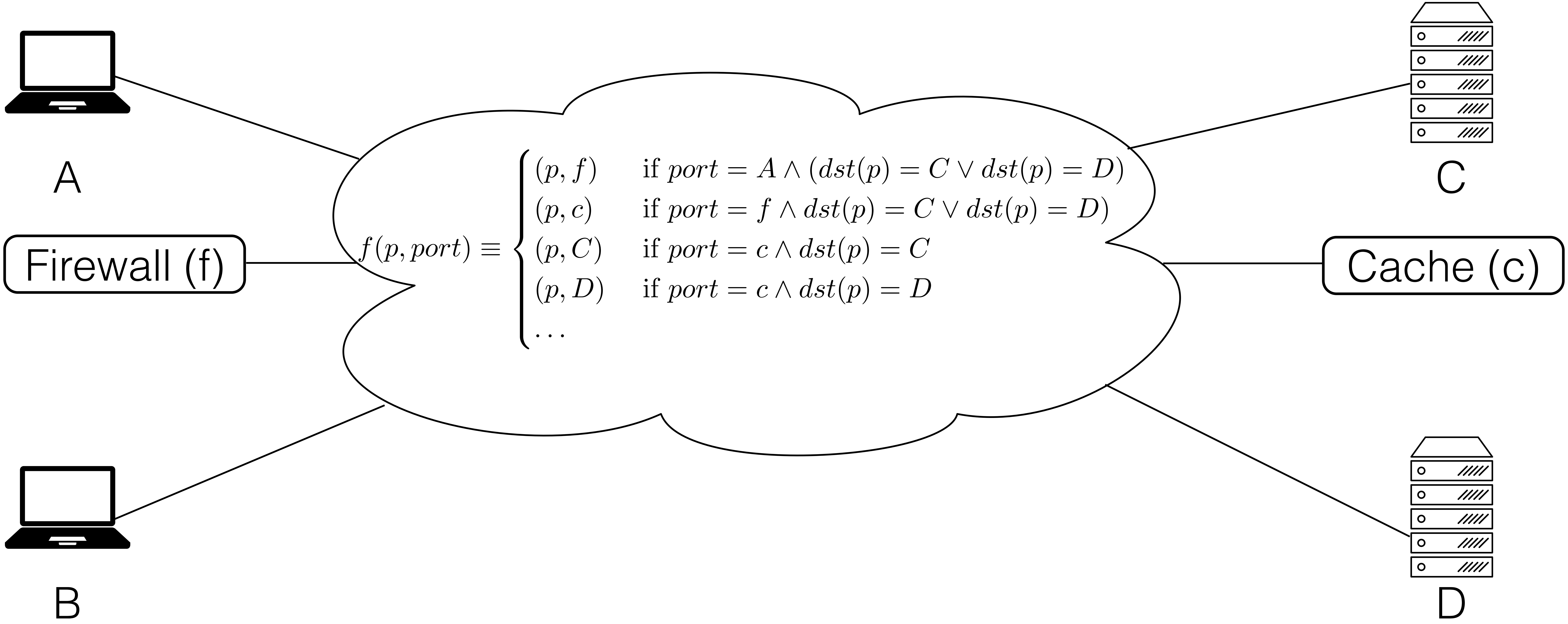
Network Transfer Functions

- Kazemian 2012 developed the idea of a network transfer function.
  - A single function modeling the behavior of the entire network.
- VMN models static elements in the network using a transfer function.

Network Transfer Function



Network Transfer Function



$$f(p, port) \equiv \begin{cases} (p, f) & \text{if } port = A \wedge (dst(p) = C \vee dst(p) = D) \\ (p, c) & \text{if } port = f \wedge dst(p) = C \vee dst(p) = D) \\ (p, C) & \text{if } port = c \wedge dst(p) = C \\ (p, D) & \text{if } port = c \wedge dst(p) = D \\ \ldots & \end{cases}$$

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Networks are Large

- Networks are huge in practice
  - For example Google had 900K machines (approximately) in 2011
  - ISPs connect large numbers of machines.
- Lots of middleboxes in these networks
  - In datacenter each machine might be one or more middlebox.
- How do we address this?

Scaling Techniques Thus Far

- Abstract middlebox models
    - Simplify what needs to be considered per-middlebox.
- Abstract network
    - Simplify network forwarding.

