# Data Provenance at Internet Scale: Architecture, Experiences, and the Road Ahead

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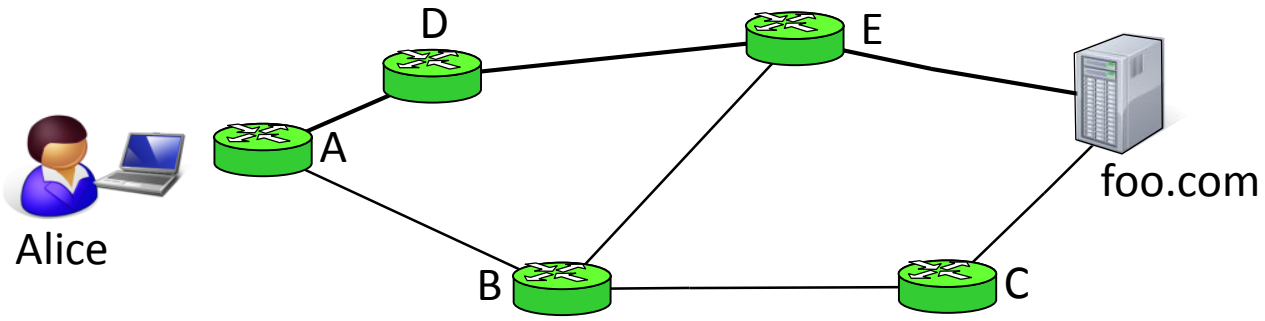
**Boon Thau Loo, Wenchao Zhou**

Penn

GEORGETOWN UNIVERSITY

# Motivation

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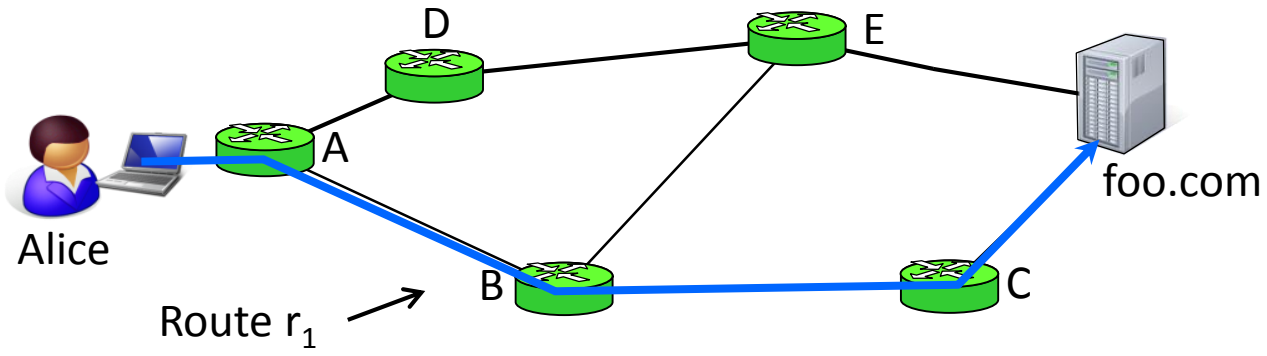


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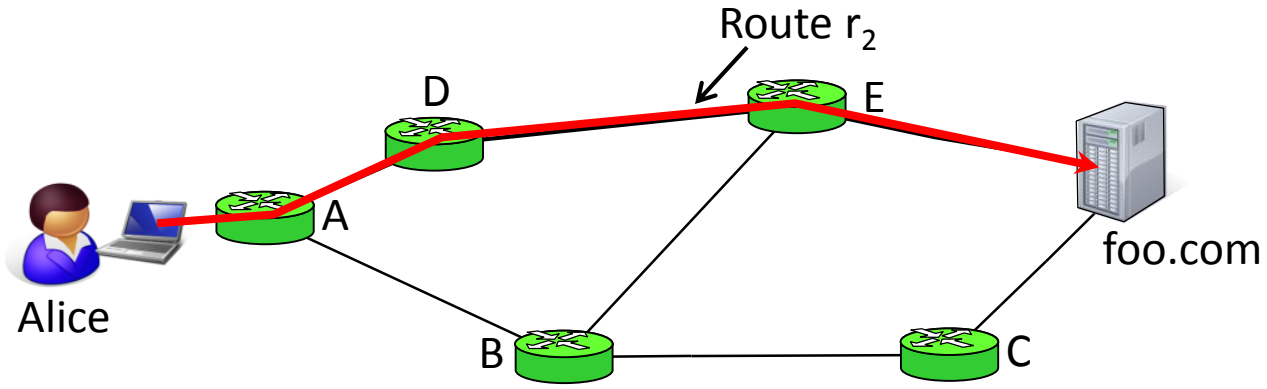


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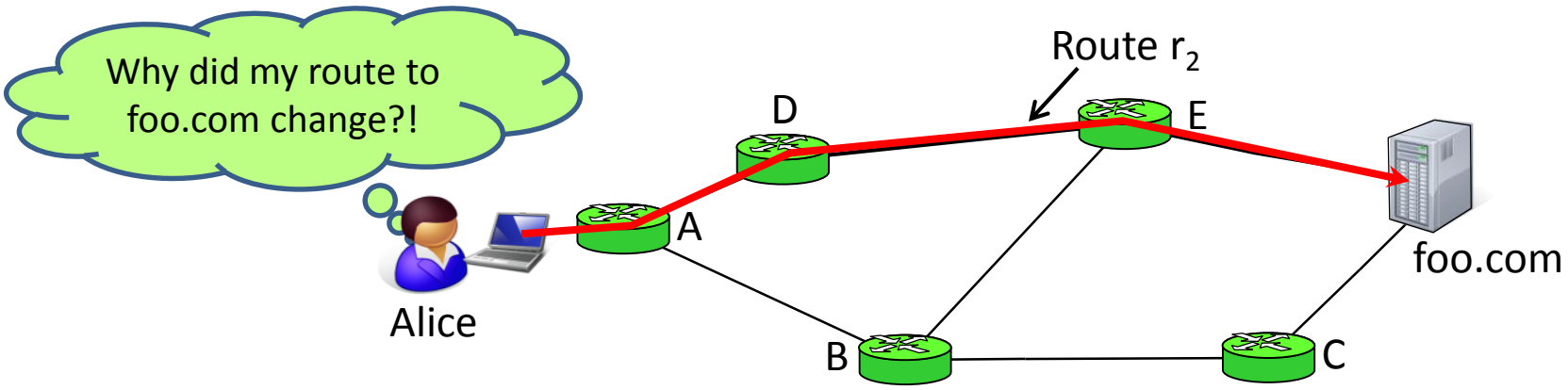


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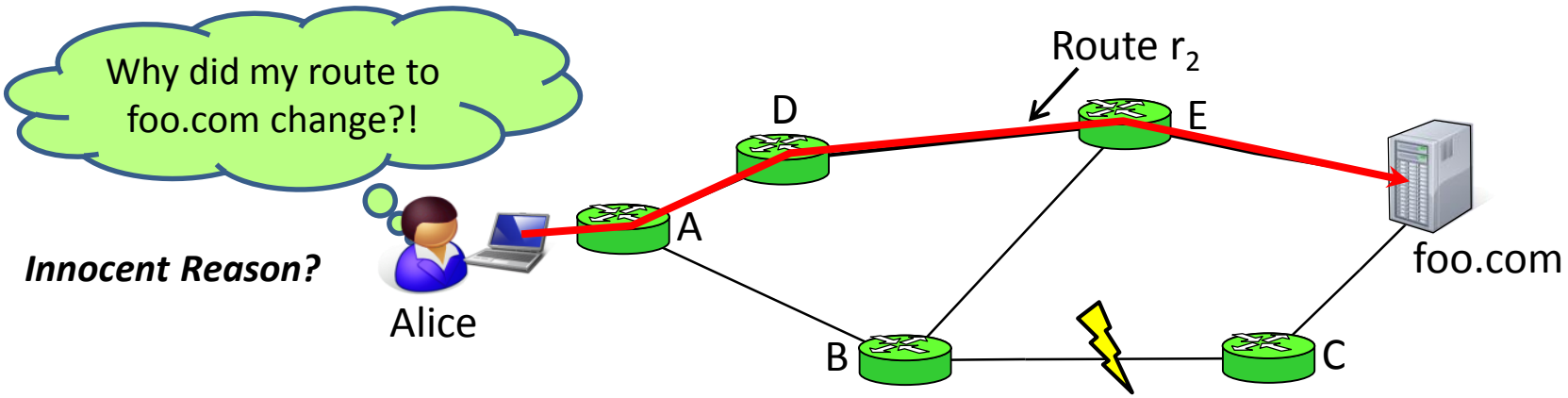


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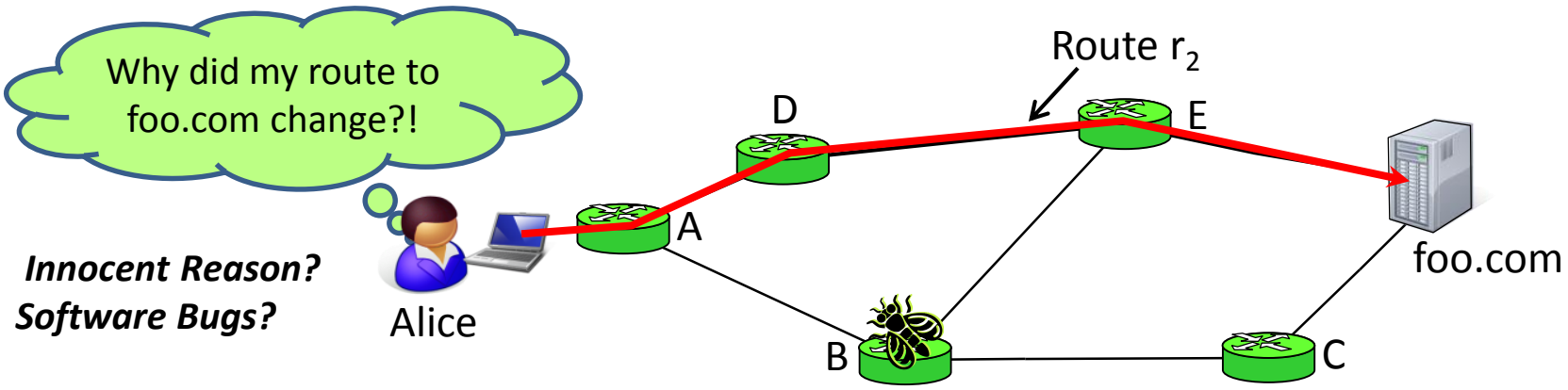


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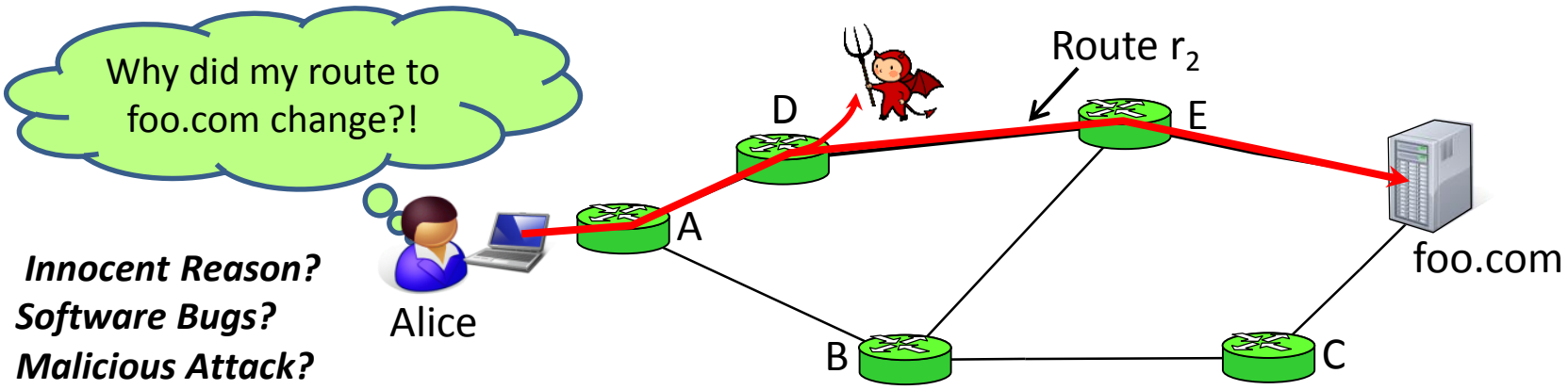


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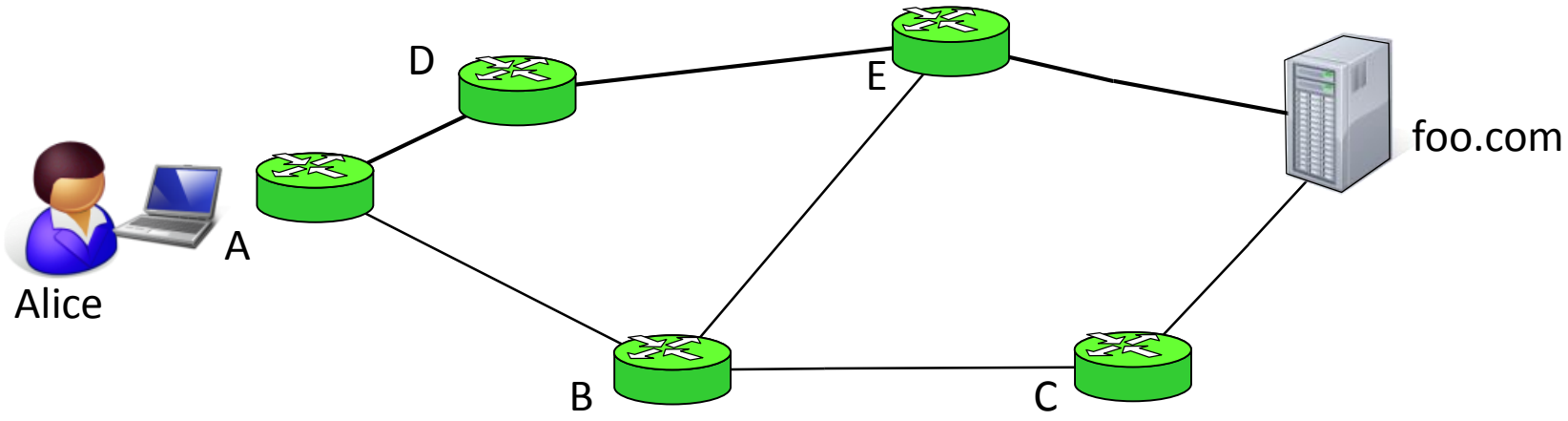


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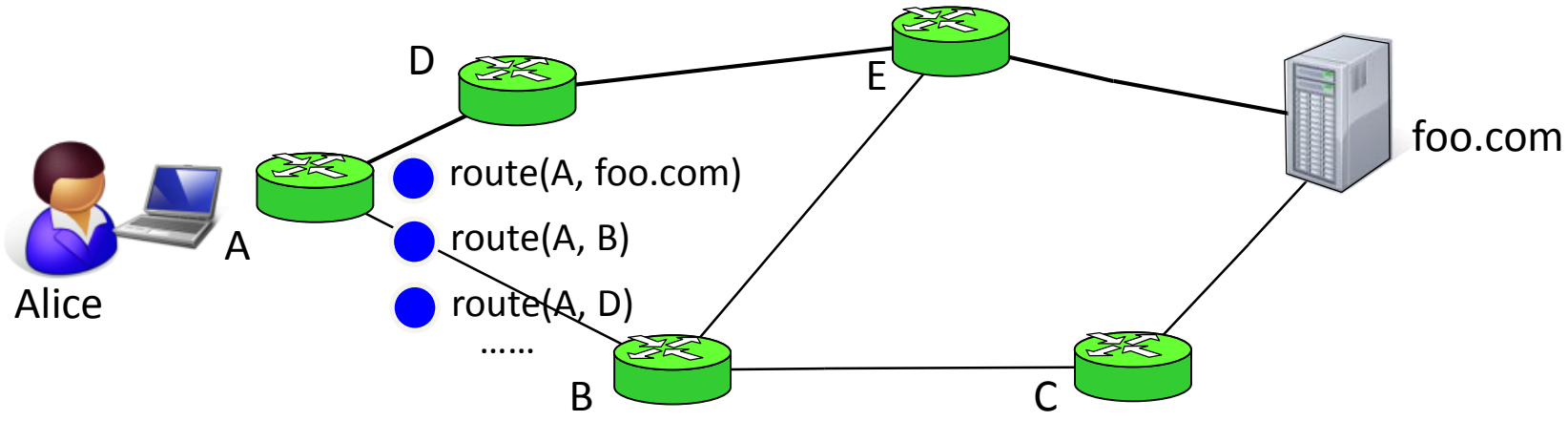


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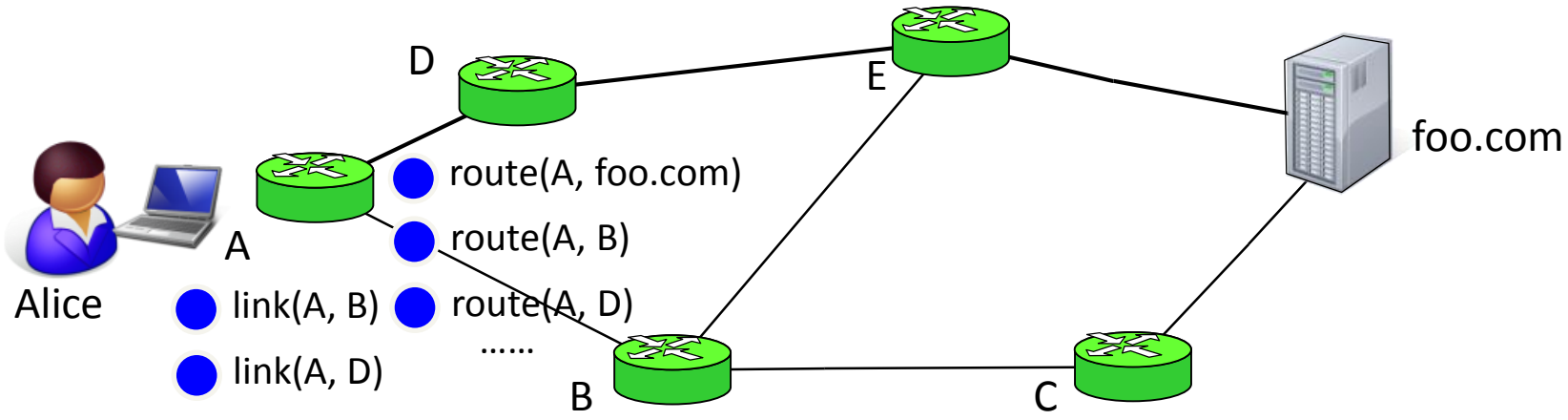


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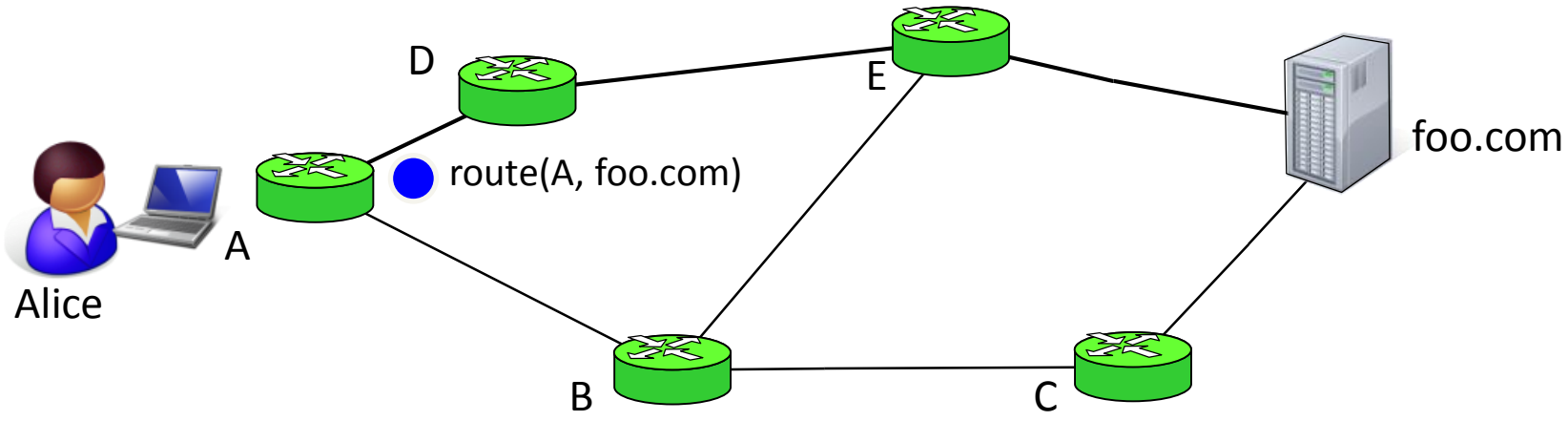


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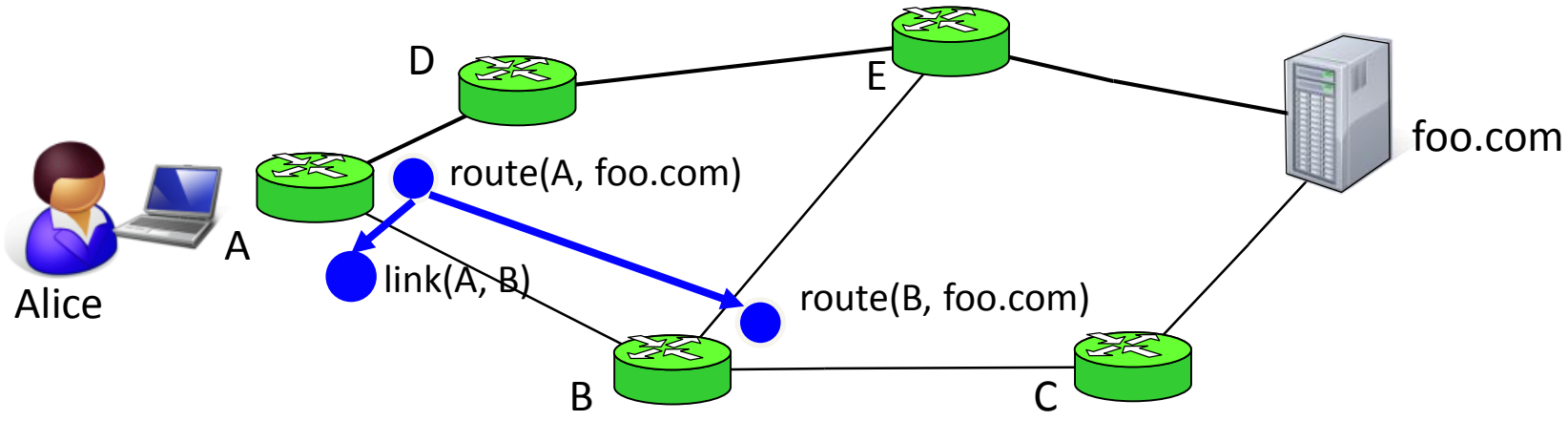


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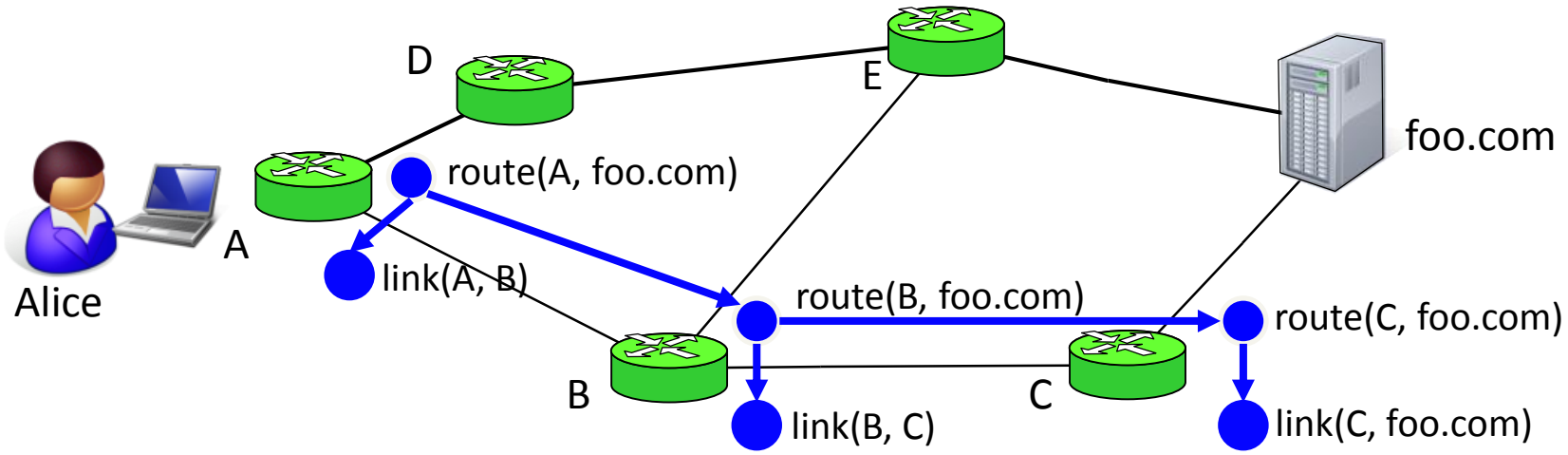


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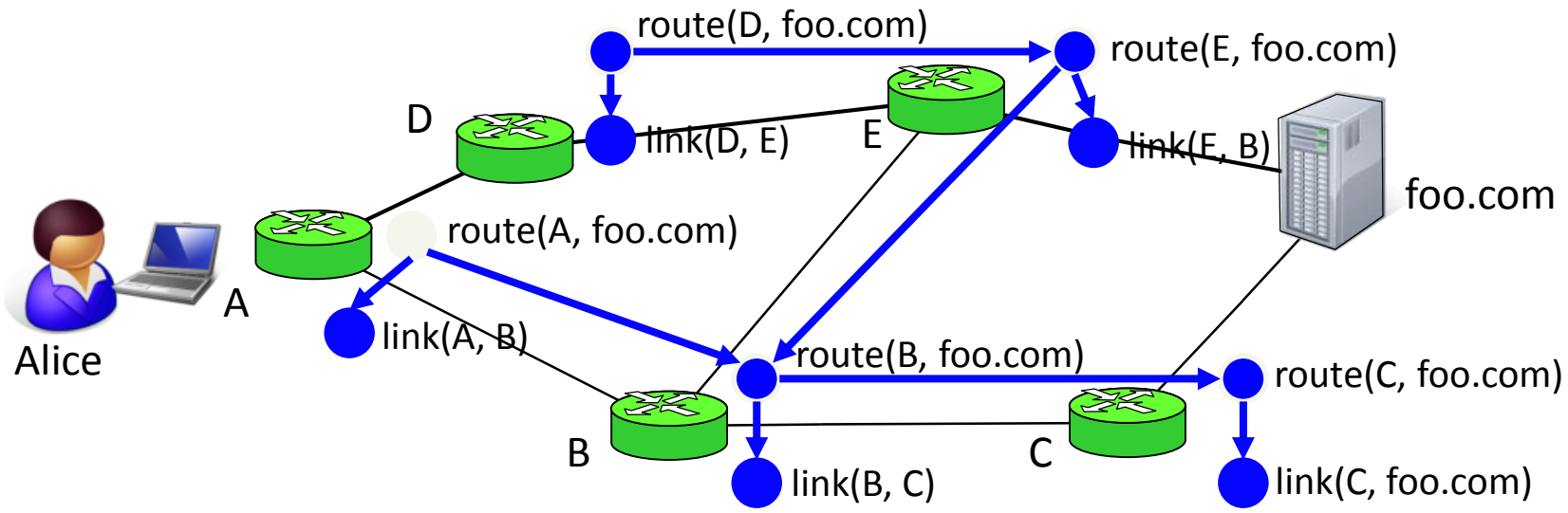

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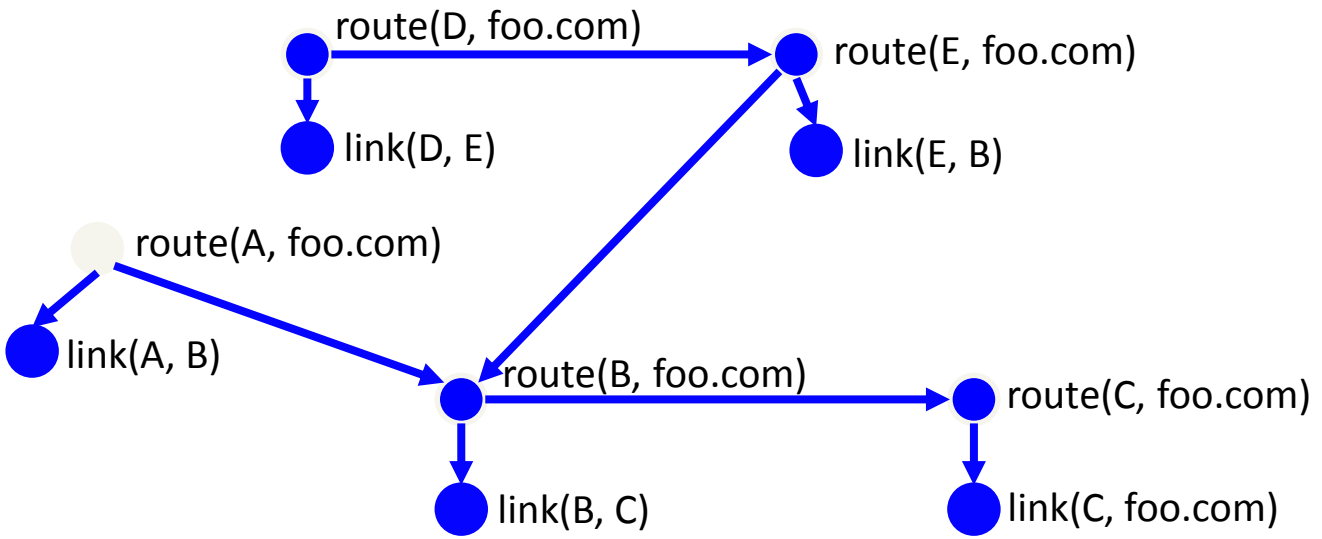


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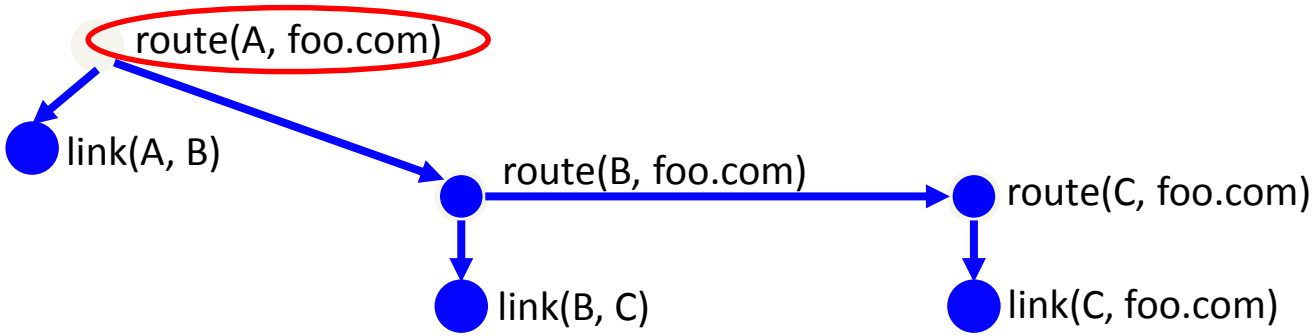
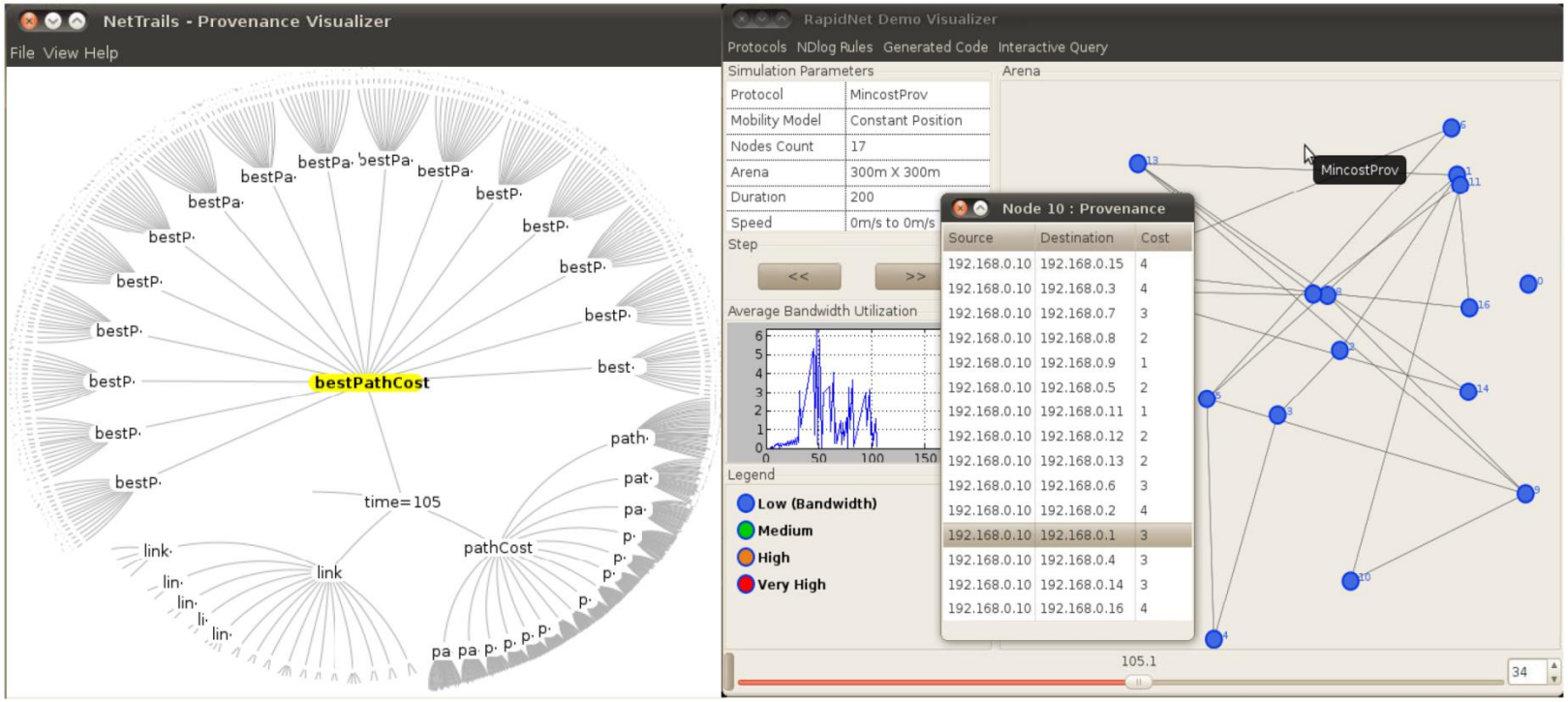



- **Provenance for encoding distributed state dependencies**
  - Explains the derivation of tuples
  - Captures the dependencies between tuples as a graph
  - Explanation of a tuple is an acyclic graph rooted at the tuple

# NetTrails: First Generation Network Provenance Tool

- http://netdb.cis.upenn.edu/nettrails/ [SIGMOD 2011 demo]



# Network Provenance Research (2010 – 2017)

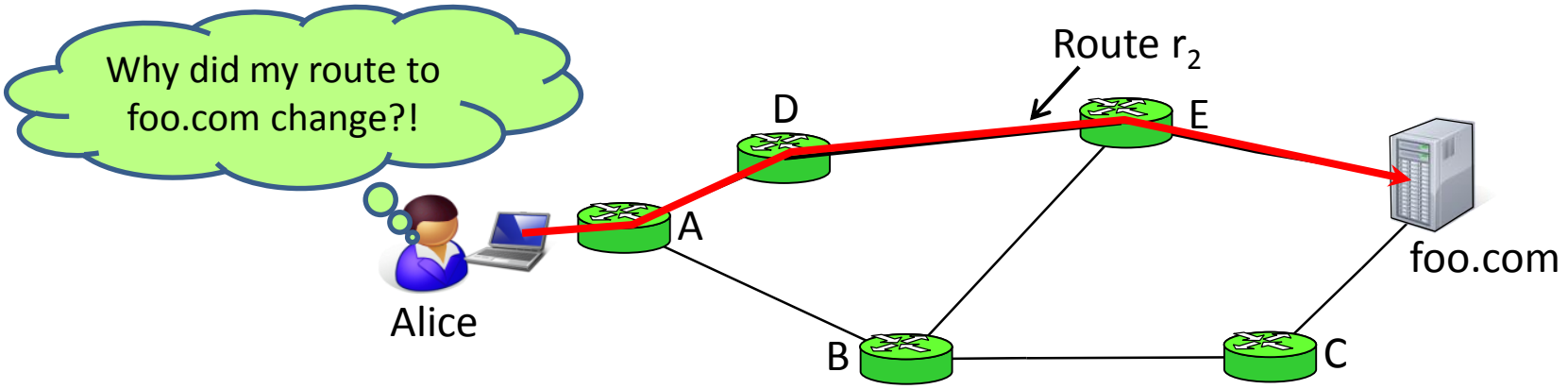
- Network provenance [SIGMOD'10]
- Secure network provenance [SOSP'11]
- Provenance in dynamic environments [VLDB'13]
- Negative provenance [SIGCOMM'14]
- Distributed provenance compression [SIGMOD'17]
- Differential provenance [SIGCOMM'16]
- Meta-provenance [NSDI'17]

Explanations

Deeper diagnostics and repair

Ph.D. dissertation work of Ang Chen (2017), Chen Chen (2017), Yang Wu (2017), and Wenchao Zhou (2012).

# Assumption #1: All nodes in the network can be trusted



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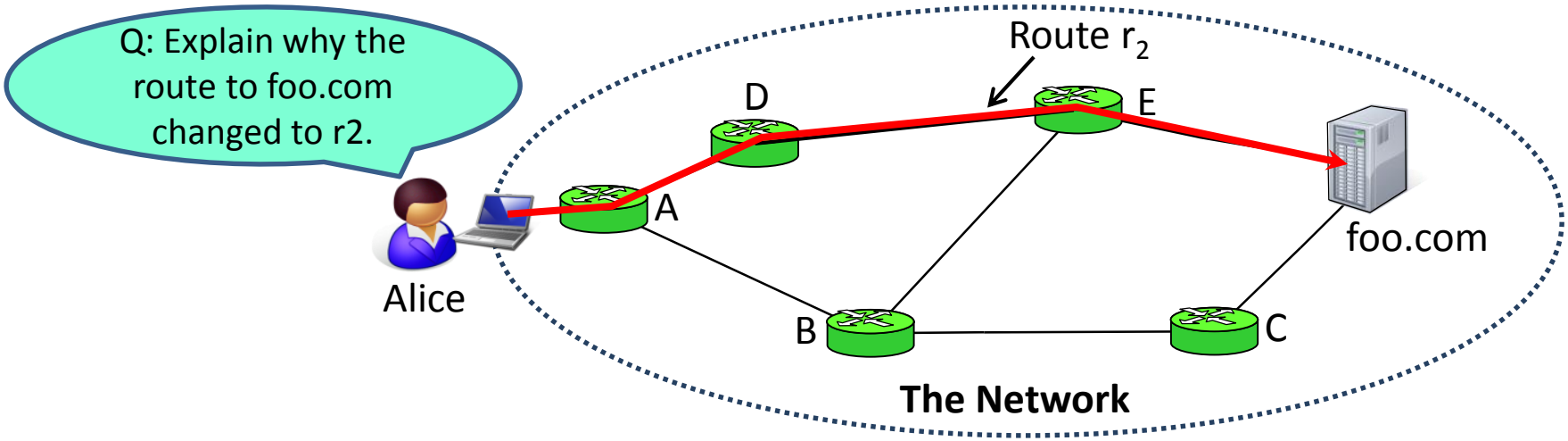

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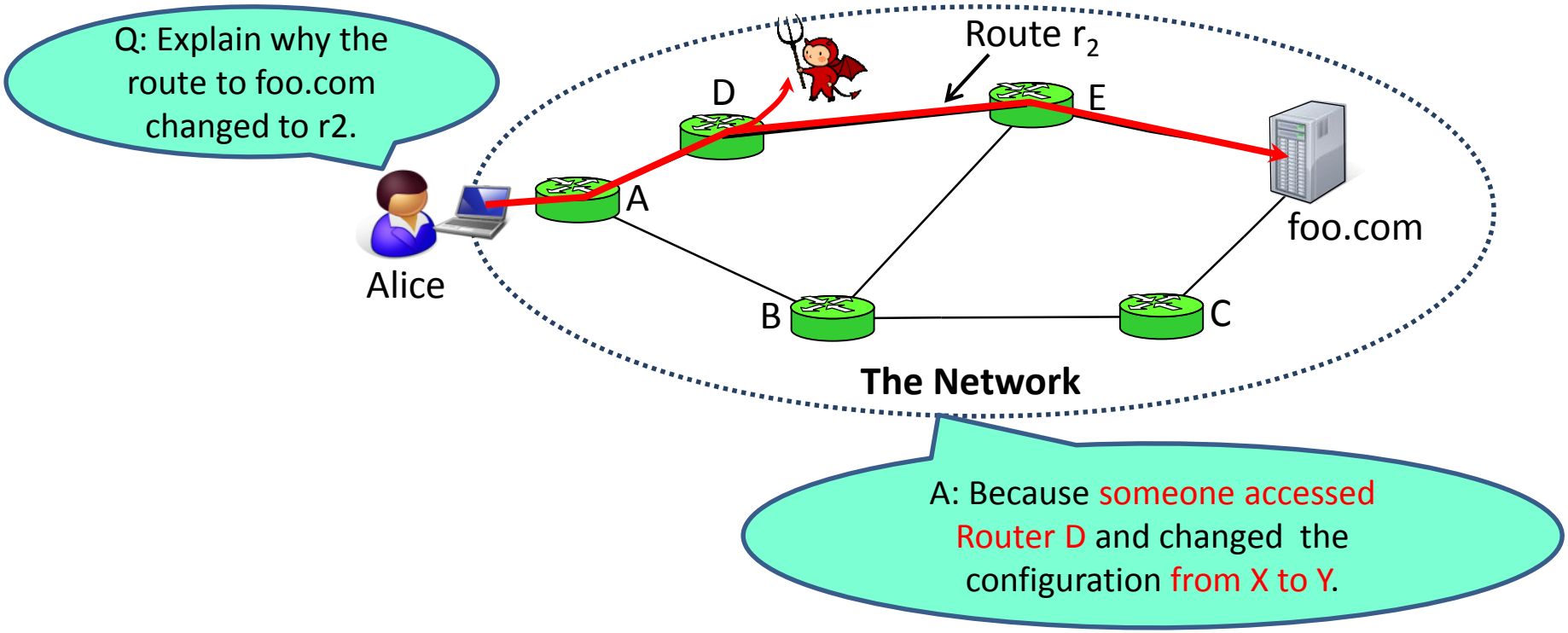

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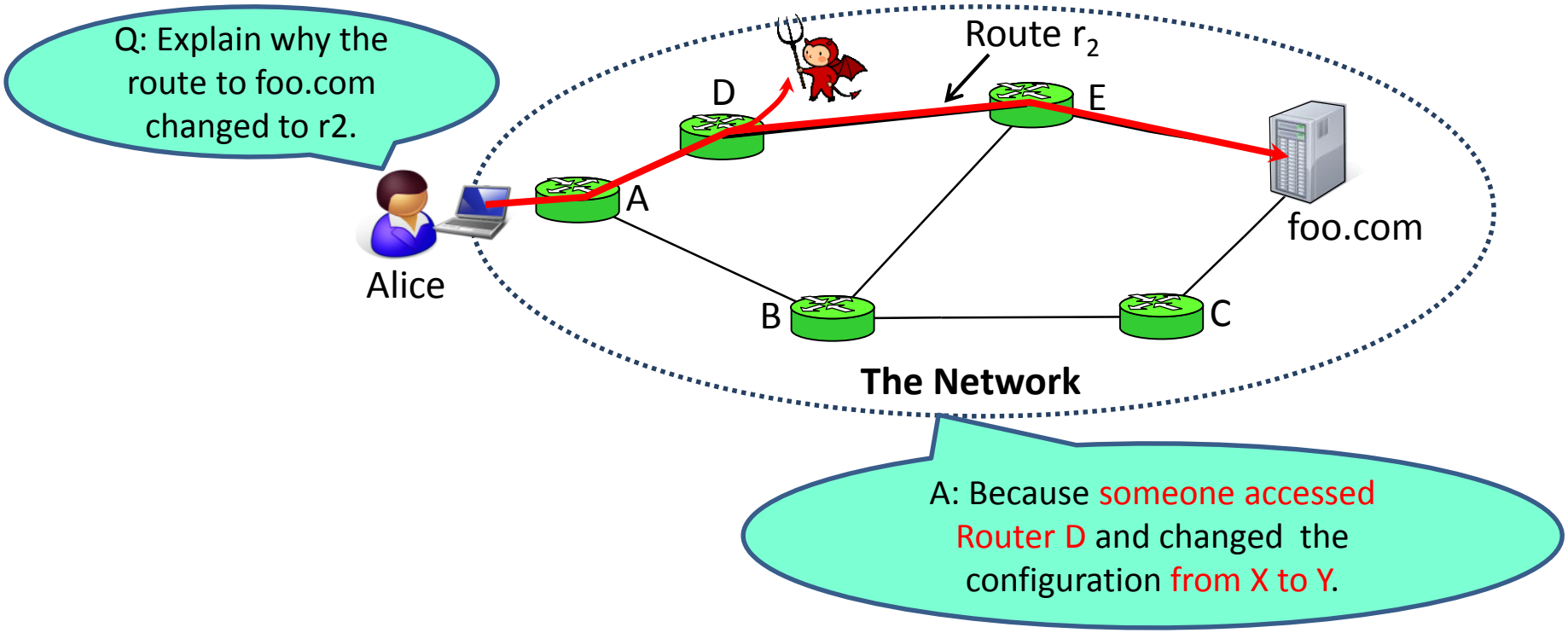
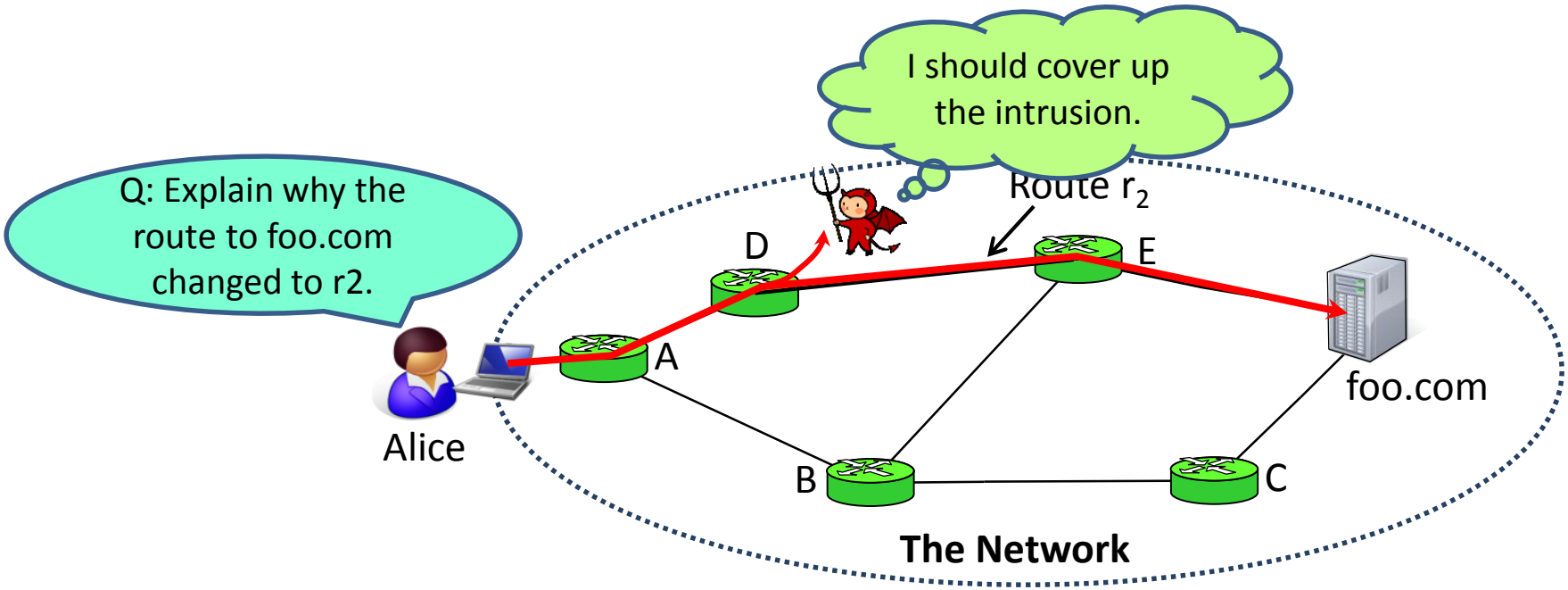