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- Practically for us SMT solvers timeout with large instances.
- **Other methods also do not handle such large instances**
    - Symbolic execution is exponential in number of branches, not better.
- Our techniques work for small instances, what to do about large instances?

Scaling Verification

- Challenge: Run verification on a subnetwork of size independent of network.
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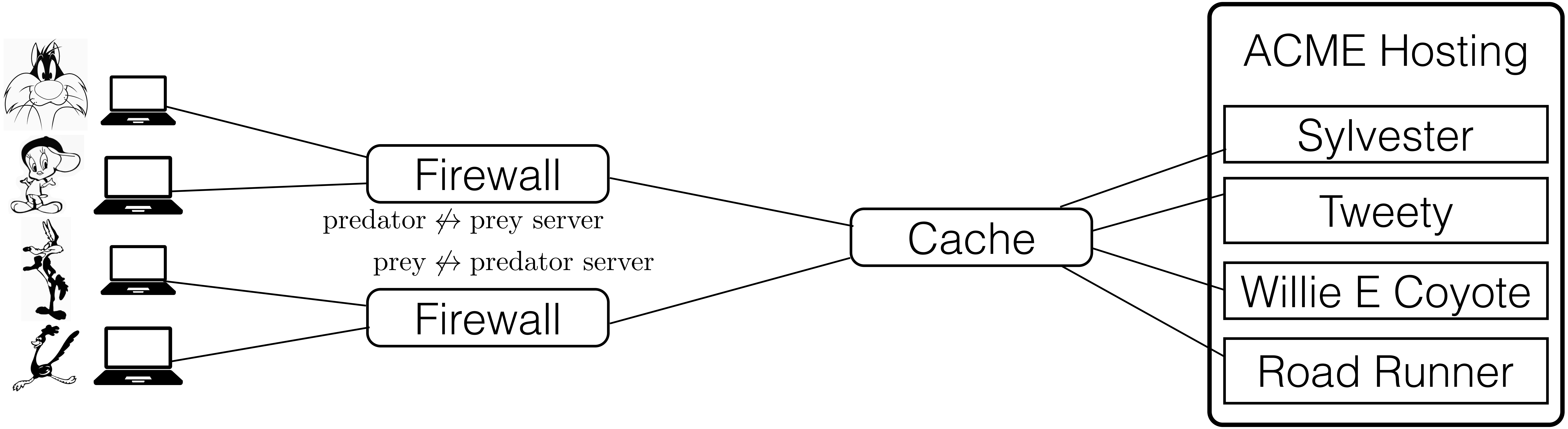
    - Avoid instability and scale to arbitrary network sizes.
- **Goal**: Identify subnetwork where verification results translate to whole network.

Network Slices

- **Slices:** Subnetworks for which a bisimulation with the original network exists.
    - Ensures equivalent step in subnetwork for each step in the original network
- Slices are selected depending on the invariant being checked.

Network Slices



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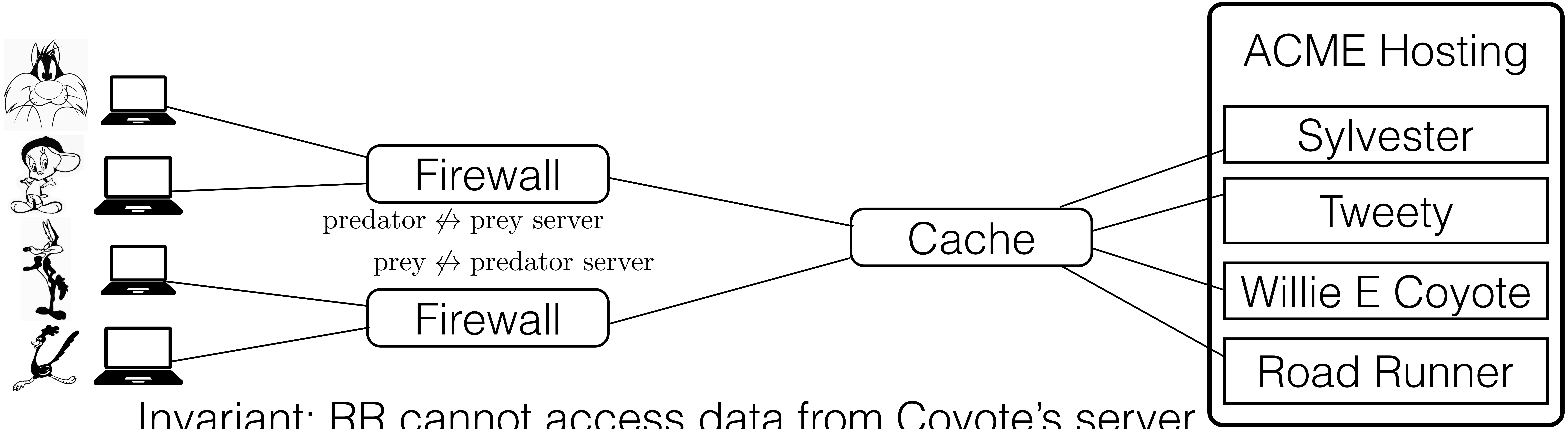