**Not realistic: adversary can tell lies**

# Challenge: Adversaries Can Lie

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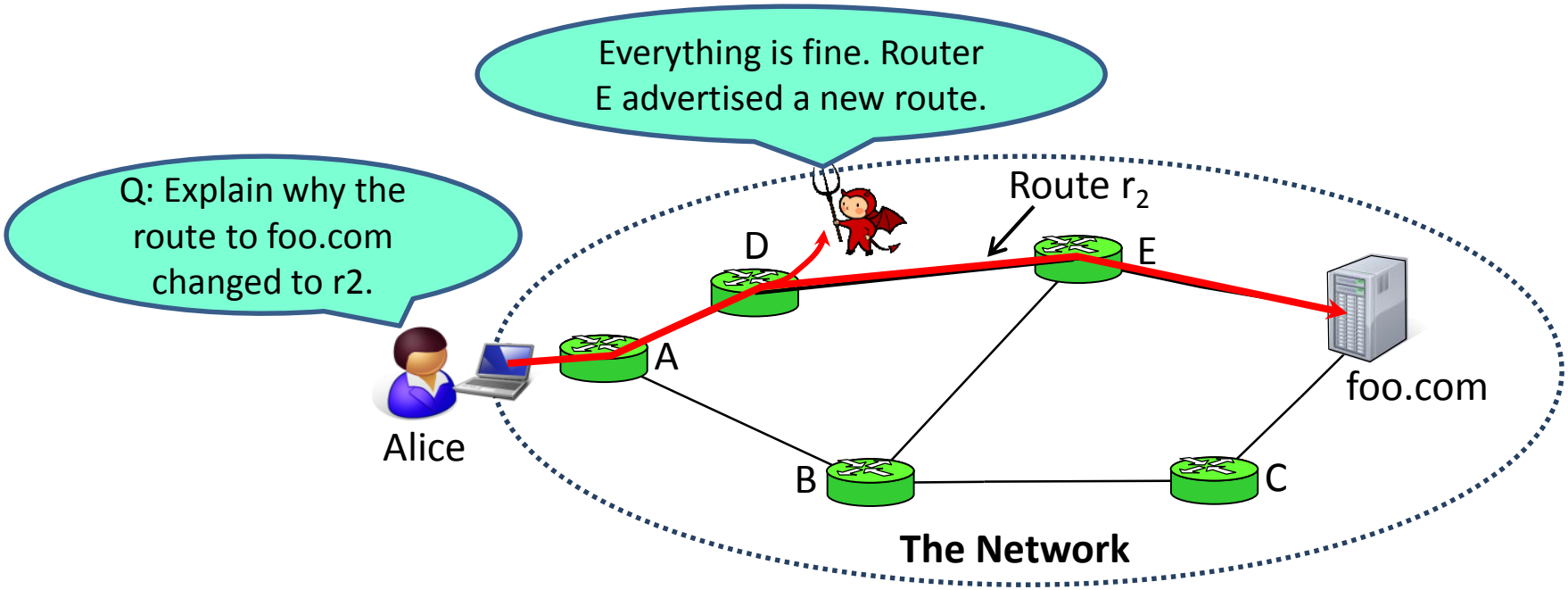


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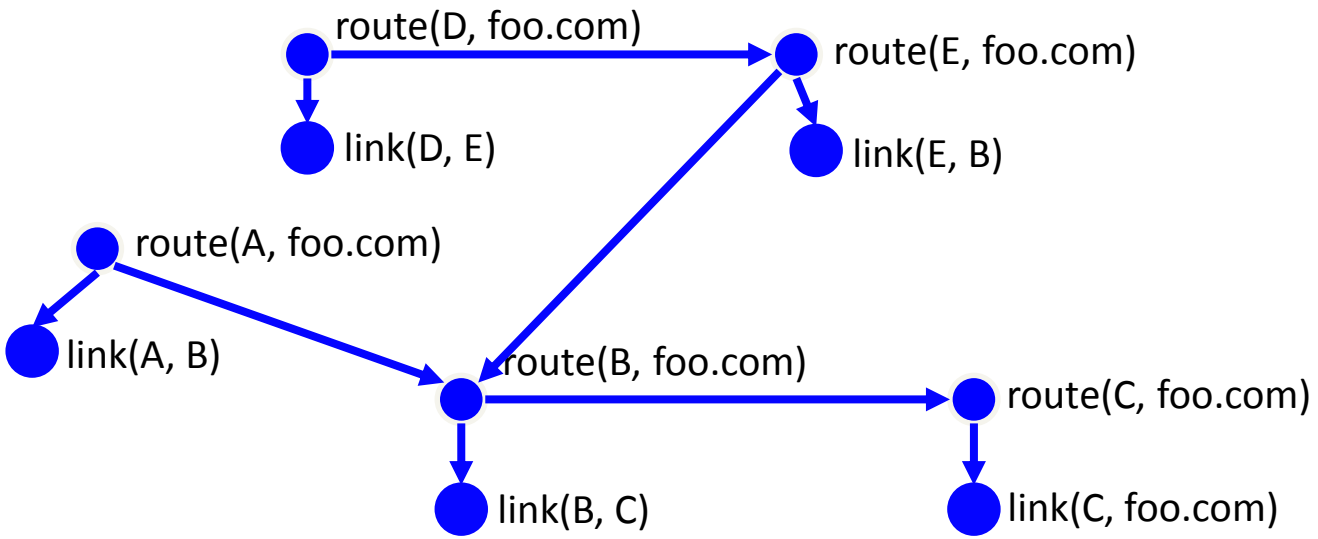
SOSP 2011




- **Step 1: Each node keeps vertices about local actions**
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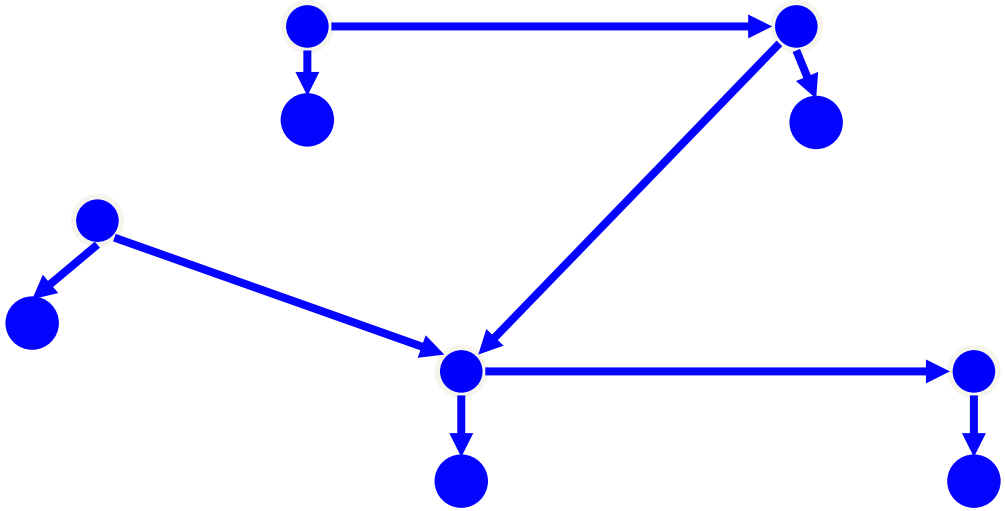

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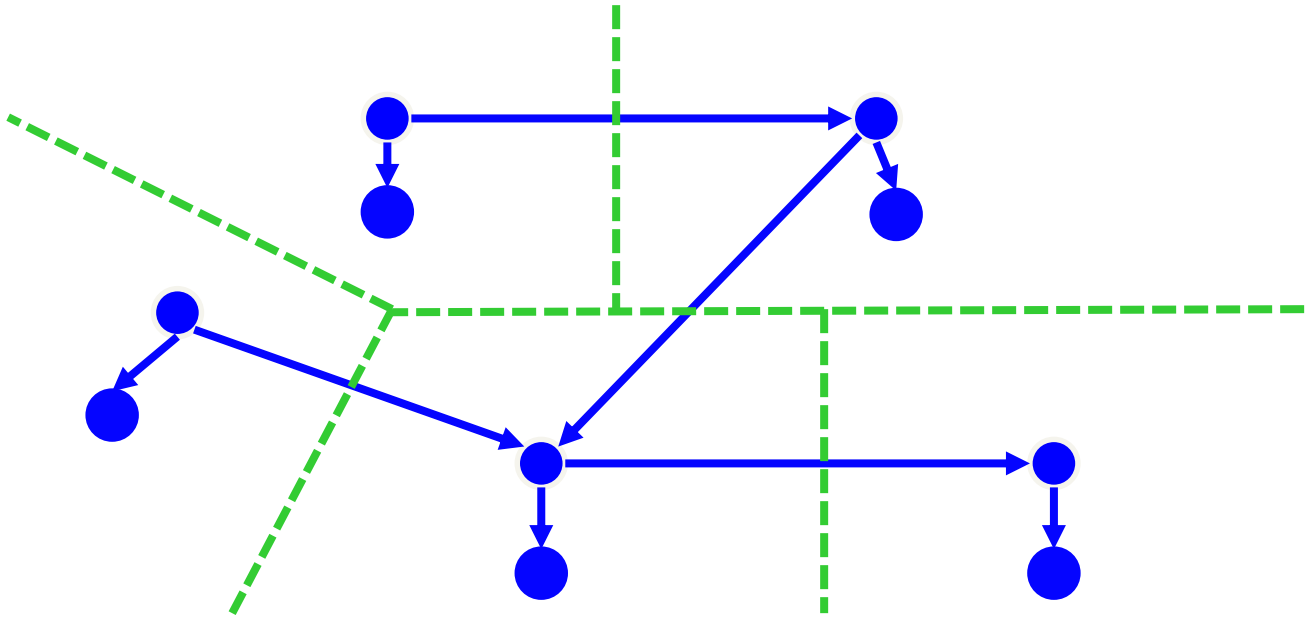

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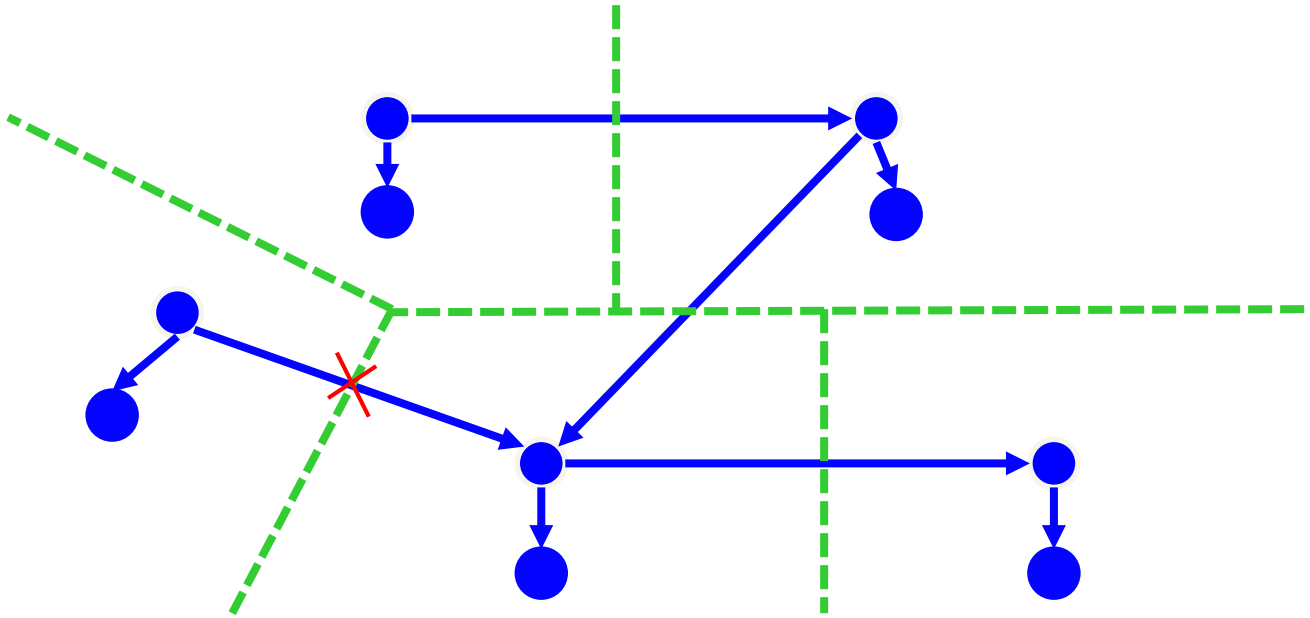

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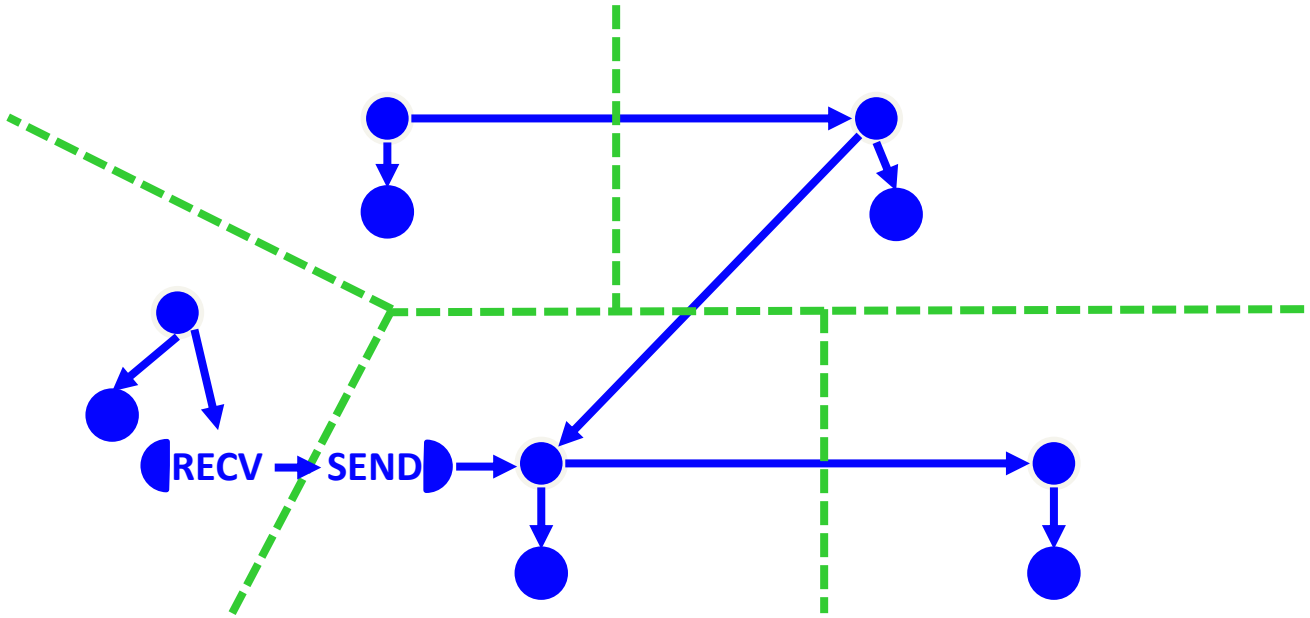


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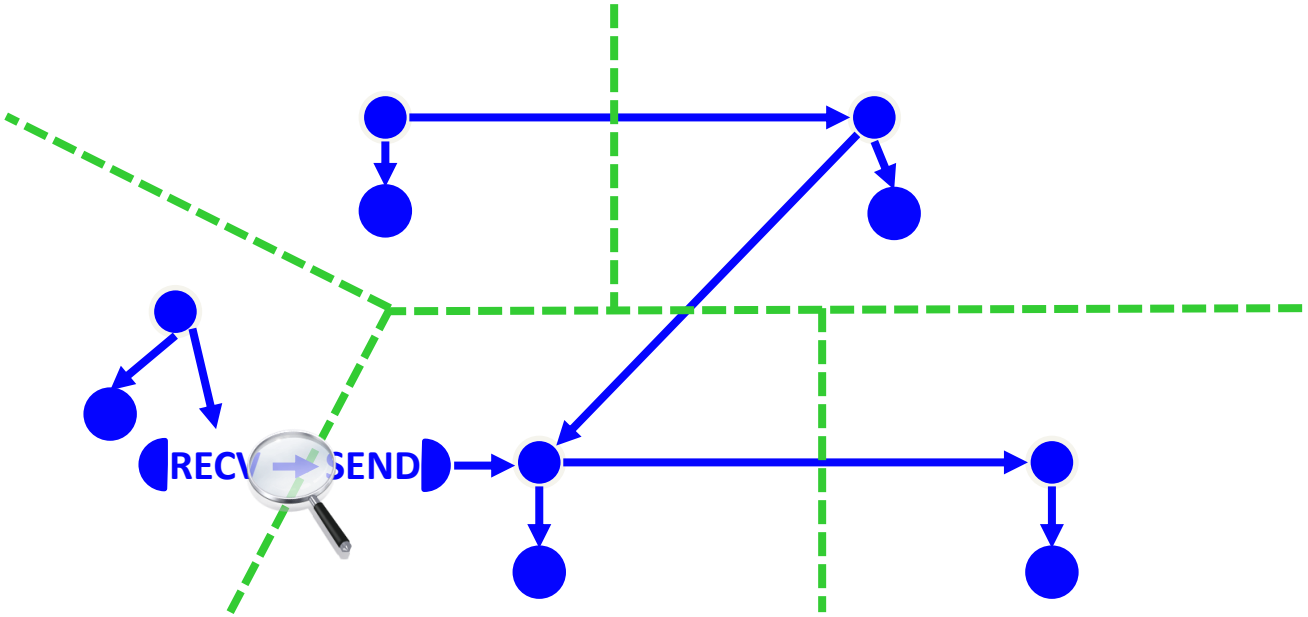


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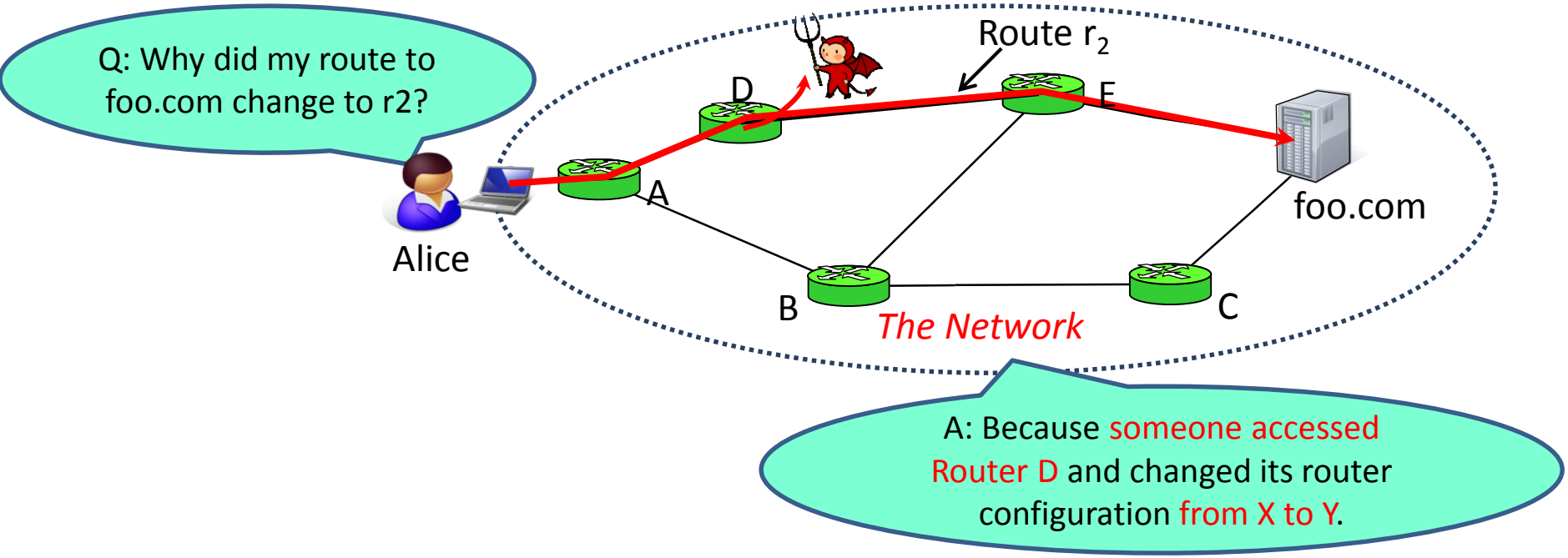
- **Step 2: Make the graph *tamper-evident***

# SNP Guarantees

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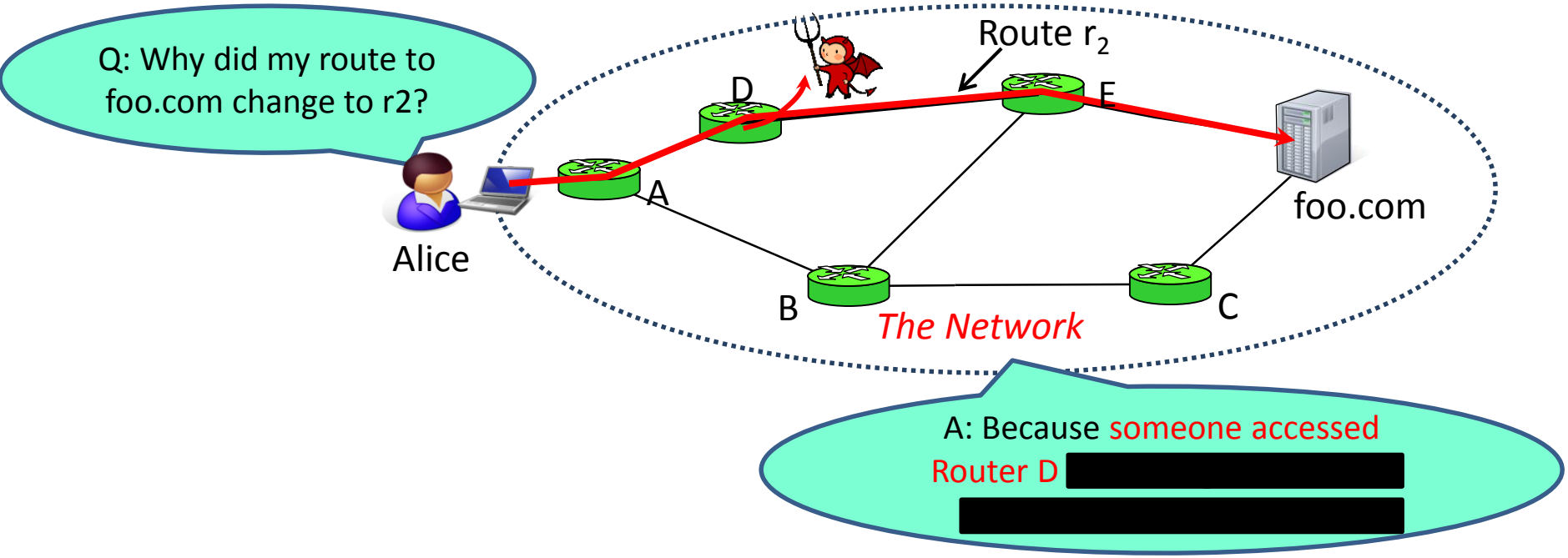


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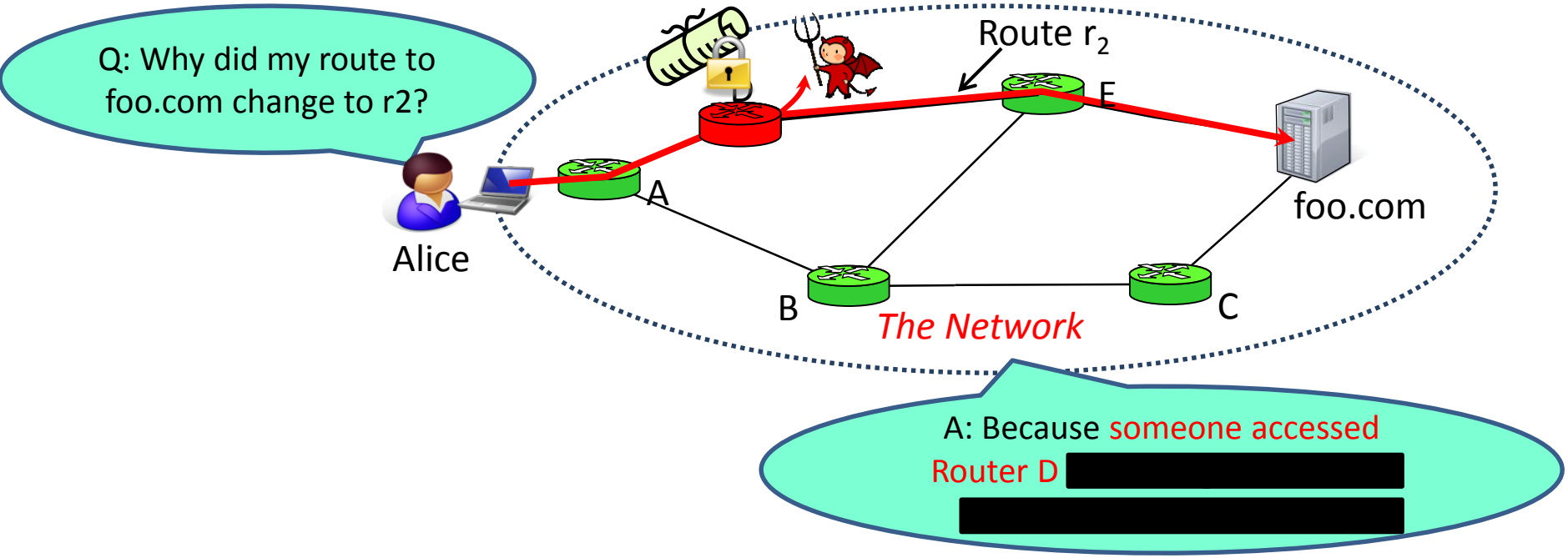


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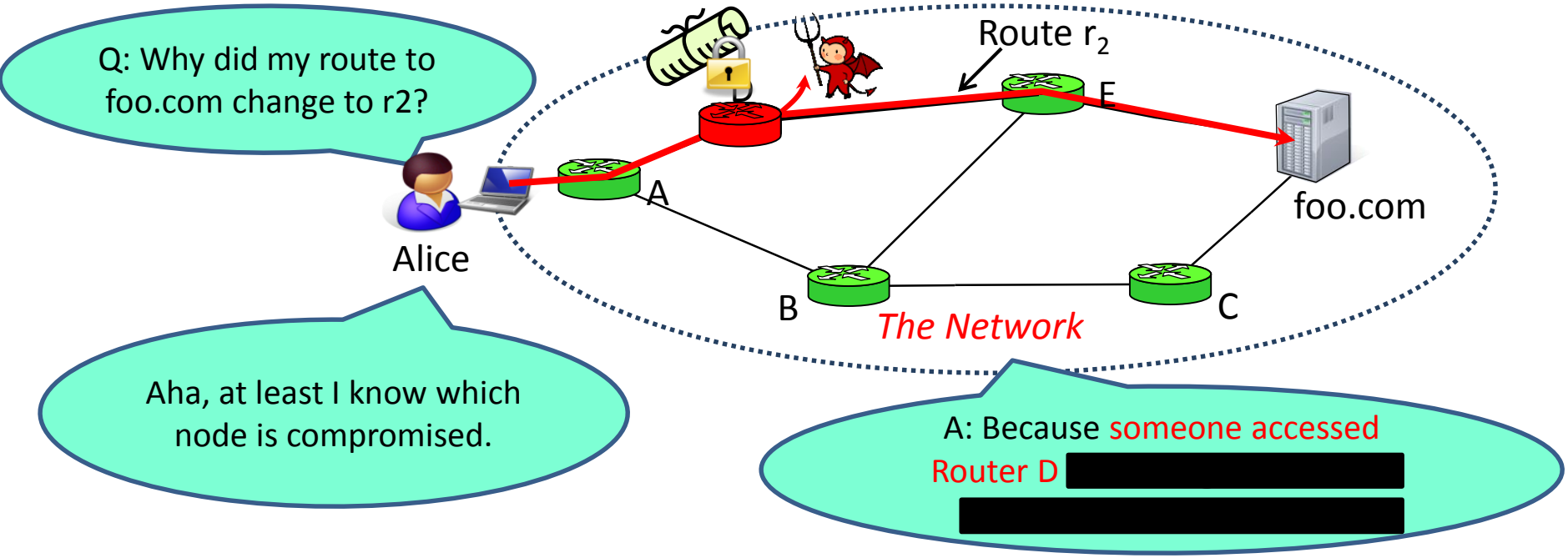


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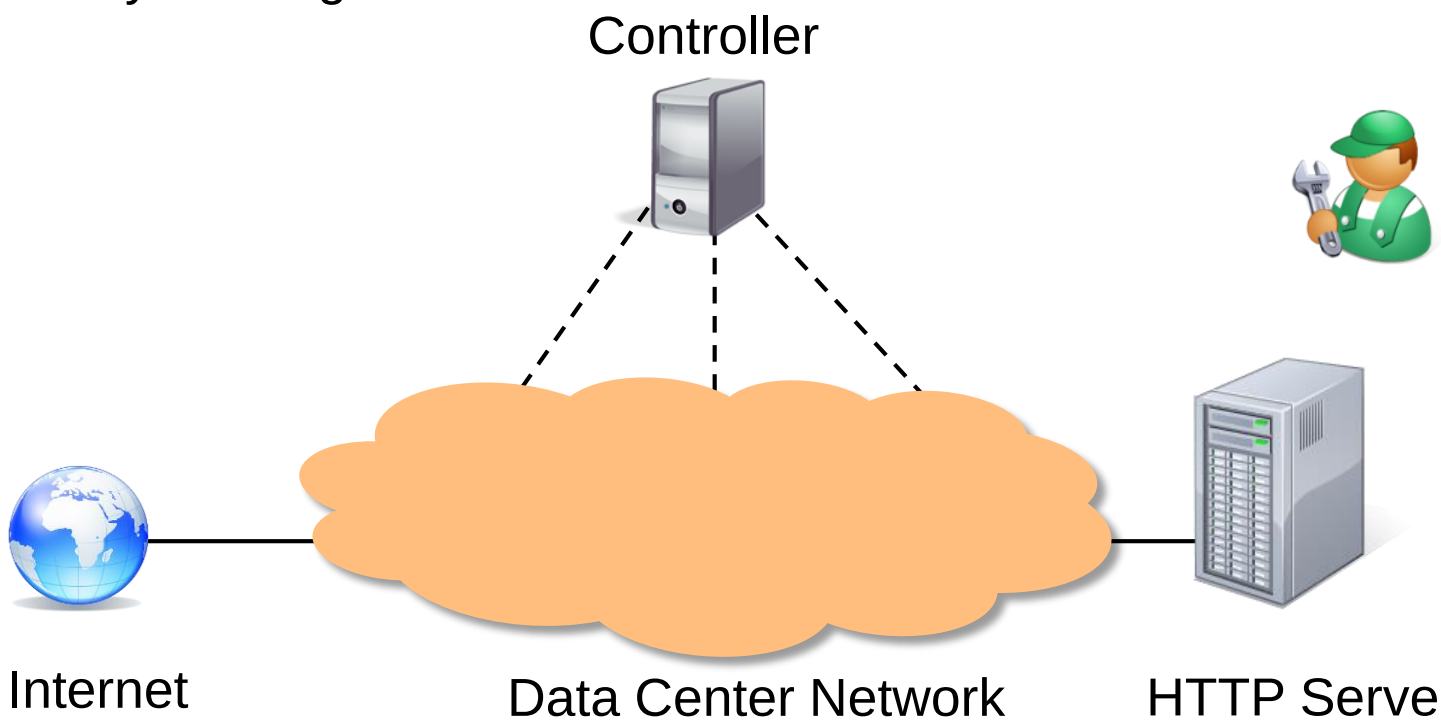

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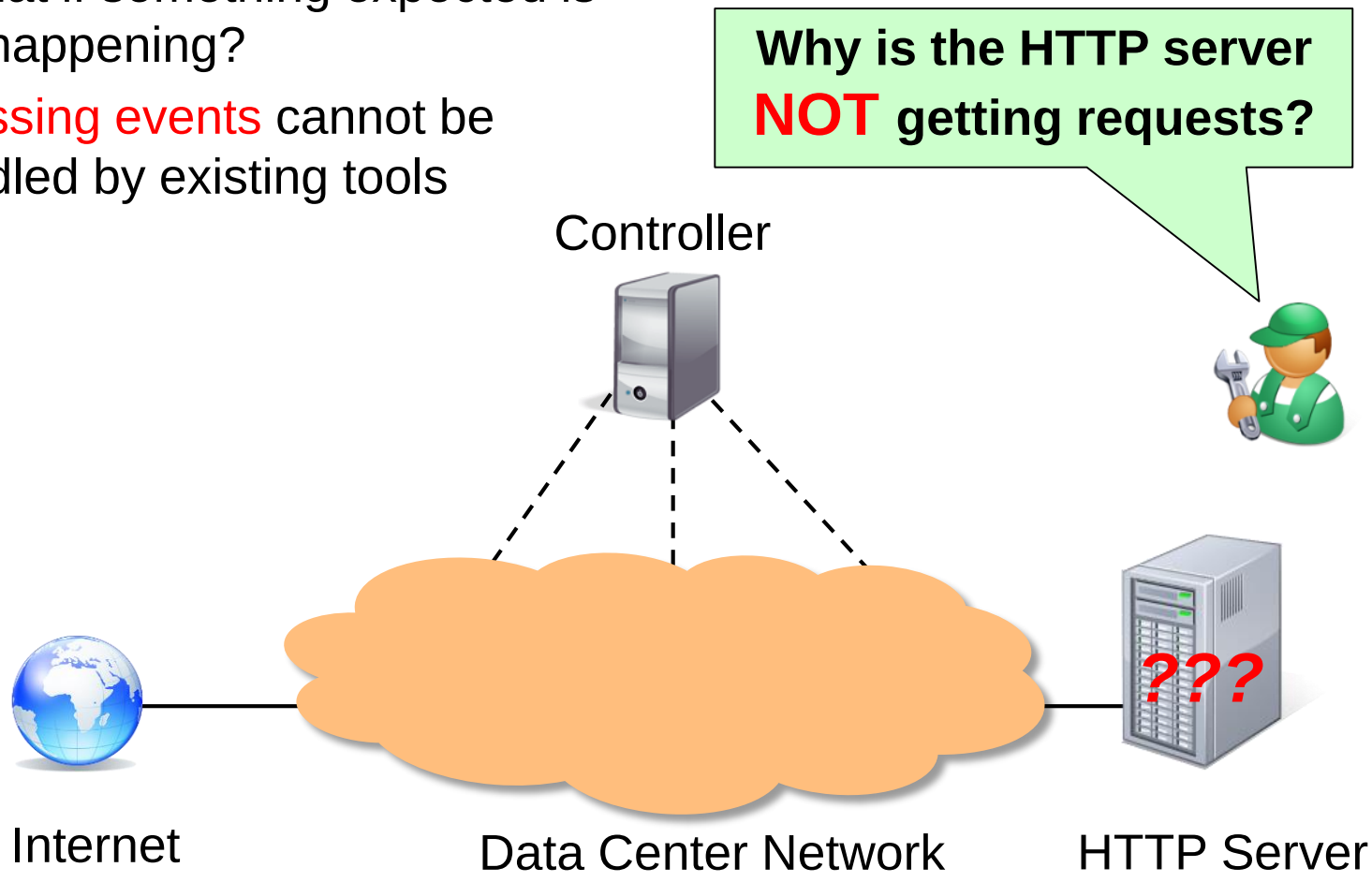
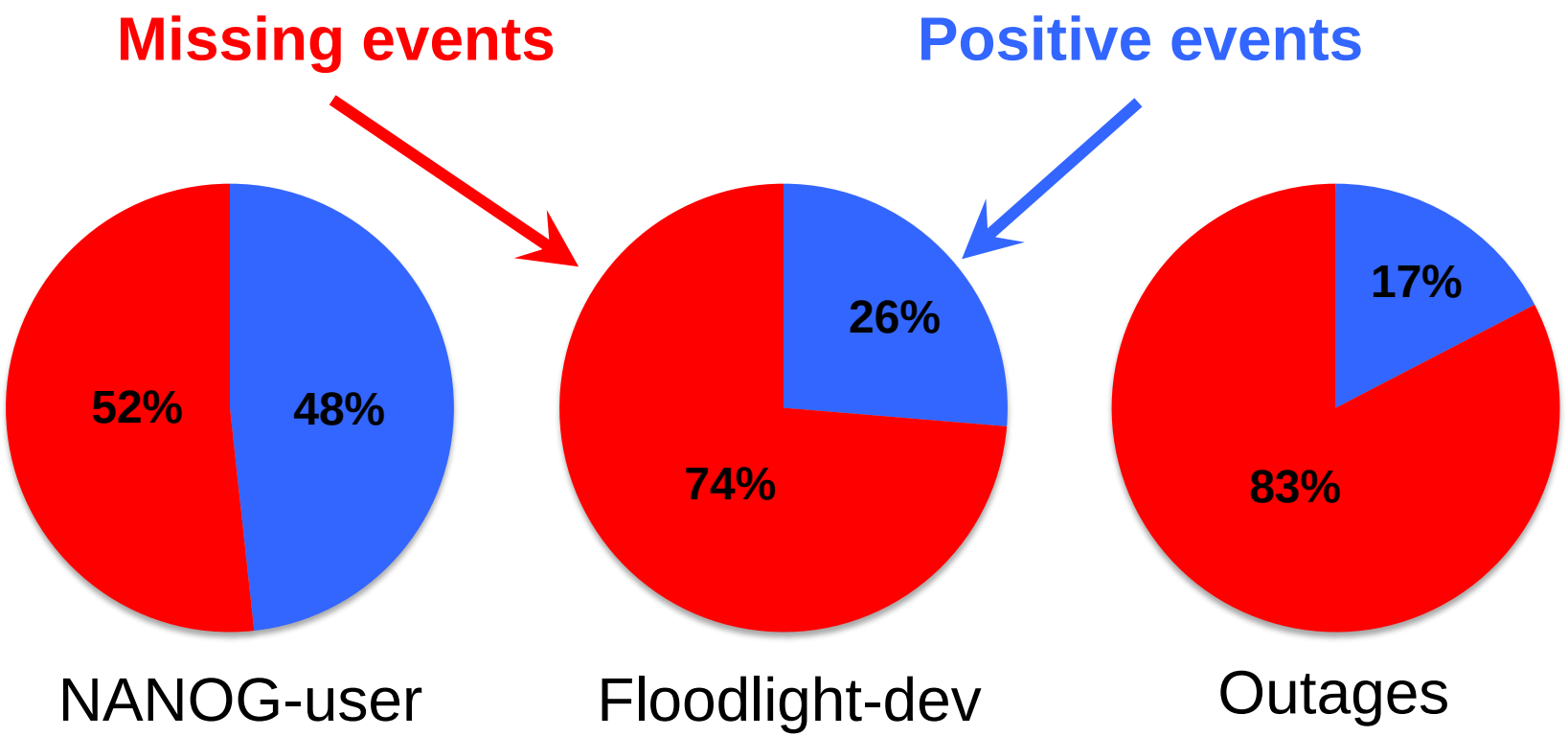


# How common are missing events?

- Missing events are consistently in the majority
- Lengthier email threads for missing events



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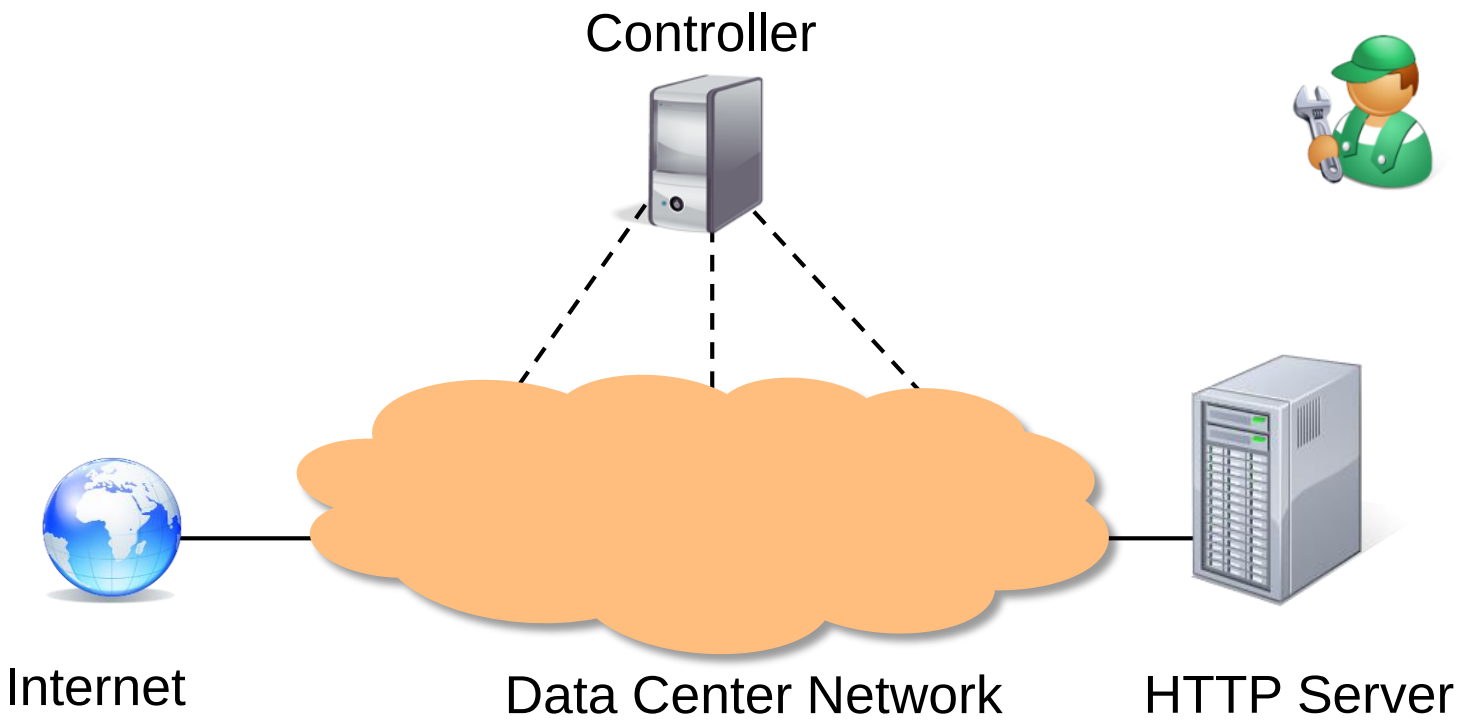

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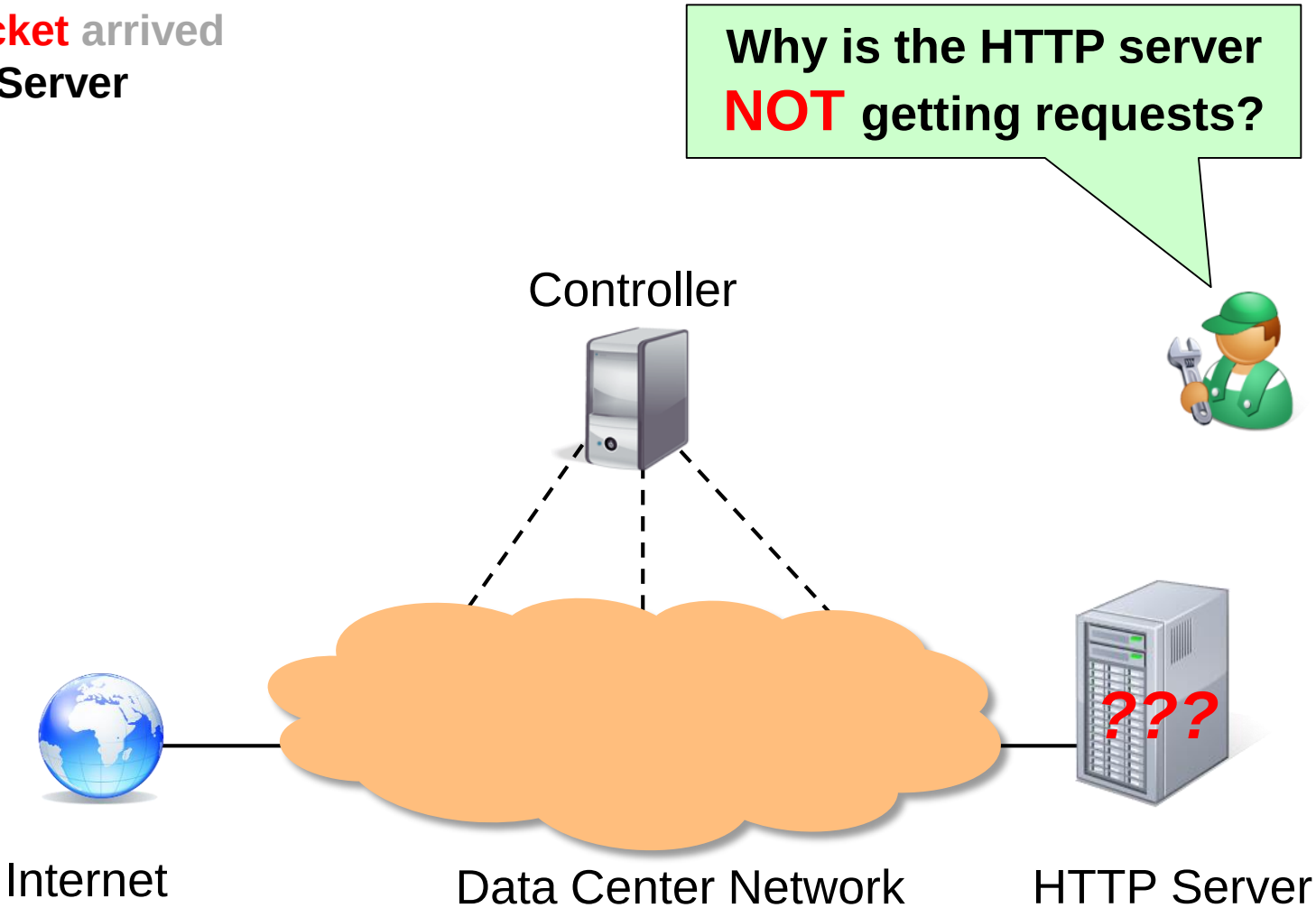

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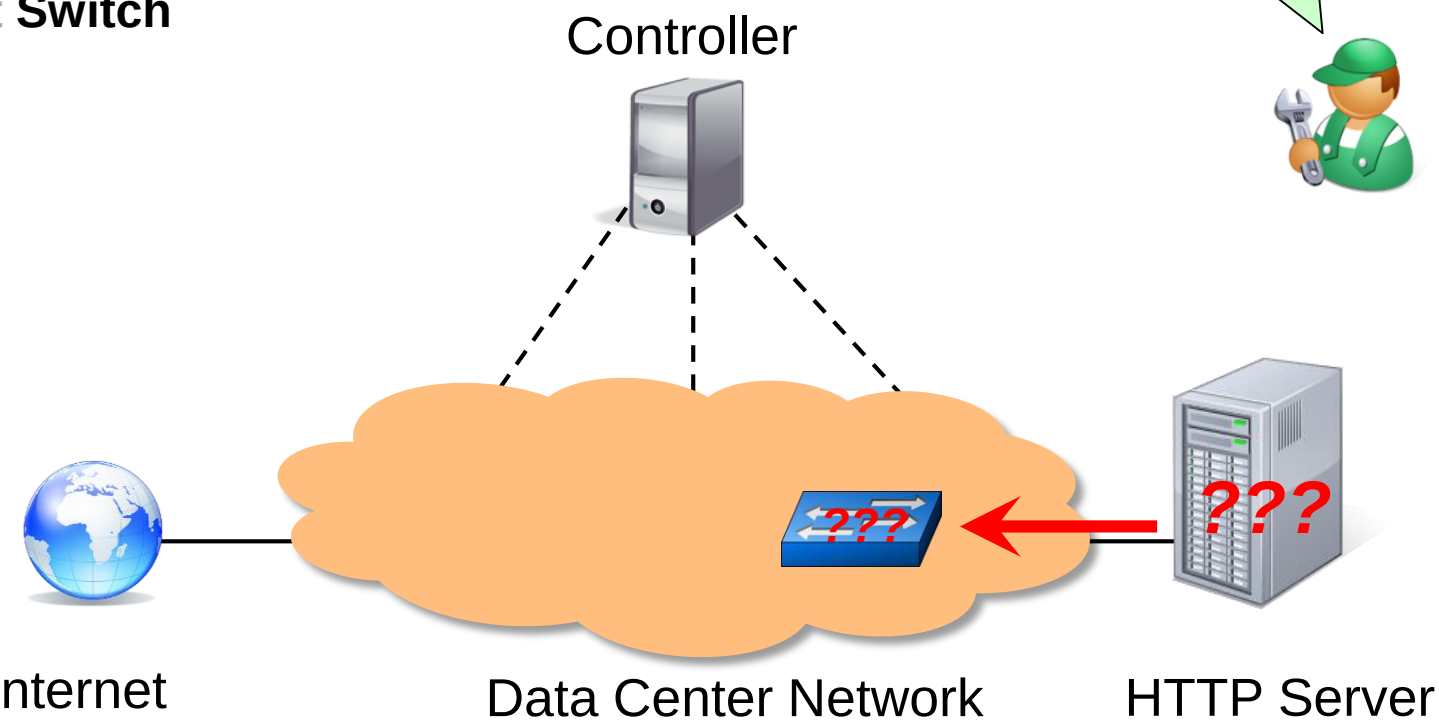
**Why is the HTTP server NOT getting requests?**