Invariant: RR cannot access data from Coyote's server

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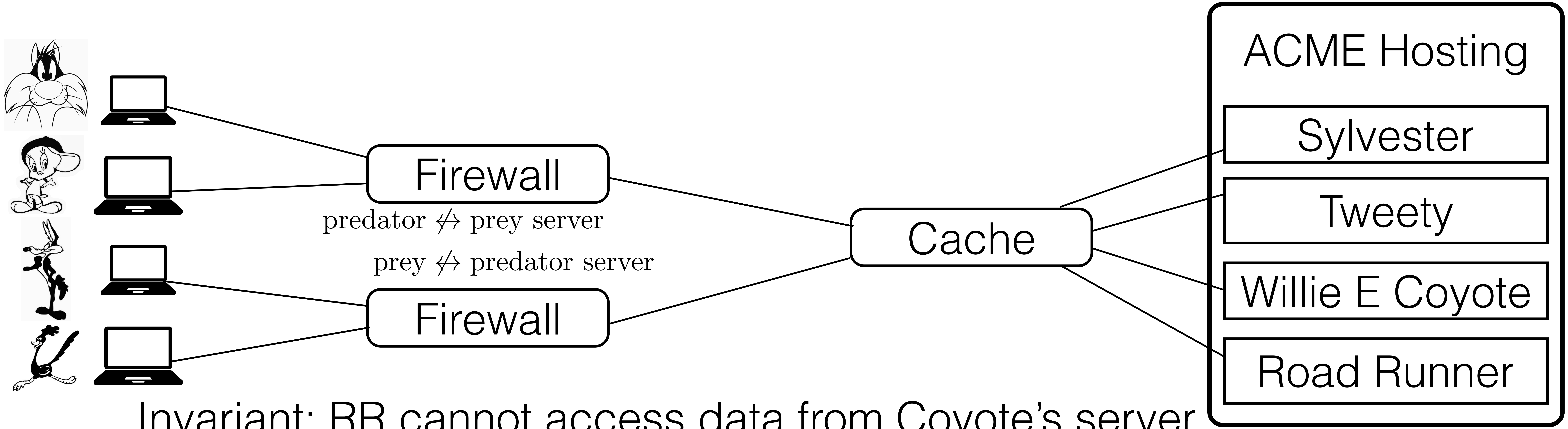