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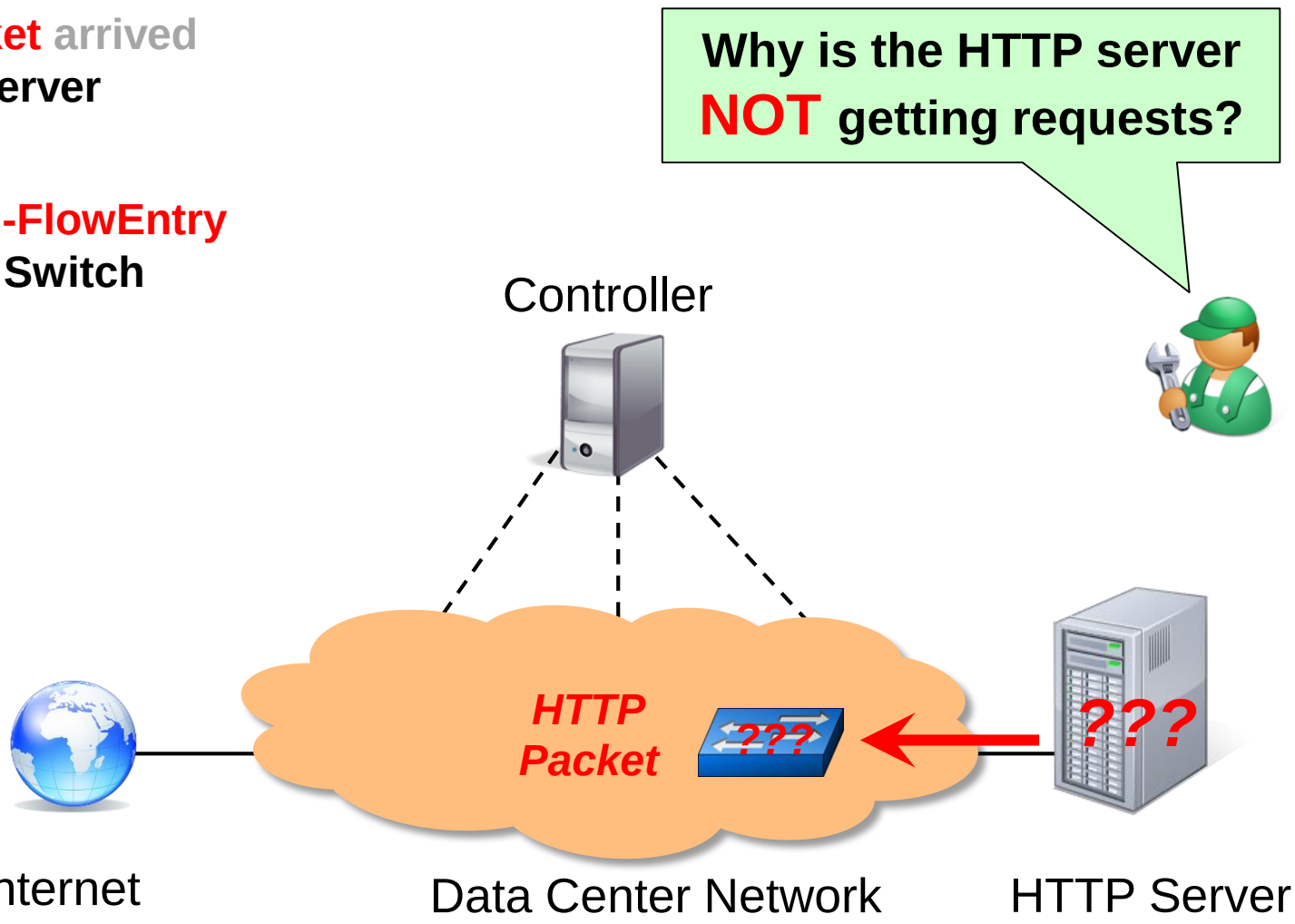

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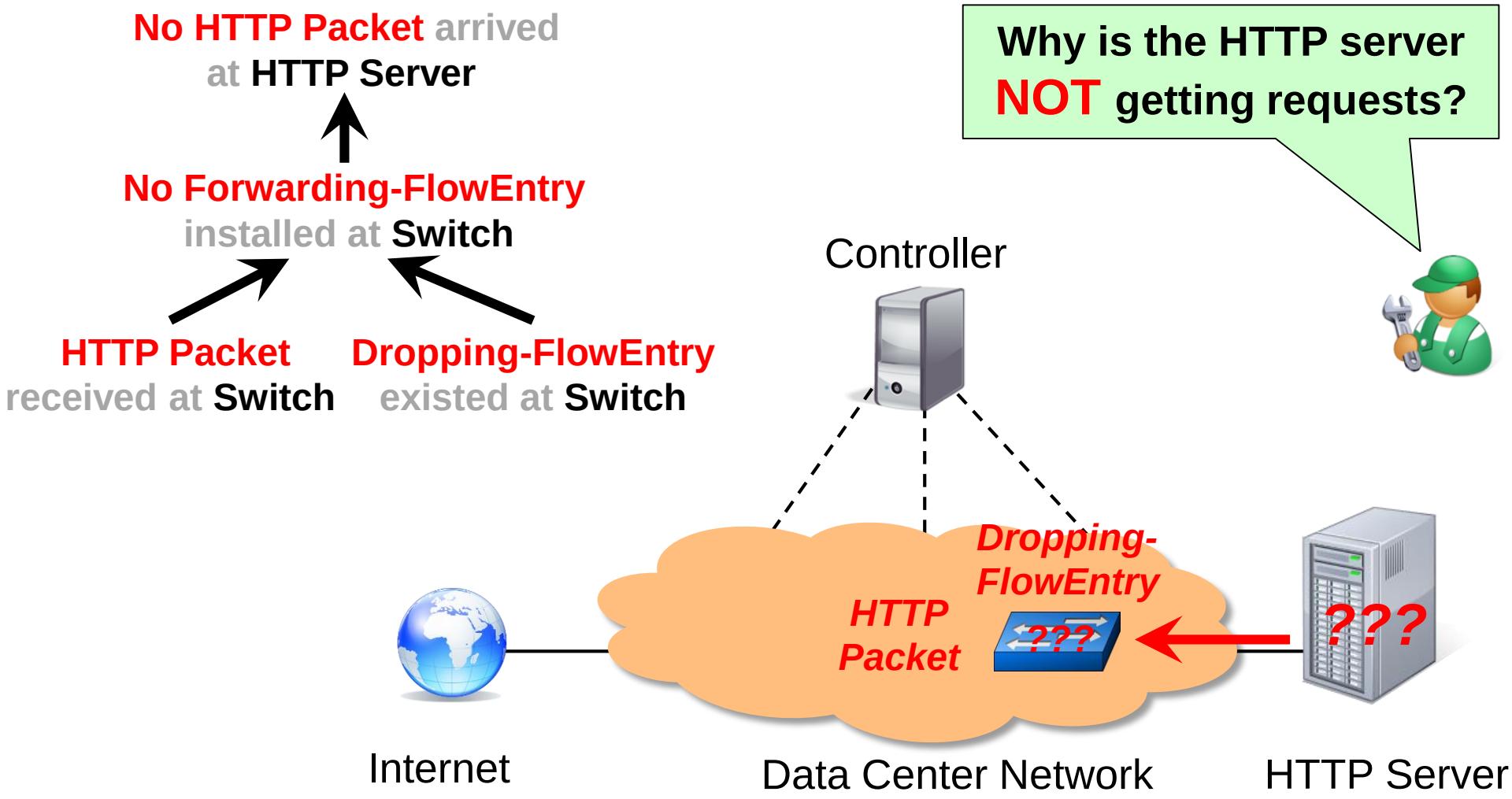
**HTTP Packet** received at **Switch**

**Dropping-FlowEntry** existed at **Switch**



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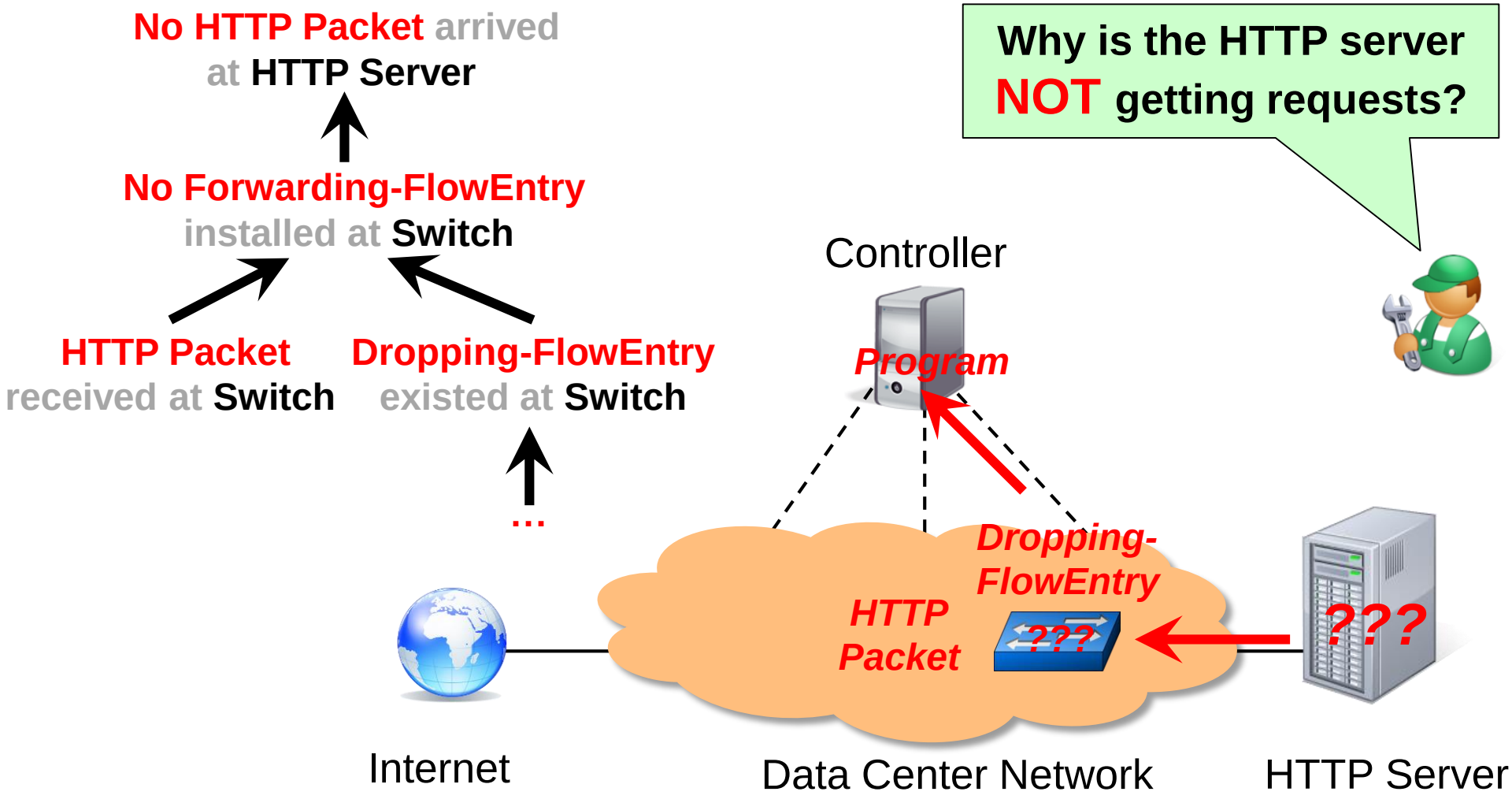

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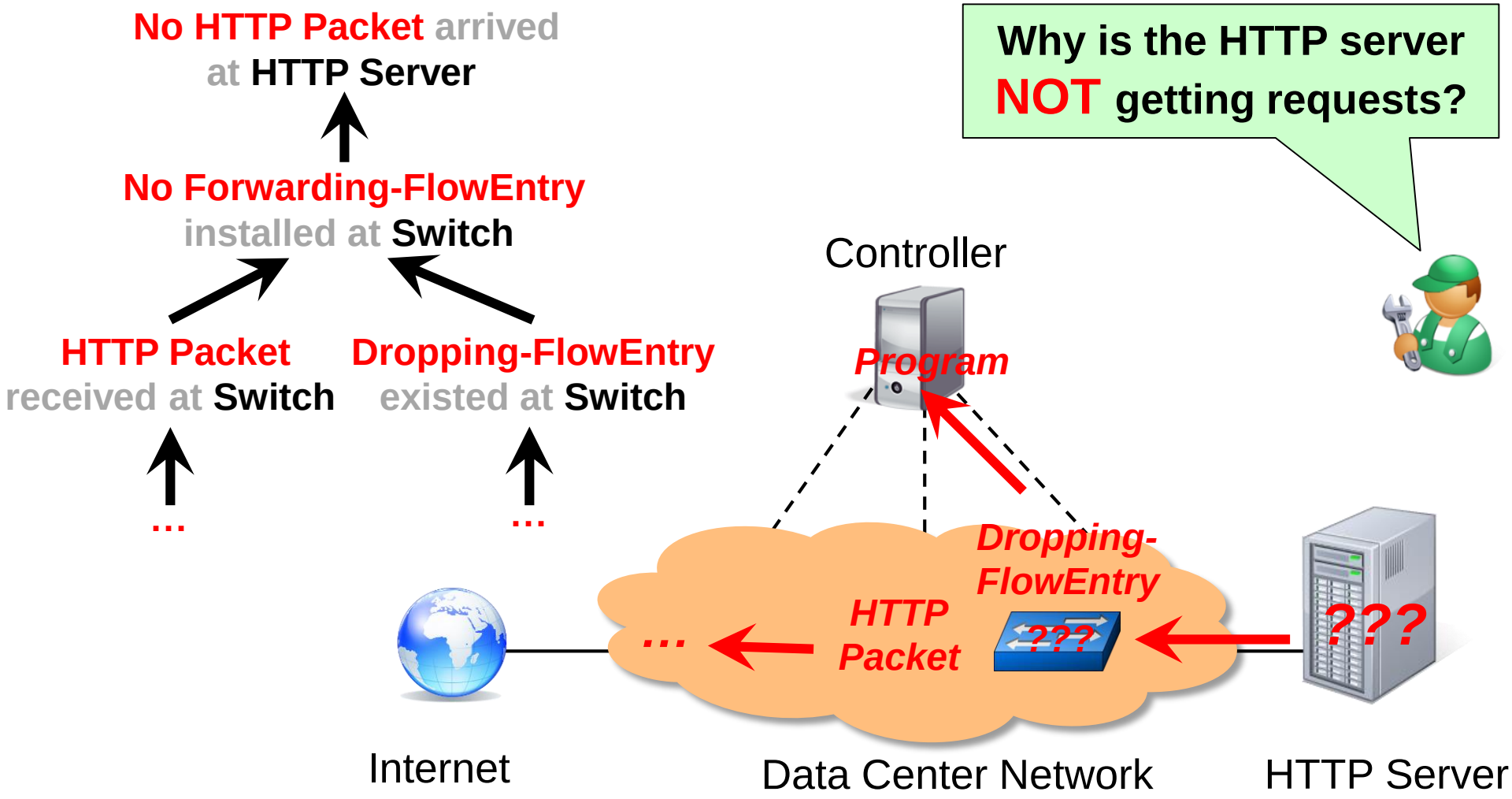

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**Why did Bob NOT arrive at CIDR?**

**Philly**

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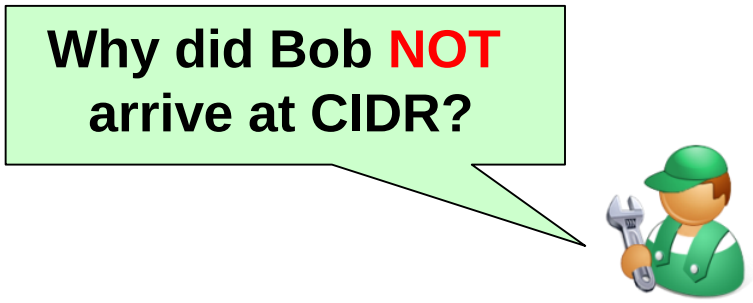


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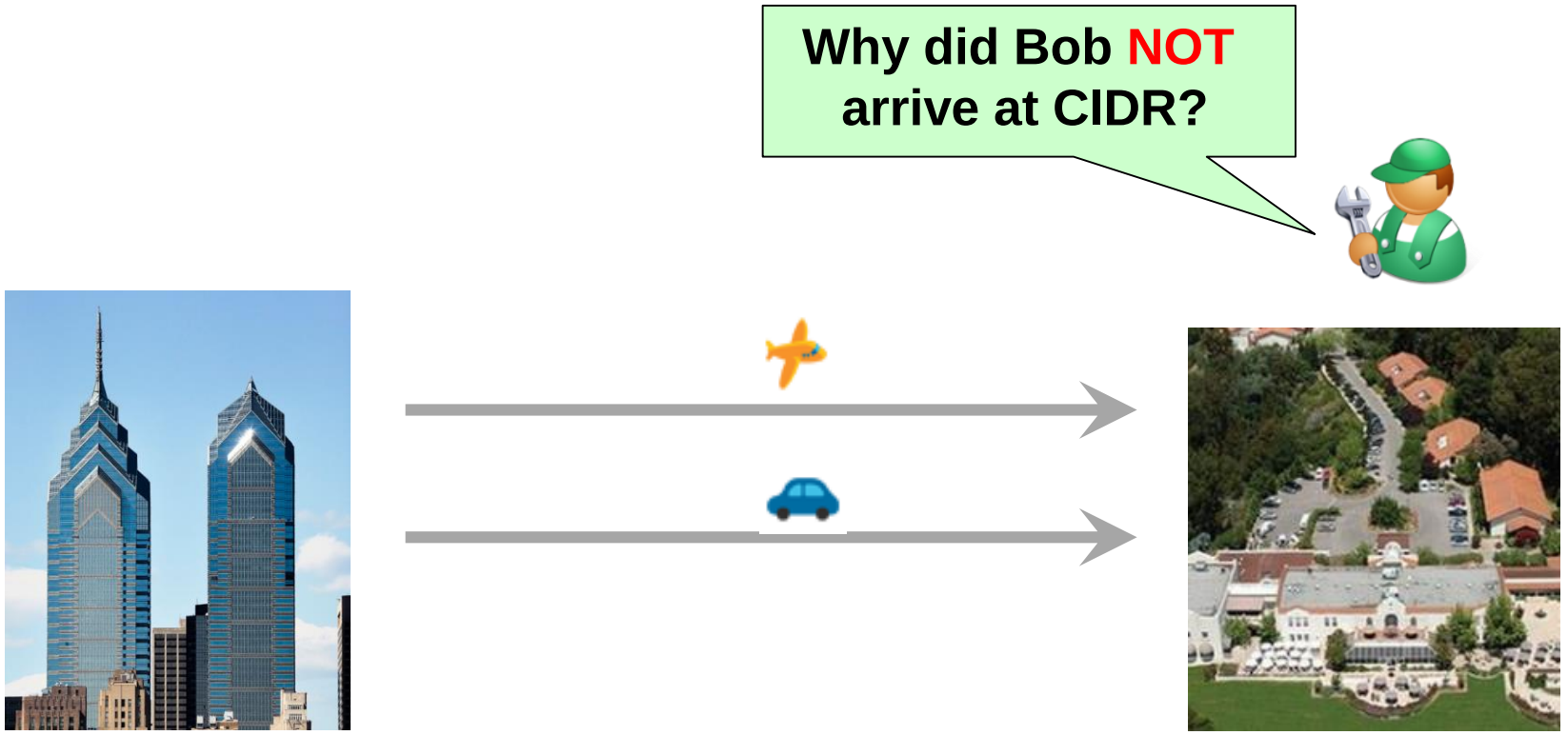

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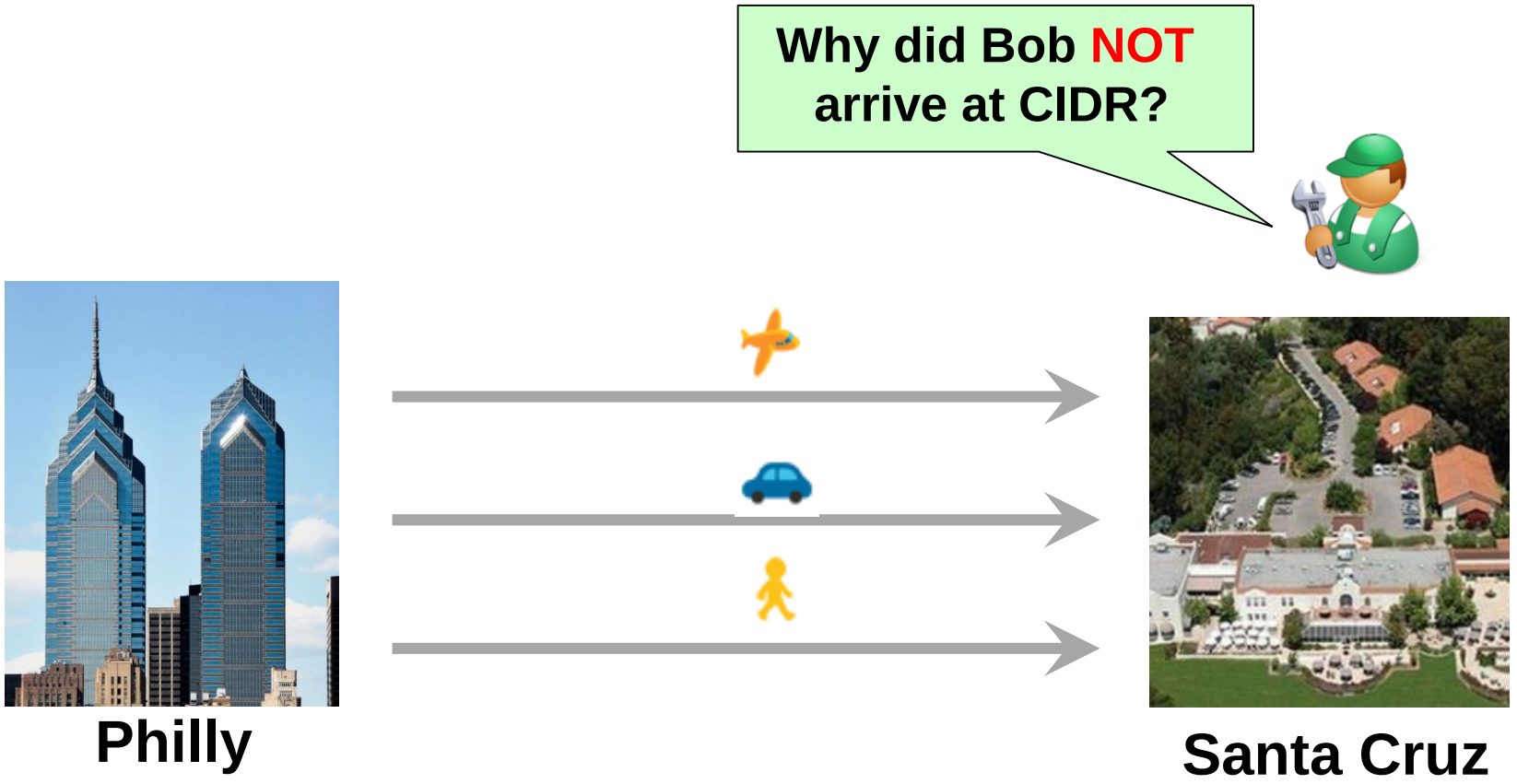

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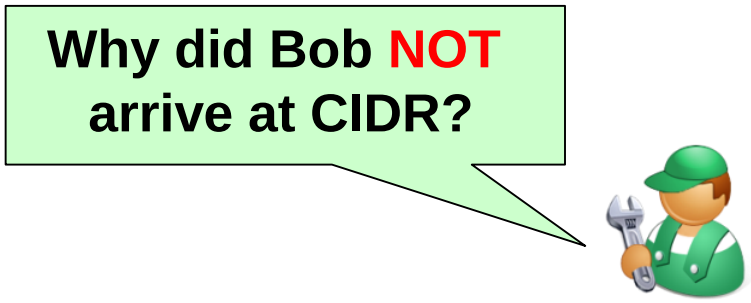
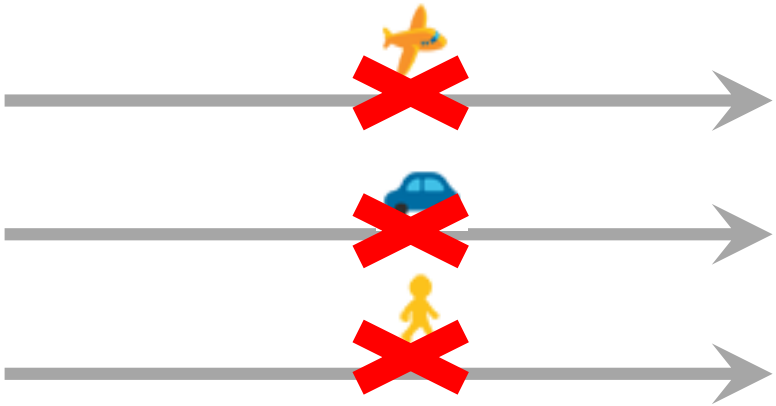



**Philly**



**Santa Cruz**

# Assumption #3: Provenance trees alone are sufficient for diagnostics

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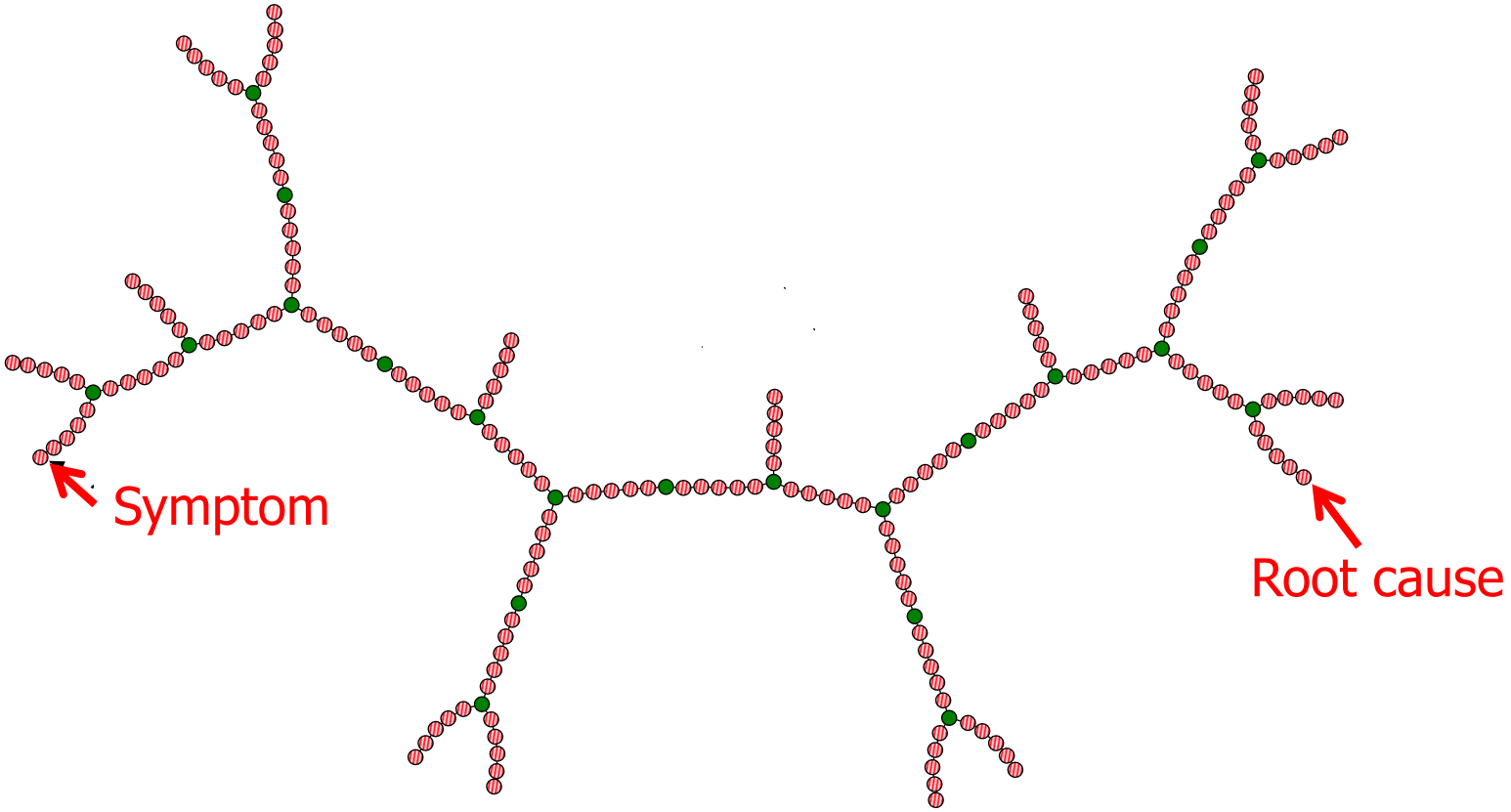

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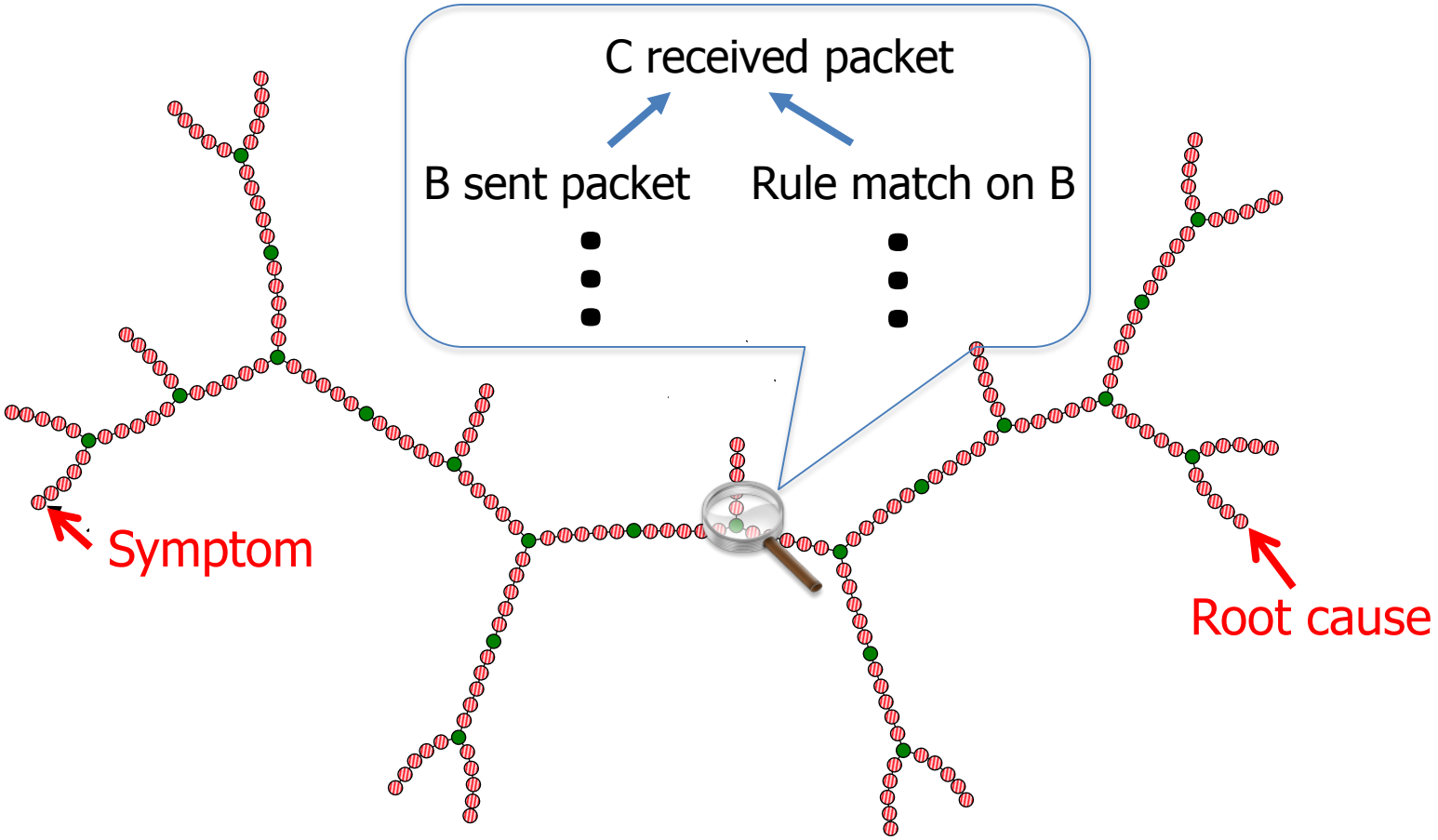

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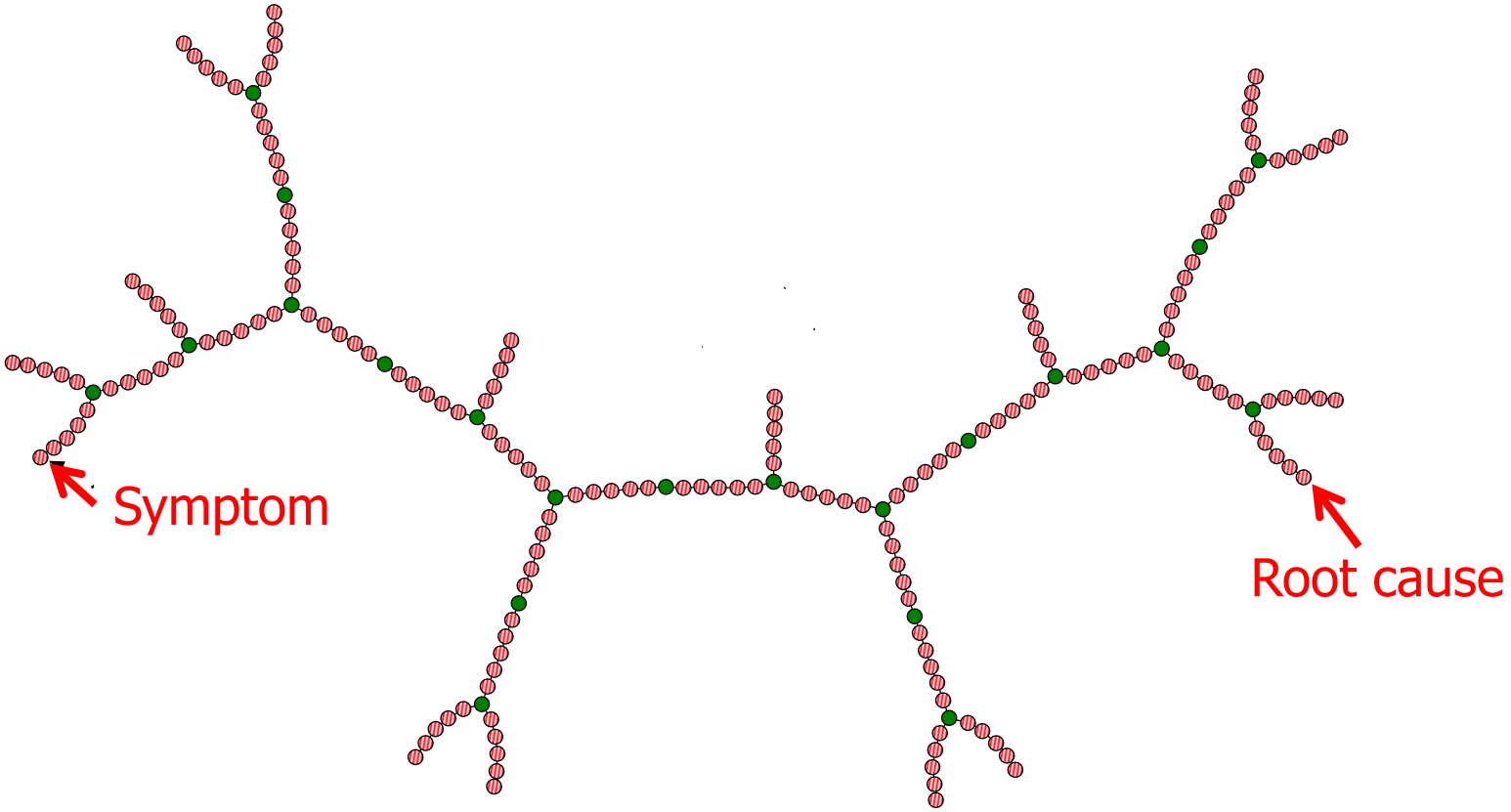

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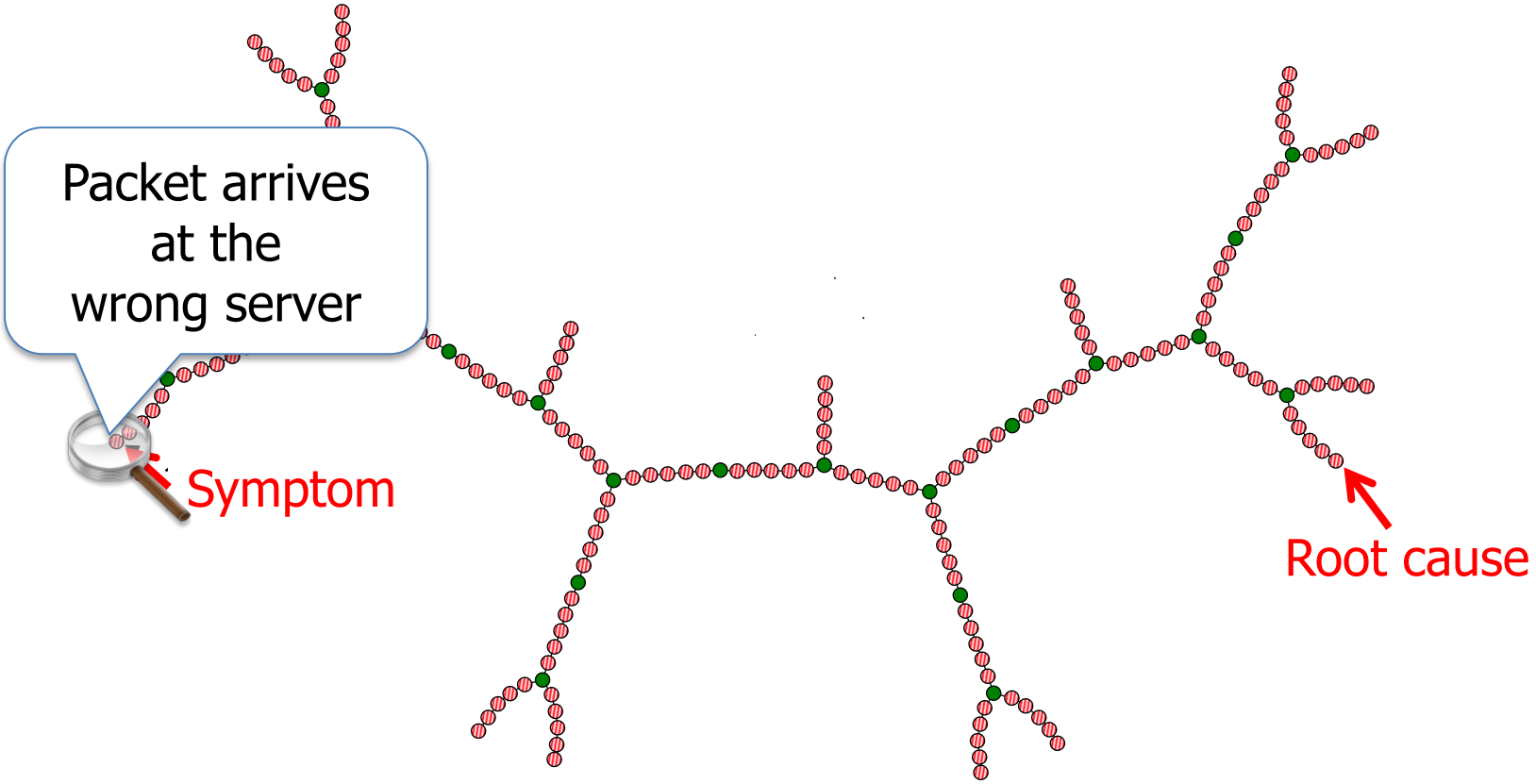

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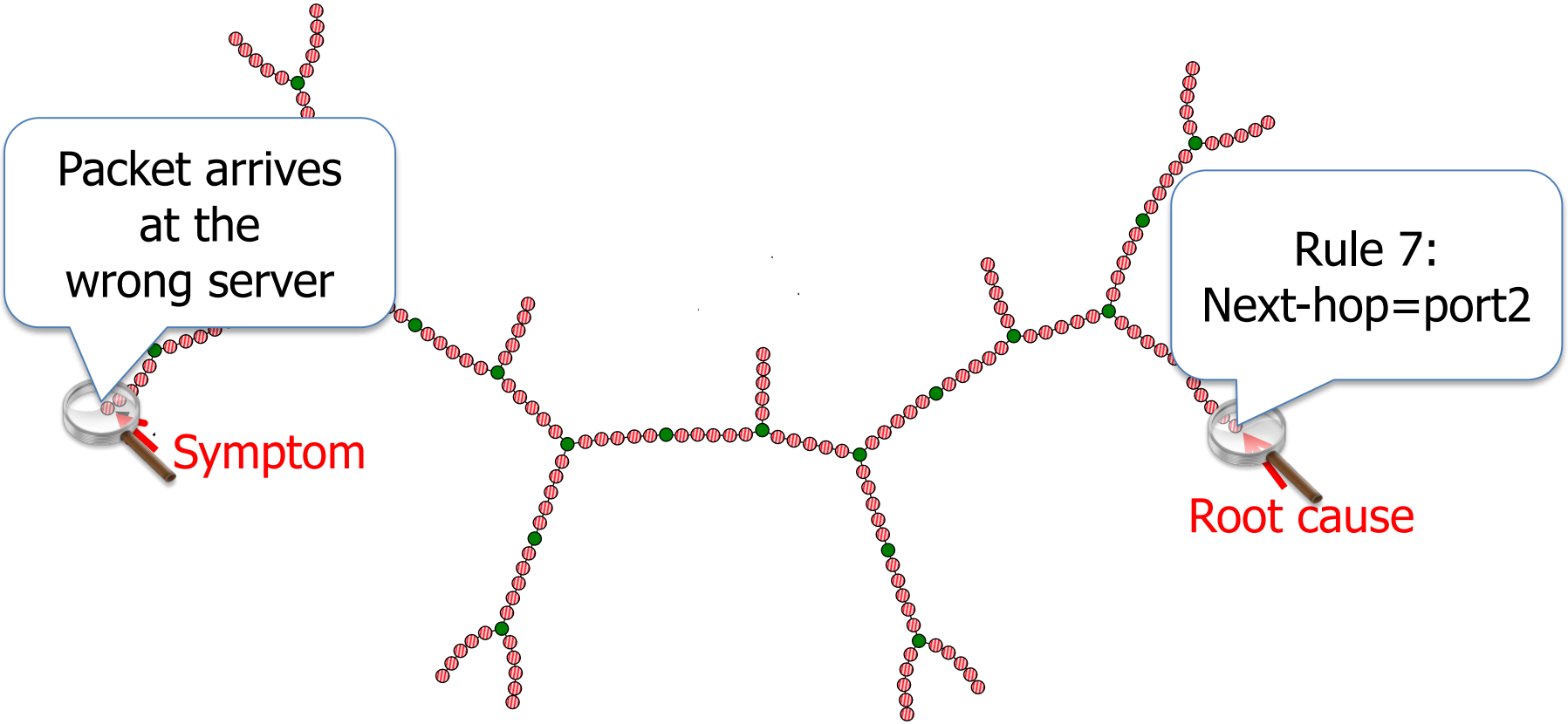

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From: alice@xyz.com
To: Admin (bob@xyz.com)
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My server is receiving suspicious traffic from 4.3.2.0/24--it should have been sent to the low-security server. Packets from 4.3.3.0/24 are still being routed correctly. Can you help?

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**Working reference!**

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**Working reference!**

Outages mailing list Sept.—Dec. 2014:
**66%** have references!

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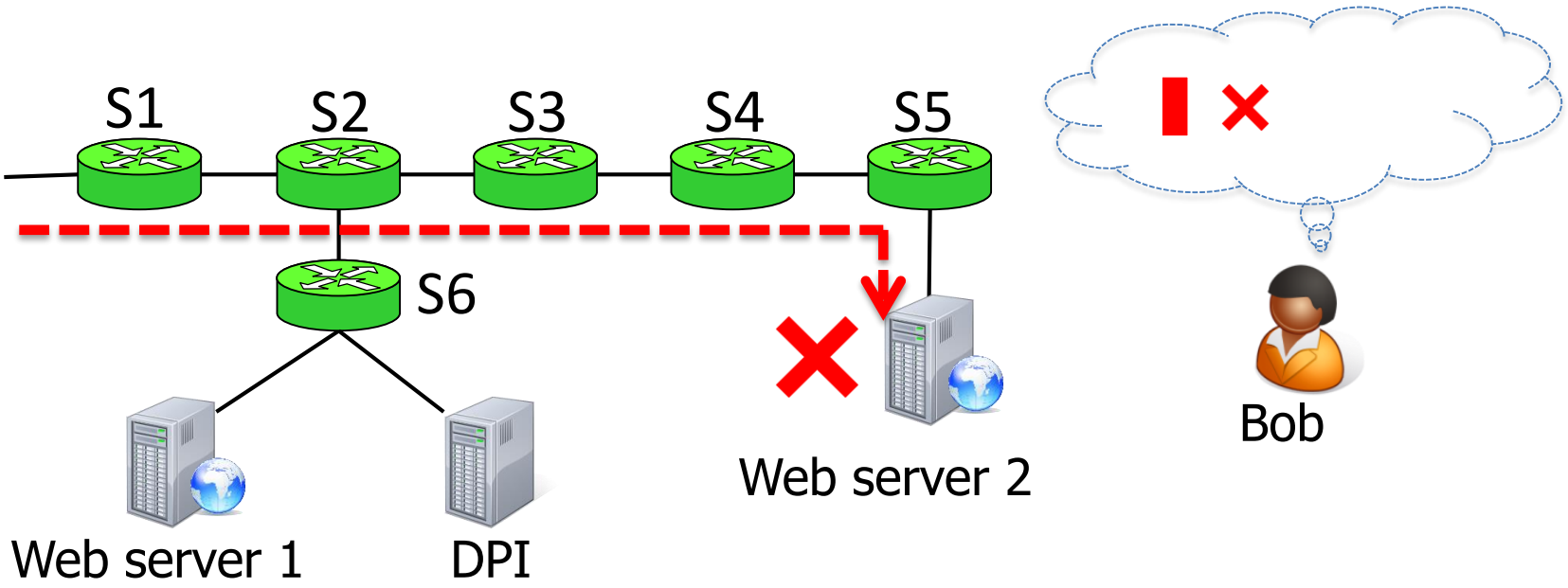