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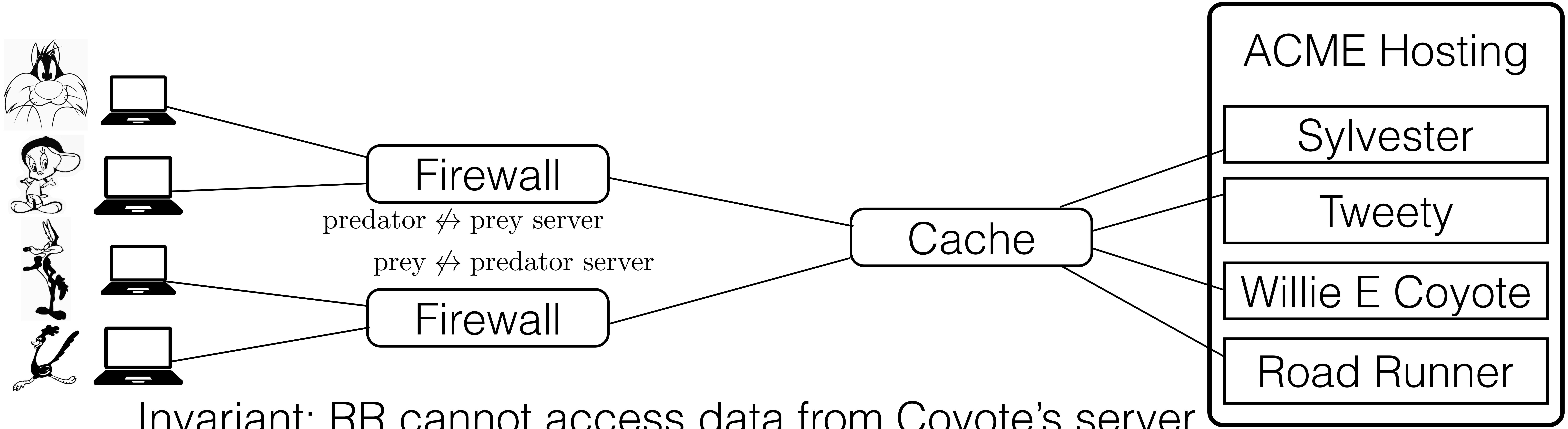

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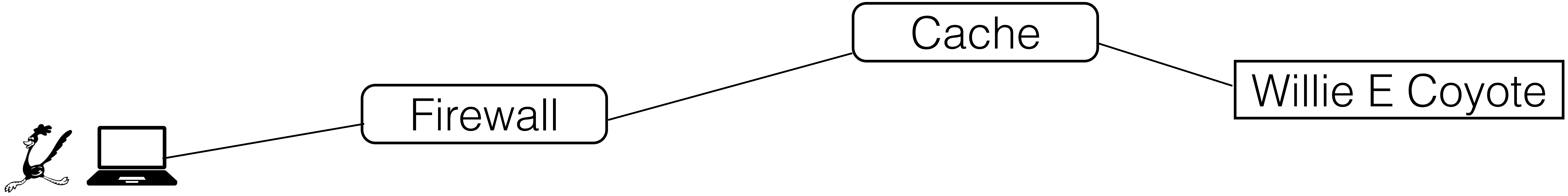

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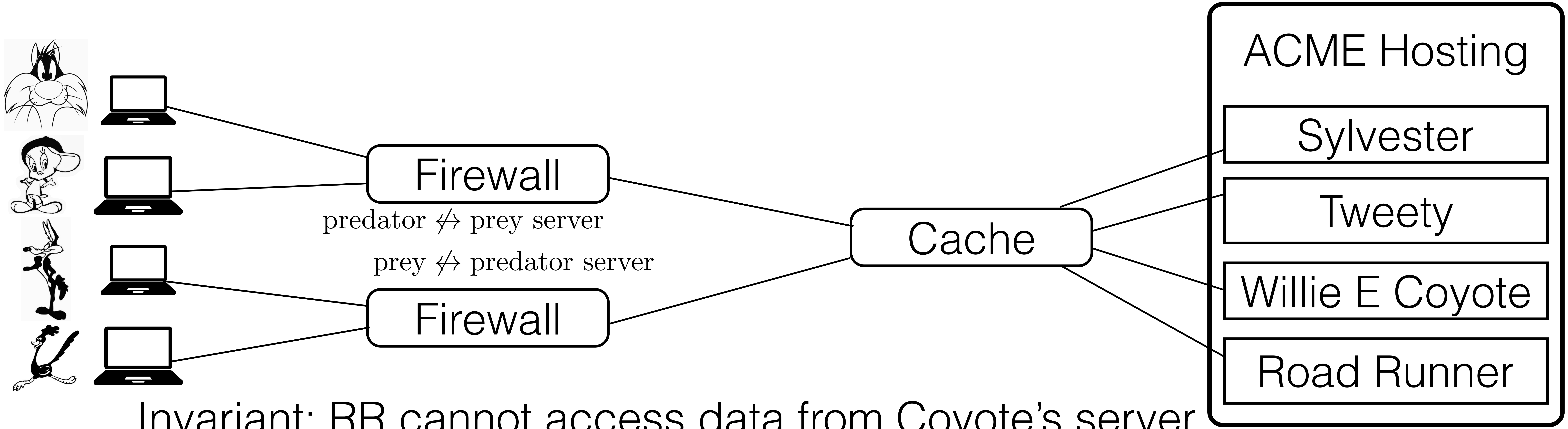