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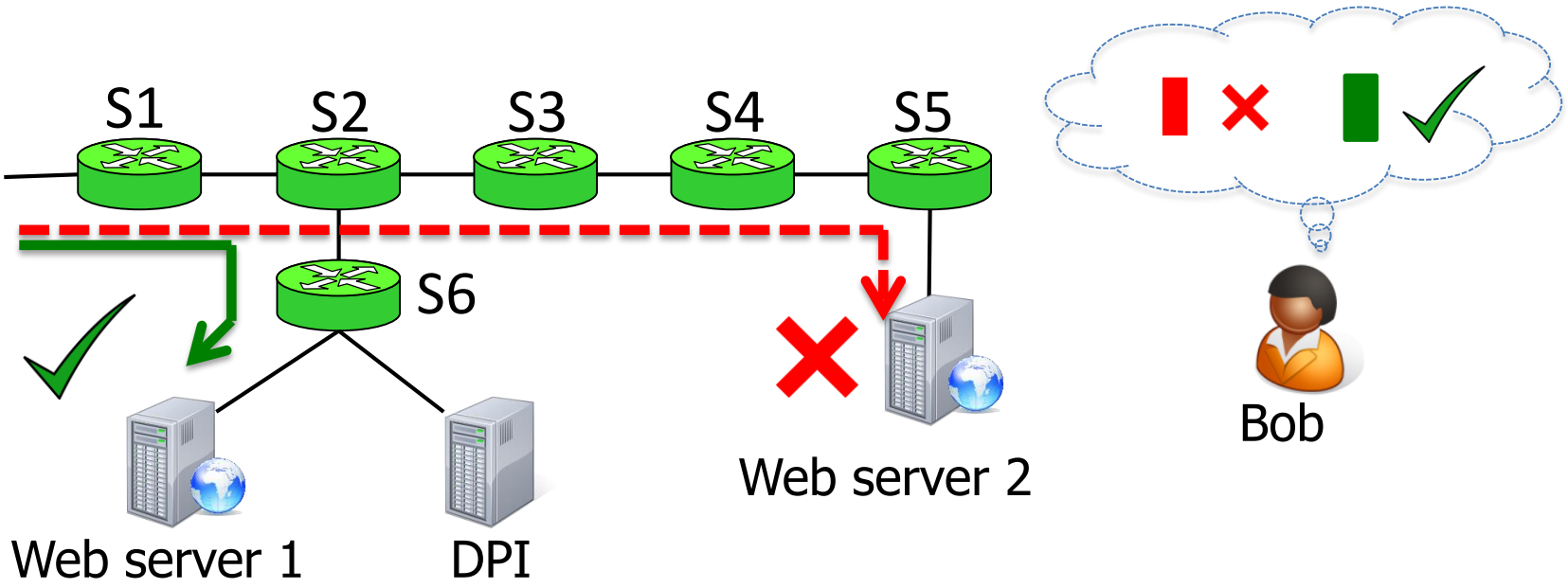



- Idea: Reason about the differences between the symptom and the reference

# Differential provenance

[SIGCOMM 2016]

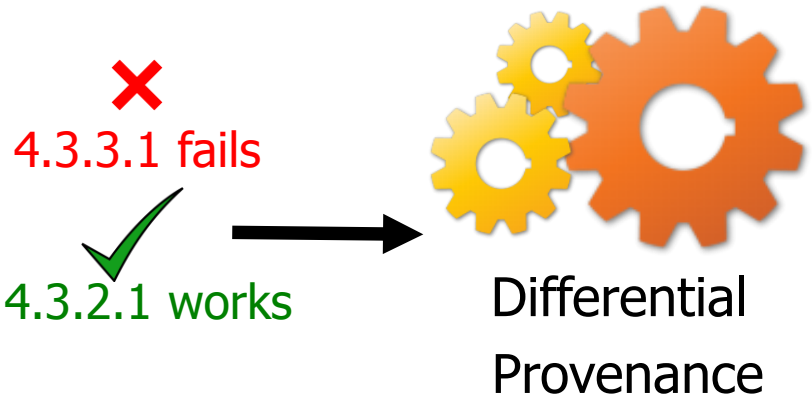
4.3.3.1 fails

4.3.2.1 works

- Input: a bad symptom and a good reference

# Differential provenance

[SIGCOMM 2016]

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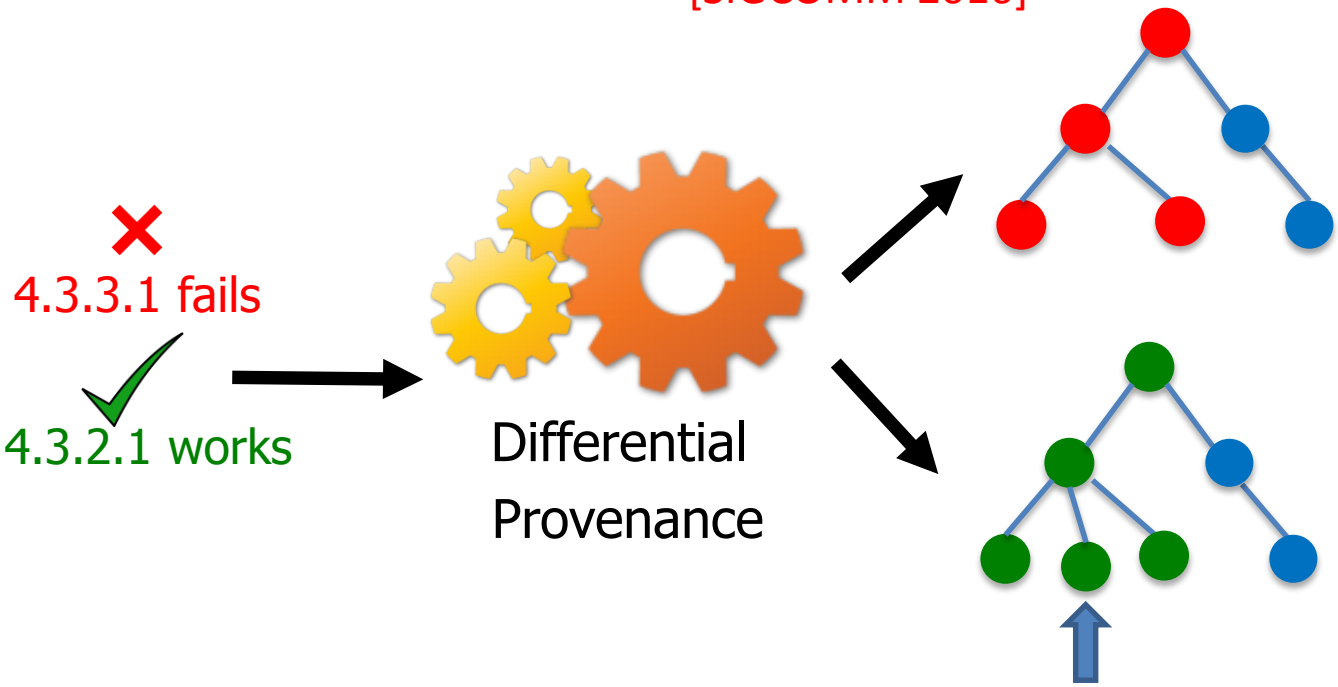
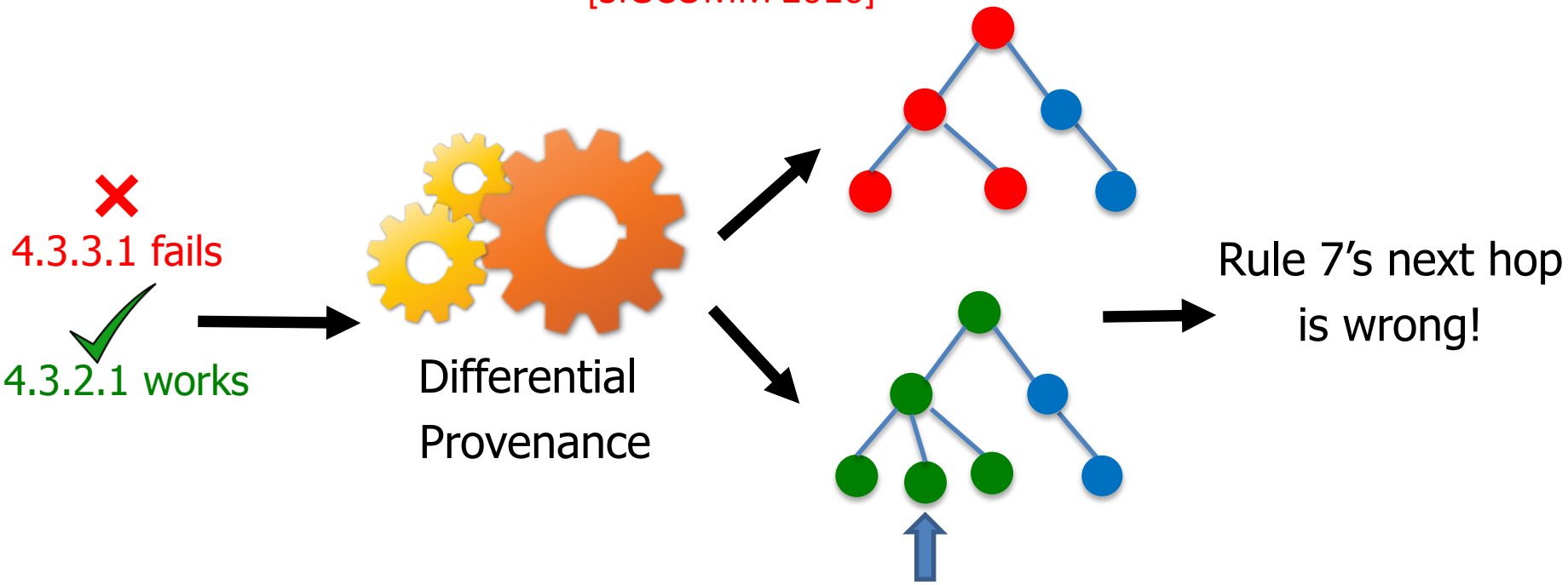
[SIGCOMM 2016]




- Input: a bad symptom and a good reference
- Debugger reasons about the differences

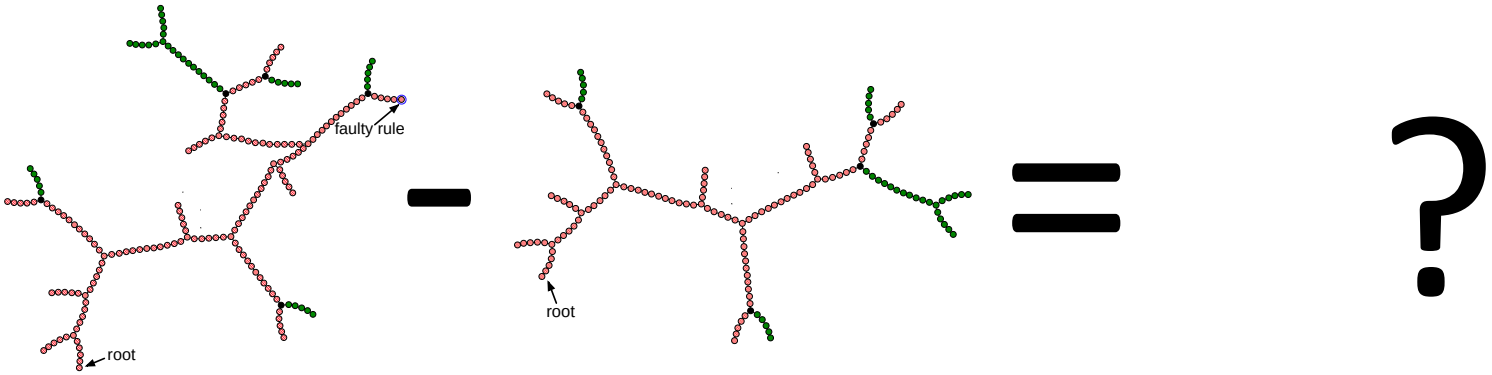
# Differential provenance

[SIGCOMM 2016]




- Input: a bad symptom and a good reference
- Debugger reasons about the differences
- Output: root cause

# Strawman solution




Provenance (Symptom) Provenance (Reference)

- Strawman solution: Find vertexes that are different in the two trees

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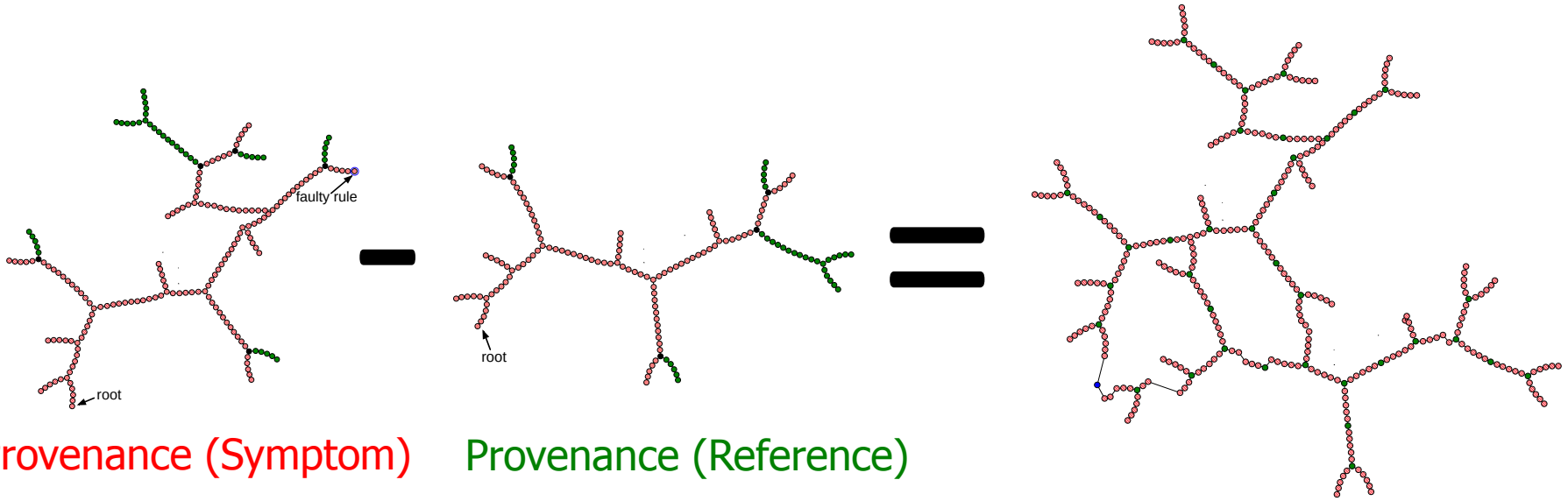
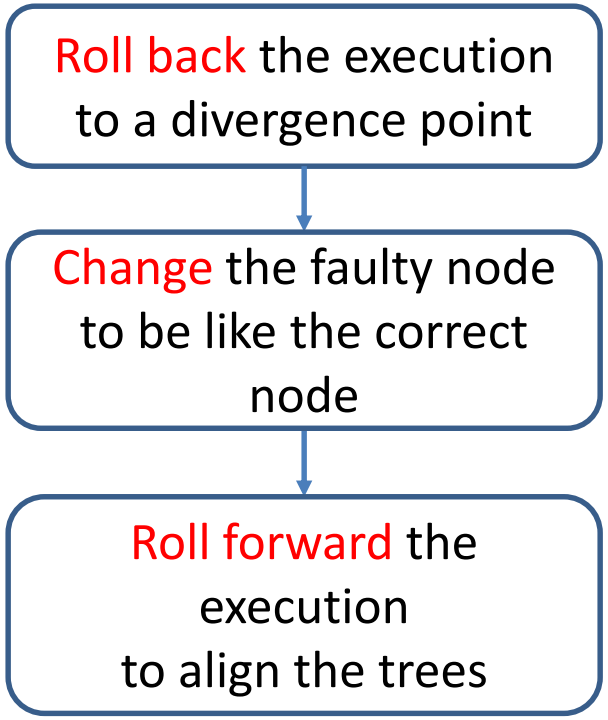



Provenance (Symptom) Provenance (Reference)

- Strawman solution: Find vertexes that are different in the two trees
- Problem: The diff can be larger than the individual trees!

# Overly Simplified Approach in a nutshell



# Assumption #4: Software is correct and static

- Networks are software and can have bugs

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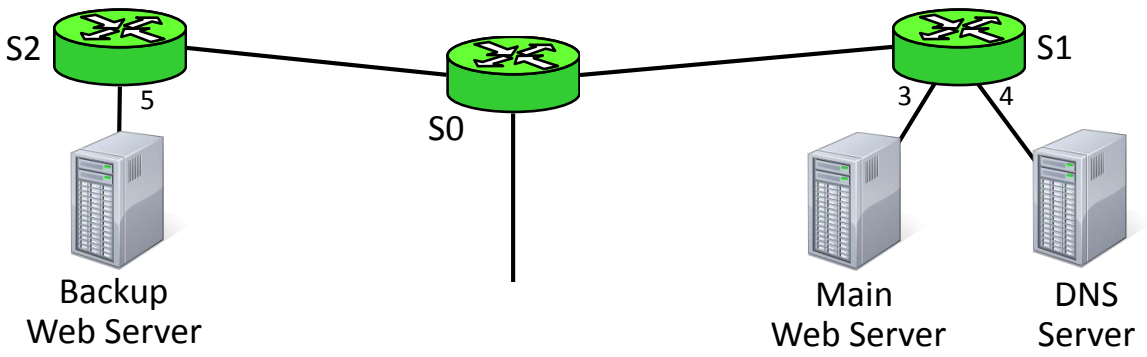

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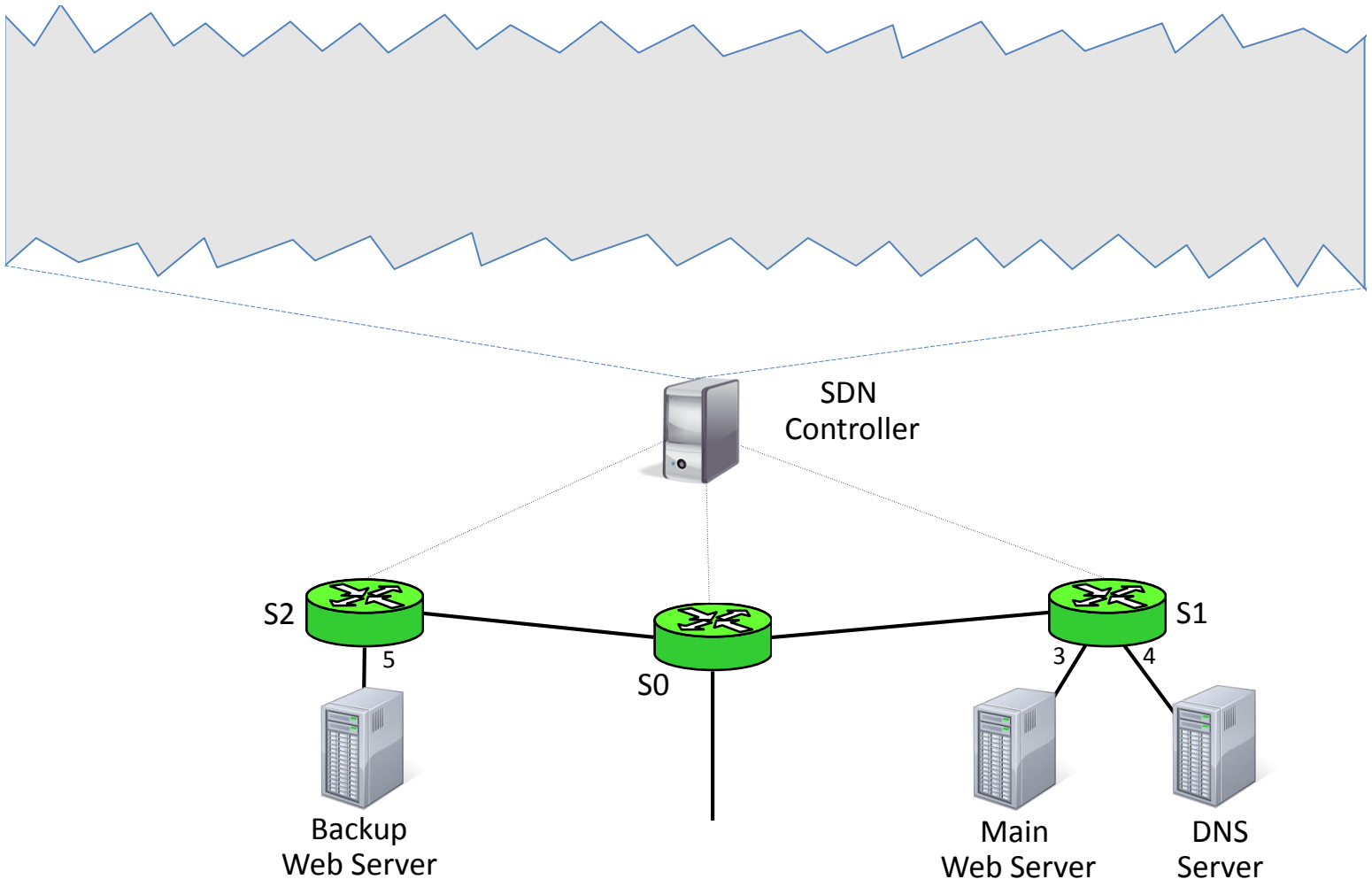

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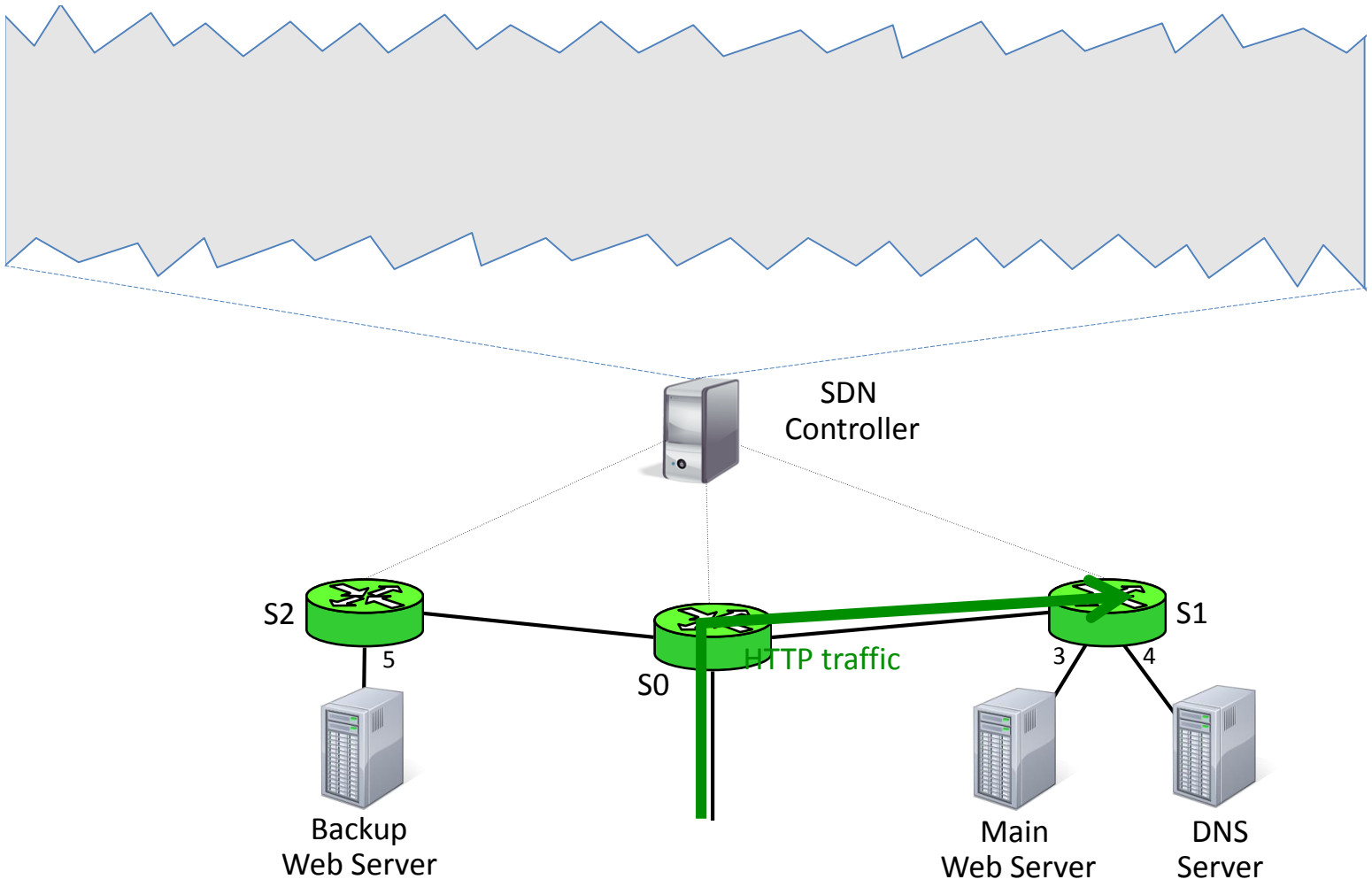

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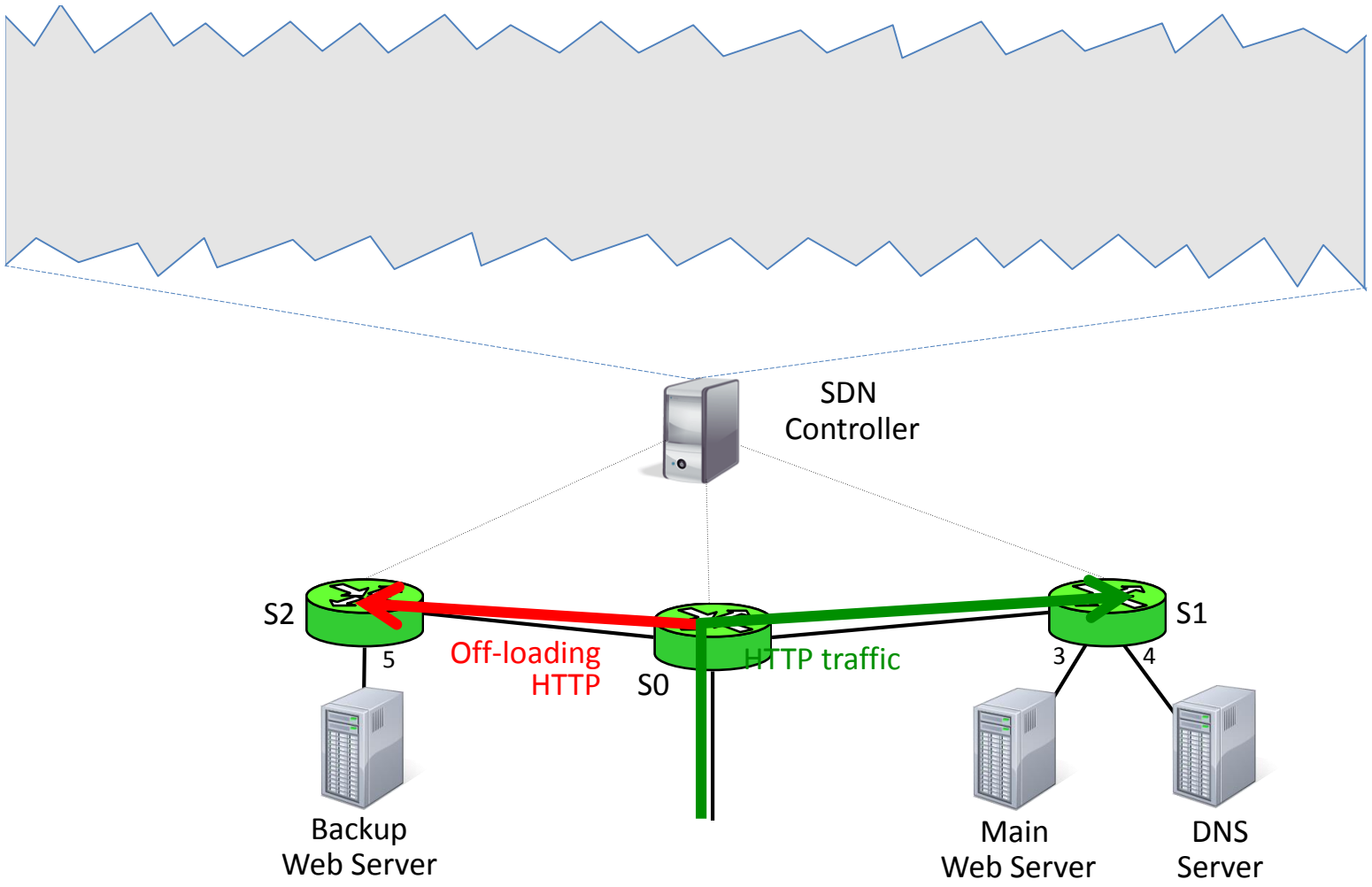

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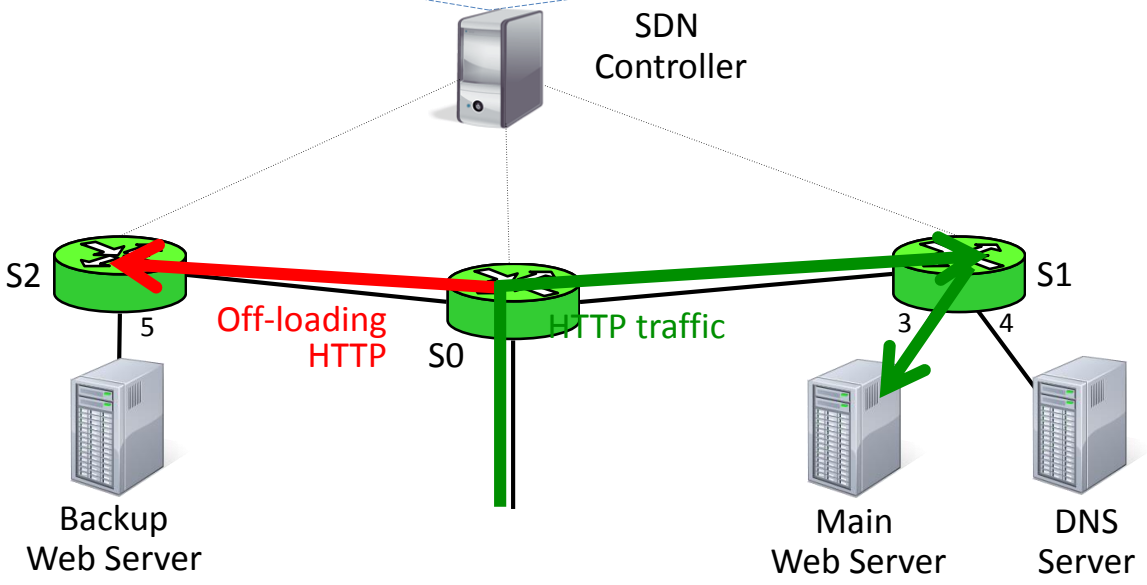

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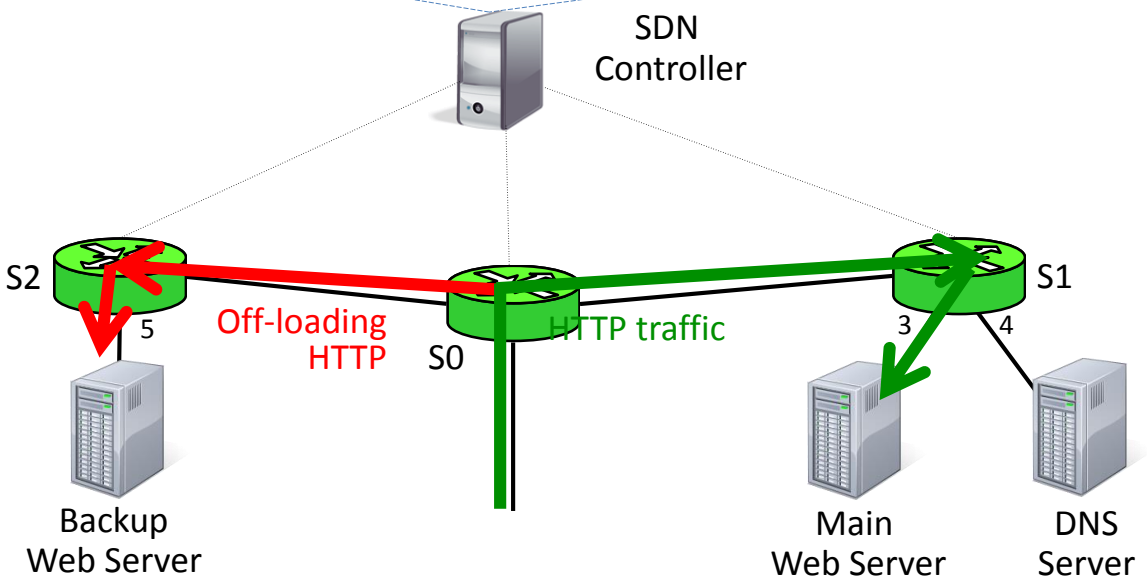

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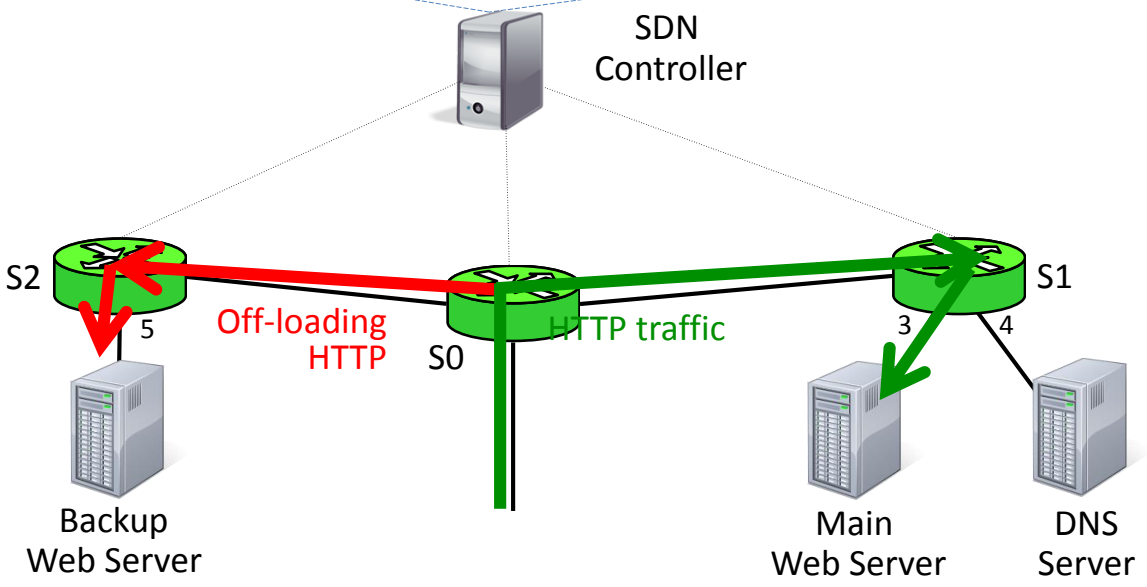

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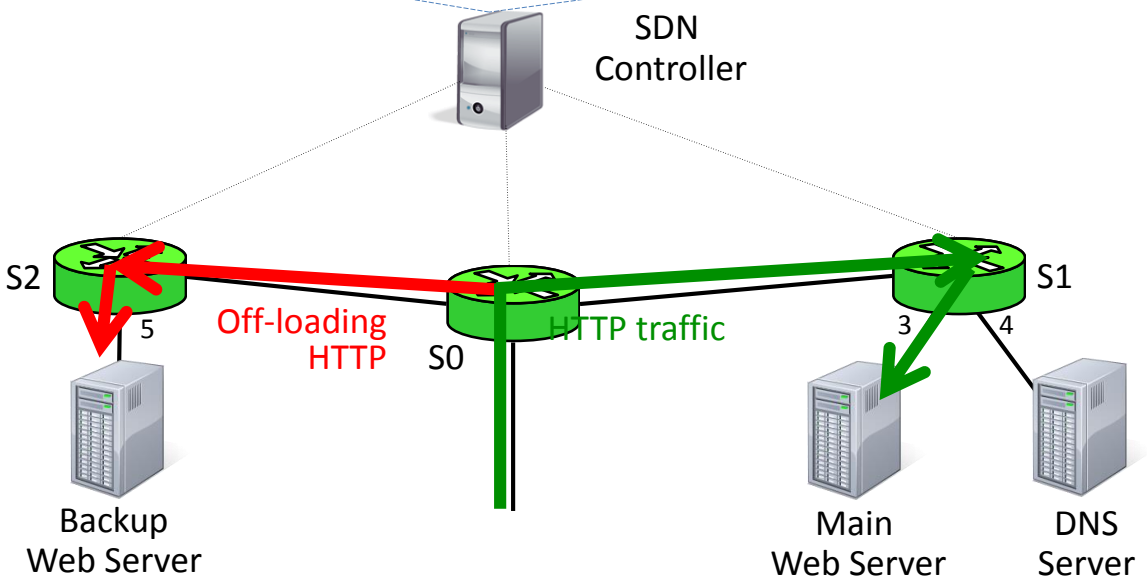

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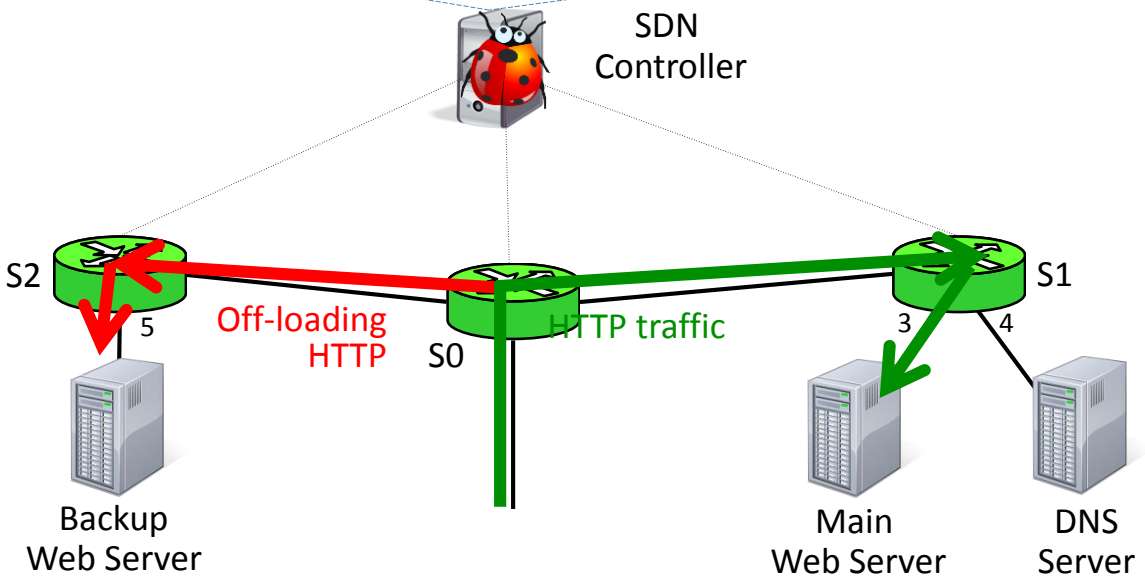

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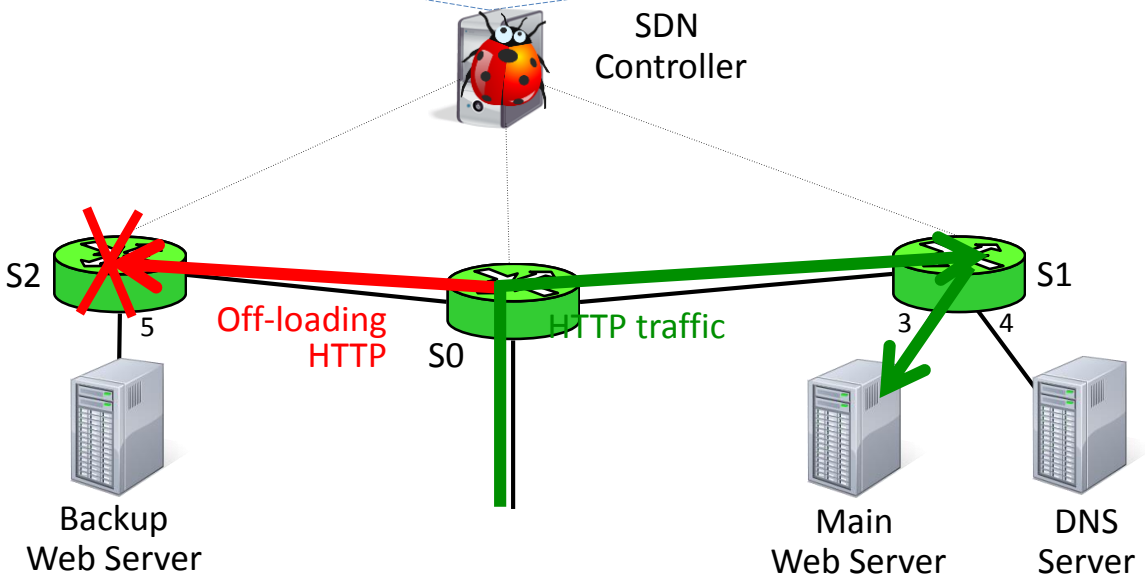

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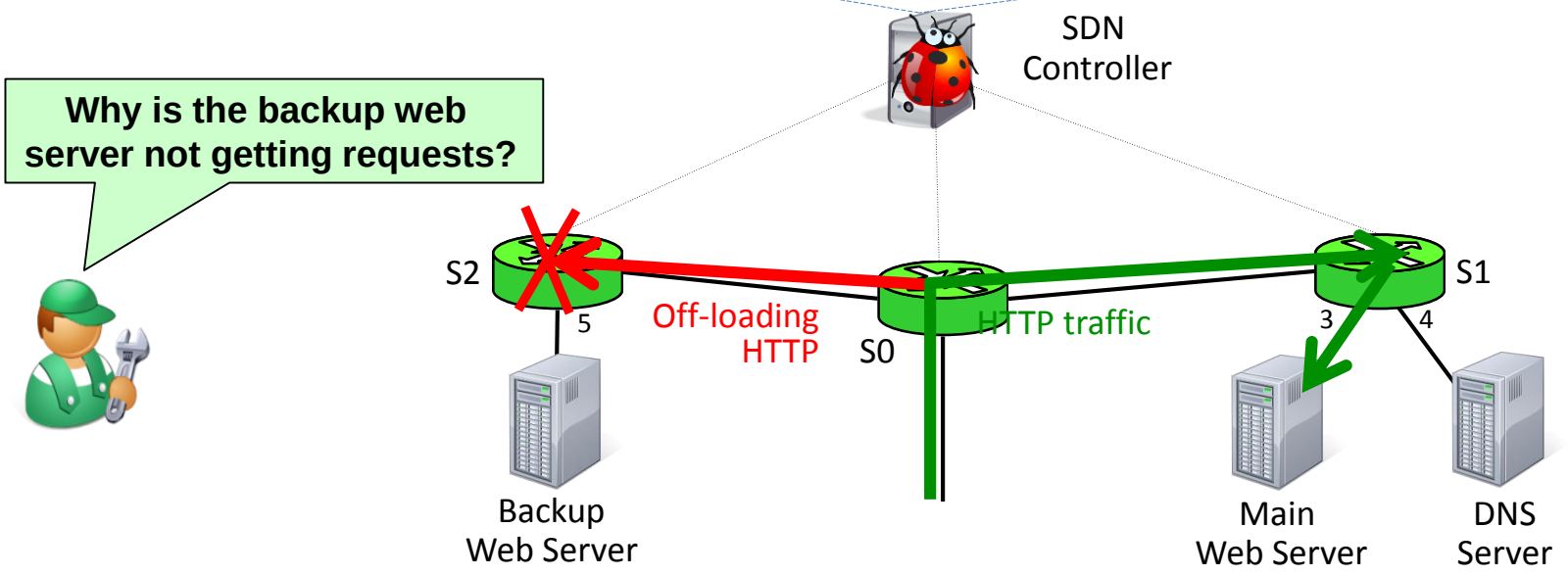

# Assumption #4: Software is correct and static

- Networks are software and can have bugs
- How can we find and fix bugs quickly?

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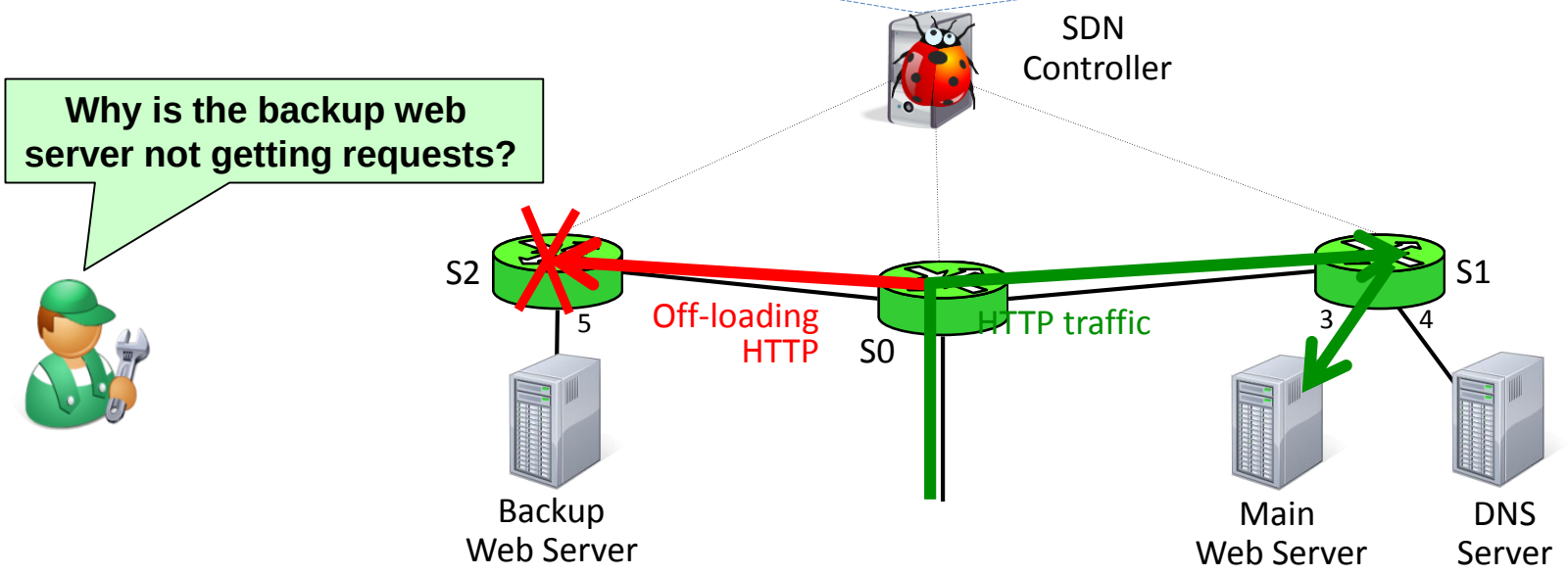
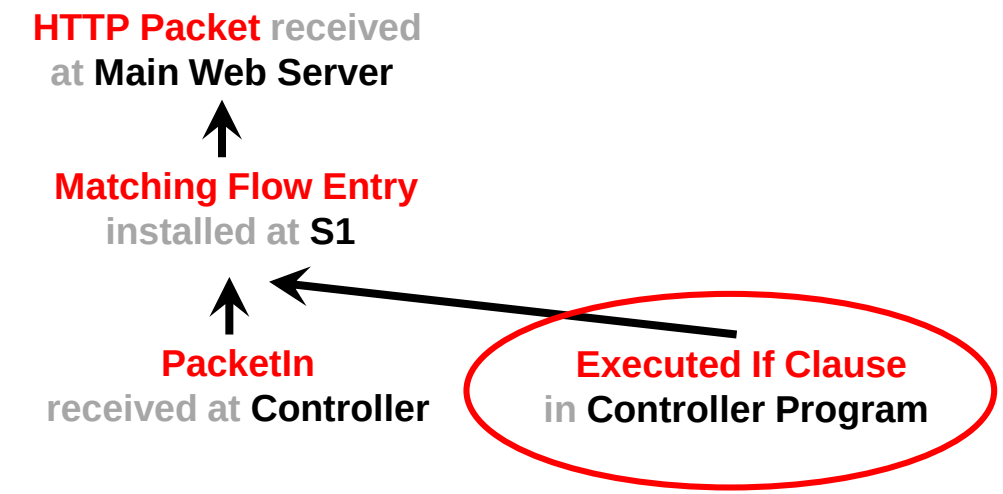


# Approach: Meta provenance

[NSDI 2017]

- Problem: Finding fixes is hard
- Idea: Provenance can pinpoint the root cause
- But previous provenance focus exclusively on data
- Key idea: Treating program as data

meta provenance



# Repairing Software-defined Networking Programs

Full support of Network Datalog (declarative)

Support a subset of Pyretic (Python + DSL)  frenetic ≫

Support a subset of Trema (imperative Ruby) 

Uses Z3 SMT solver to enumerate repairs

More details are in [HotNets'15, NSDI'17]

# Network Provenance Research (2010 – 2017)

- Network provenance model [SIGMOD'10]
- Secure network provenance [SOSP'11]
- Provenance in dynamic environments [VLDB'13]
- Negative provenance [SIGCOMM'14]
- Distributed provenance compression [SIGMOD'17]
- Differential provenance [SIGCOMM'16]
- Meta-provenance [NSDI'17]

Explanations

Deeper diagnostics and repair

Ph.D. dissertation work of Ang Chen (2017), Chen Chen (2017), Yang Wu (2017), and Wenchao Zhou (2012).

# The Road Ahead

- Network forensics meets data provenance is a rich area of exploration!
- Sampling of the problems we are working on:
  - Network forensics on the data plane
  - Privacy-preserving provenance on sensitive networks
  - Probabilistic provenance
  - Automated repairs of complex events
  - Timing-based provenance
  - and more….

# Thank You!

- Network provenance team at Penn/Georgetown:
  - Ang Chen, Chen Chen, Ling Ding, Qiong Fei, Andreas Haeberlen, Zachary Ives, Yang Li, Boon Thau Loo, Suyog Mapara, Arjun Narayan, Yiqing Ren, Micah Sherr, Shengzhi Sun, Tao Tao, Yang Wu, Mingchen Zhao, Wenchao Zhou