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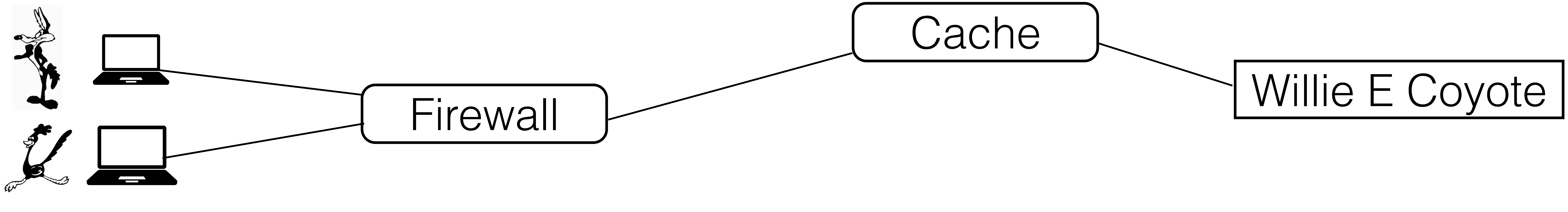

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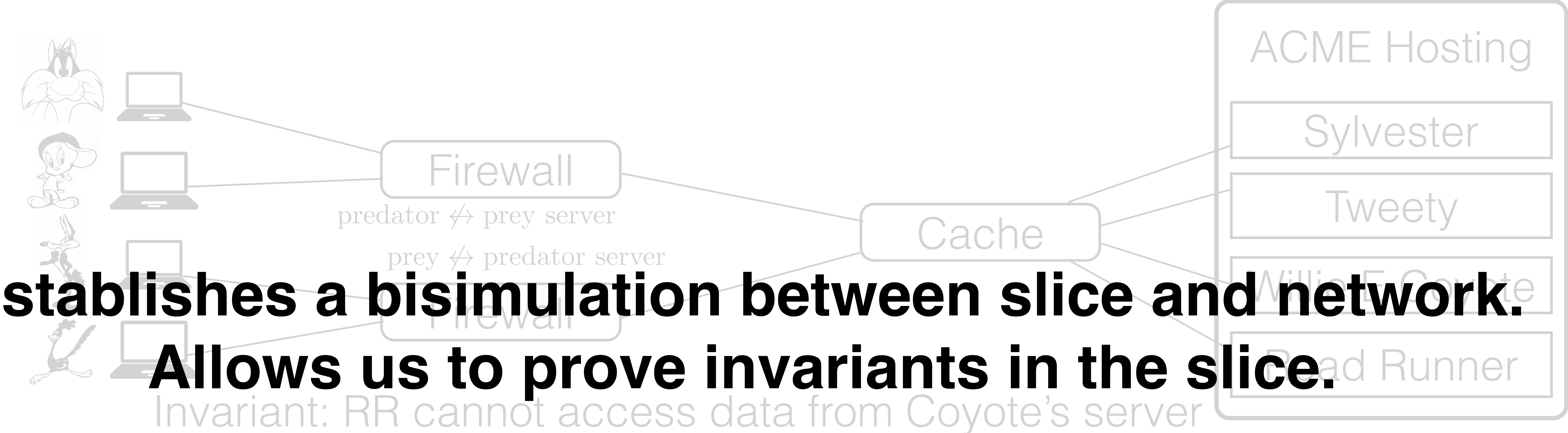


Establishes a bisimulation between slice and network.

Allows us to prove invariants in the slice.

Cannot always find such a slice.

Finding Slices: Flow Parallel Middleboxes

- To achieve performance, many middleboxes are flow parallel
  - State from one connection cannot affect another connection.
  - Example: Stateful firewall.
- For networks with only flow parallel NFs
  - Only need to consider paths between hosts.
  - Network slices whose slice is independent of network size.

Finding Slices: Origin Equivalence

- Middleboxes like caches don’t distinguish where a request originates
  - More generally, state is shared, but origin does not matter.
- In this case, need to ensure that all states in the network can appear in a slice.
  - Pick one member from each policy group.
- Scalable if increasing network size does not increase number of policy groups

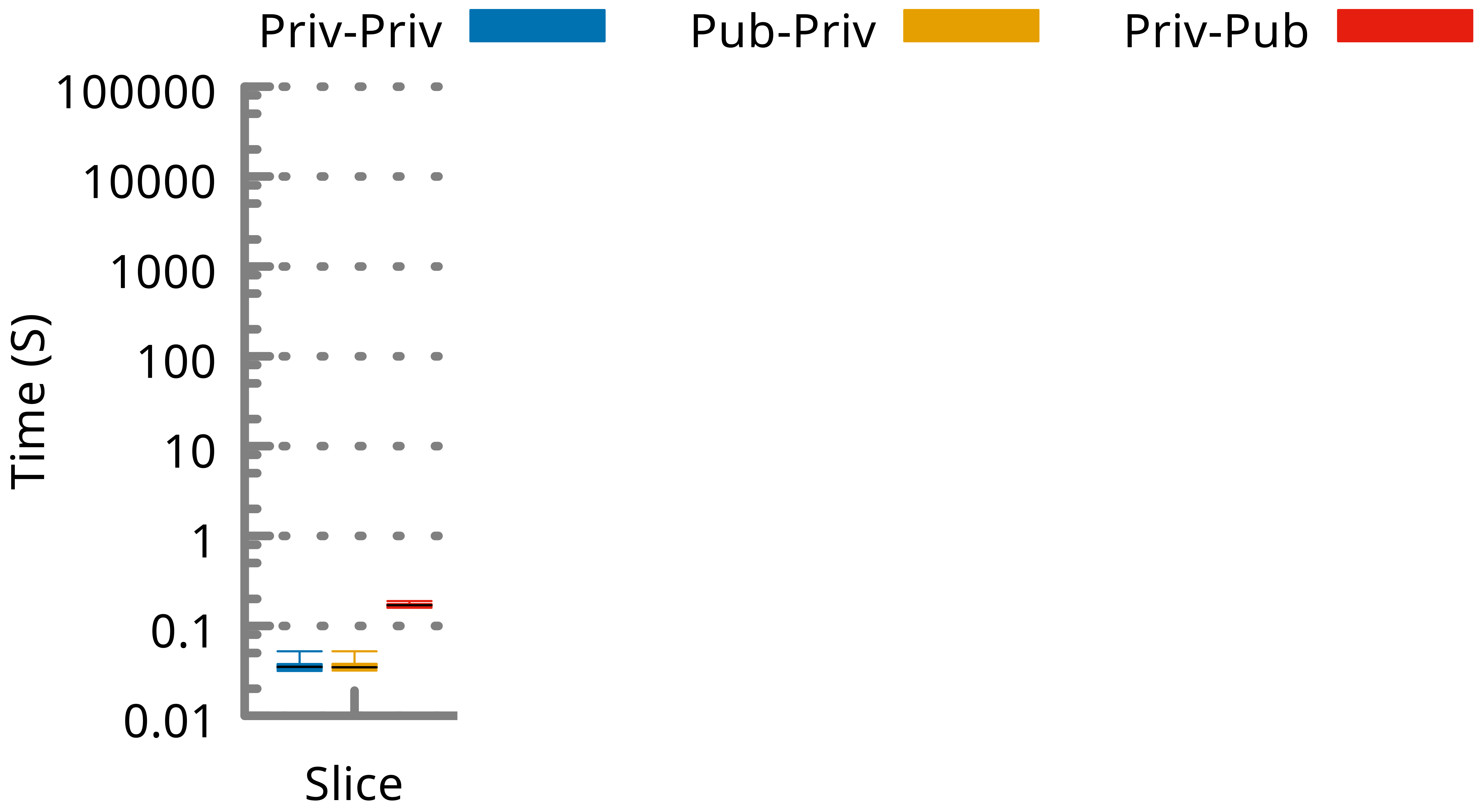
Symmetry: Going Beyond Slices

- Slices merely reduce the size of the problem for each invariant
  - Number of invariants is still a problem.
- Rely on the observation that lots of hosts in networks are symmetric
  - Policies largely applied to groups of hosts (departments, etc.)
  - Can use this symmetry to reduce number of invariants checked

Evaluation Setup: Datacenter

- Consider AWS like multi-tenant datacenter.
- Each tenant has policies for private and public hosts.
- Three verification tasks
  - Private hosts for one tenant cannot reach another
  - Public host for one tenant cannot reach private hosts for another
  - Public hosts are universally reachable.

Verification Time (Datacenter)



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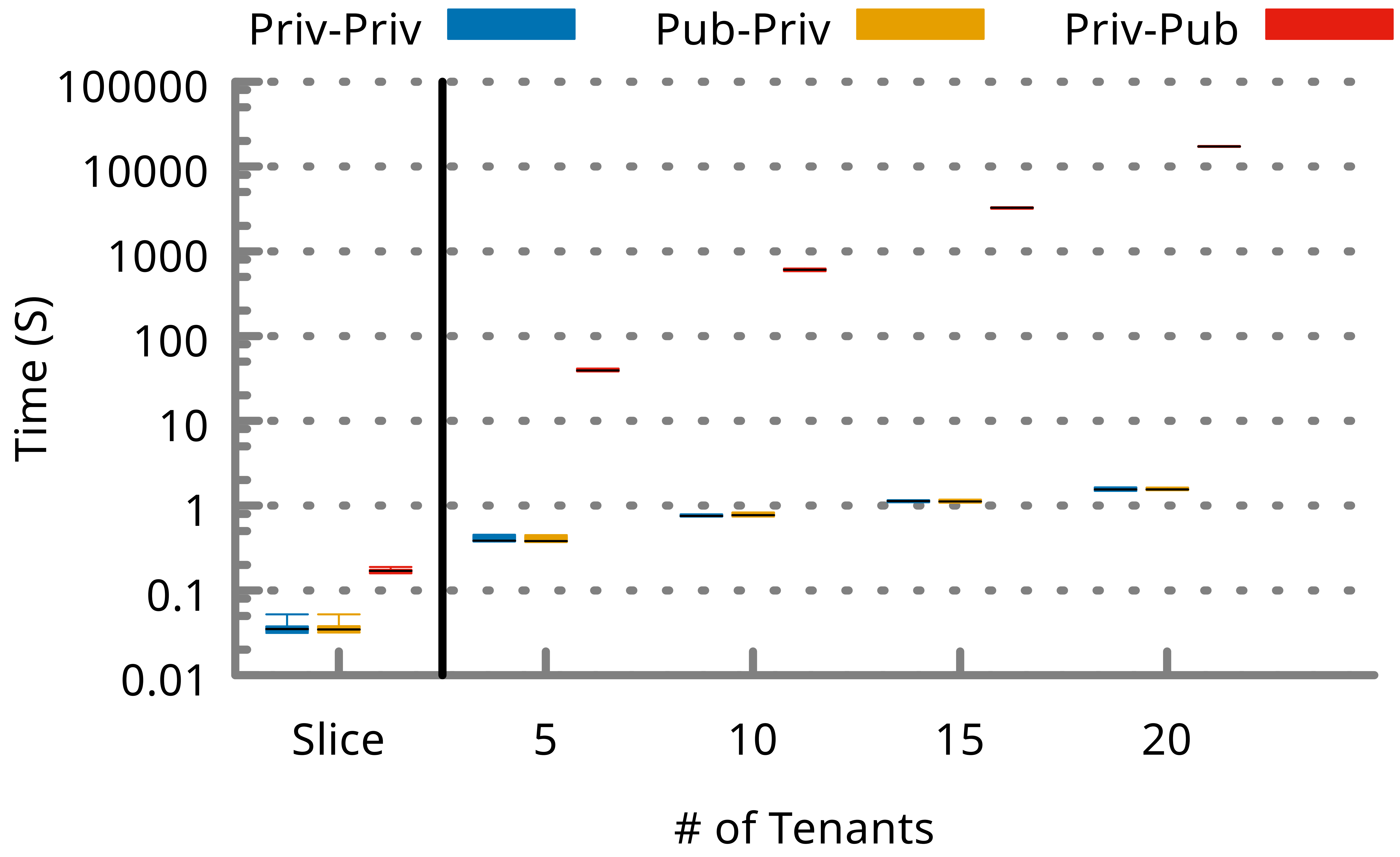
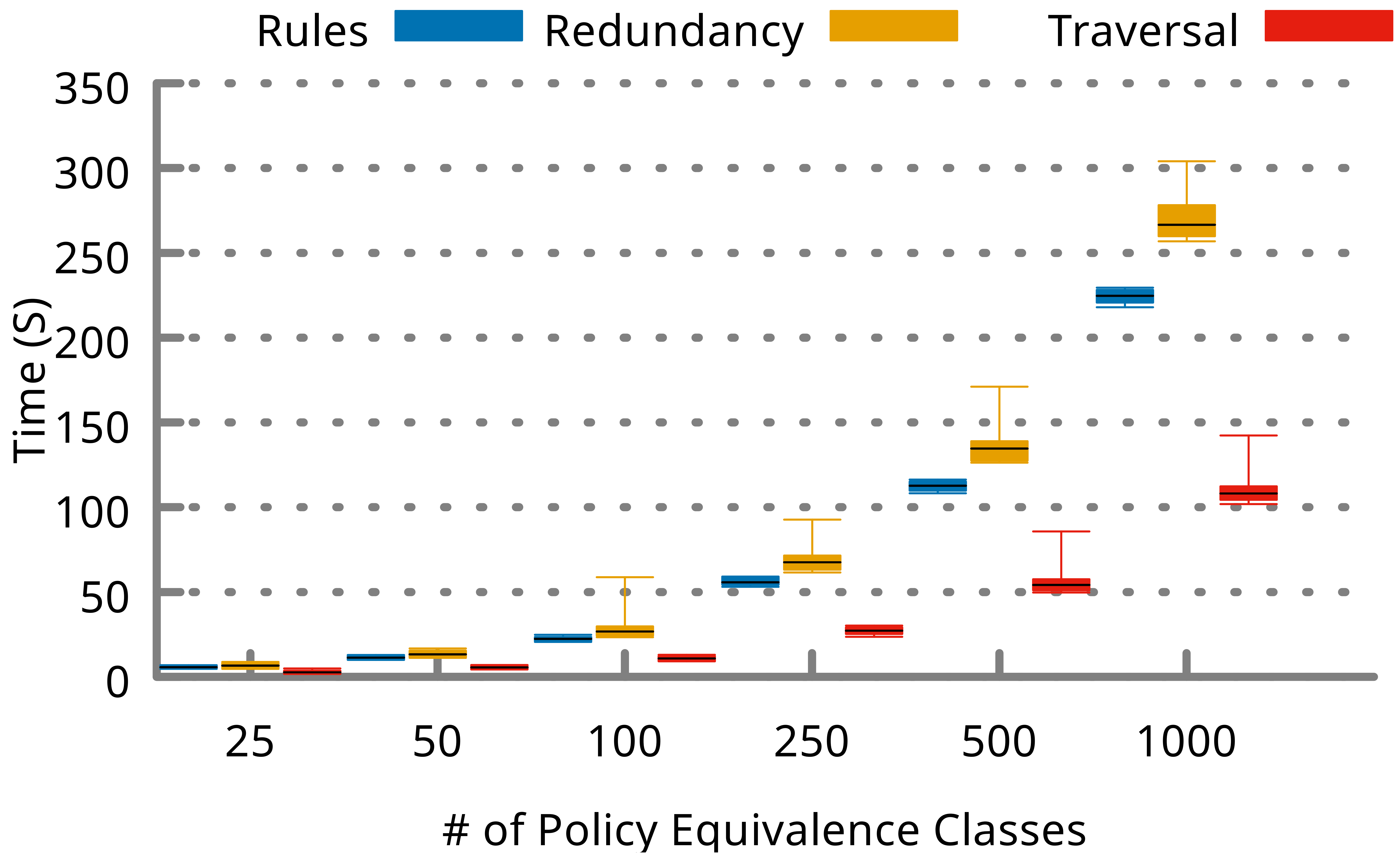


Role of Symmetry

- Consider a private datacenter
    - User verification to prevent some bugs from a Microsoft DC (IMC 2013)
- Bugs include
    - Misconfigured firewalls
    - Misconfigured redundant firewalls
    - Misconfigured redundant routing
- Measure time to verify as a function of number of symmetric policy groups

Verification Time (With Symmetry)



Conclusion

- Verifying stateful networks is increasingly more important.
- The primary challenge is scaling to realistic network.
- Splitting network into smaller verifiable portions is necessary.