Towards a Data-centric Approach to Attribution in the Cloud

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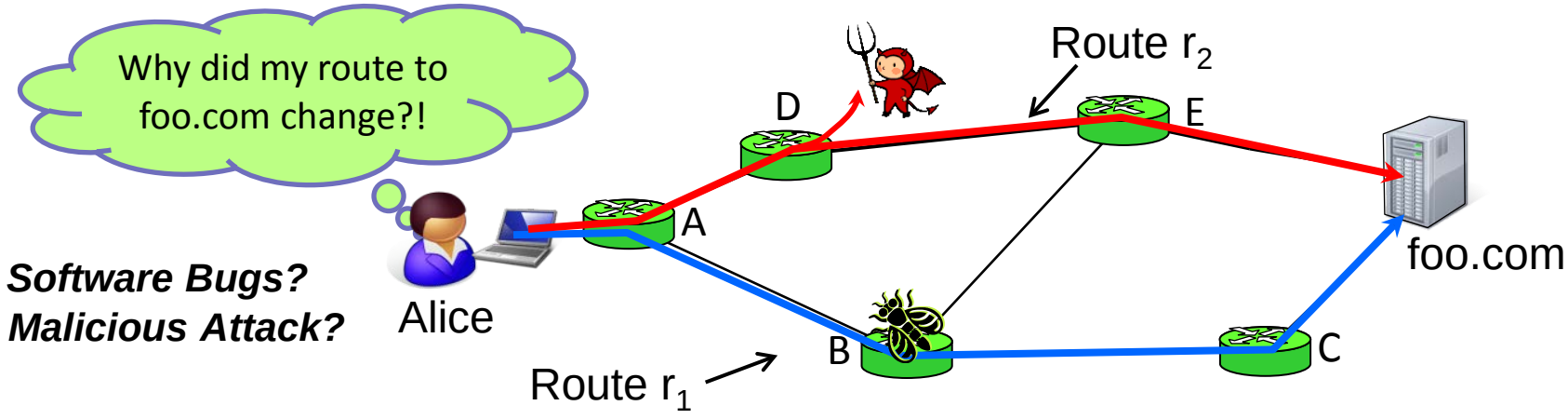
Introduction

- Success of Cloud
  - Economics of outsourcing data, computing and management
  - Virtualization of resources (storage, computing, networking)
  - Continued migration of applications to the cloud
    - Amazon EC2, Salesforce, Office 365, iCloud, etc
    - Middleware and firewalls in enterprise networks [SIGCOMM 12]
    - Interdomain routing [HotNets 12]
  - Increasing interaction between applications/clients

Motivation

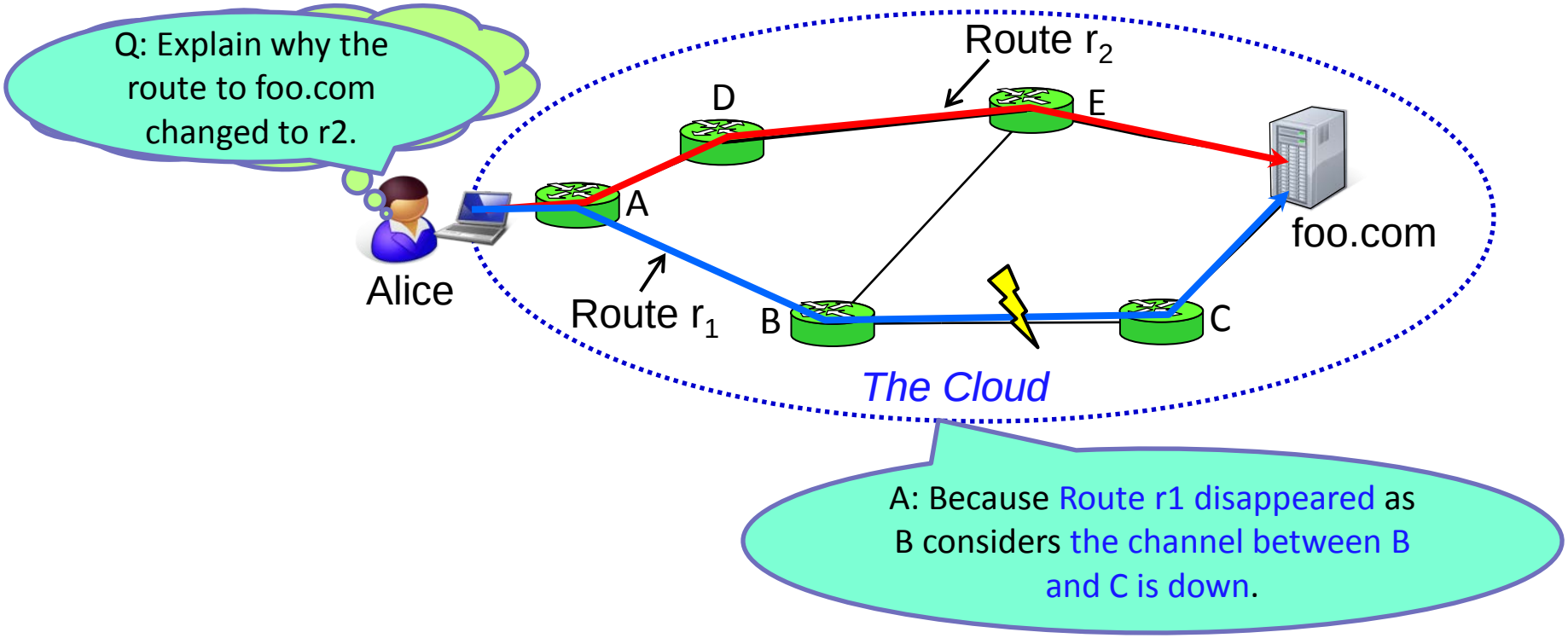
- Call for Attribution
  - Needed in tasks with collective efforts
  - Who is responsible for unexpected symptoms?
    - Attacks, bugs, client-side misbehavior
  - Evidences for accountability

A Simple Example



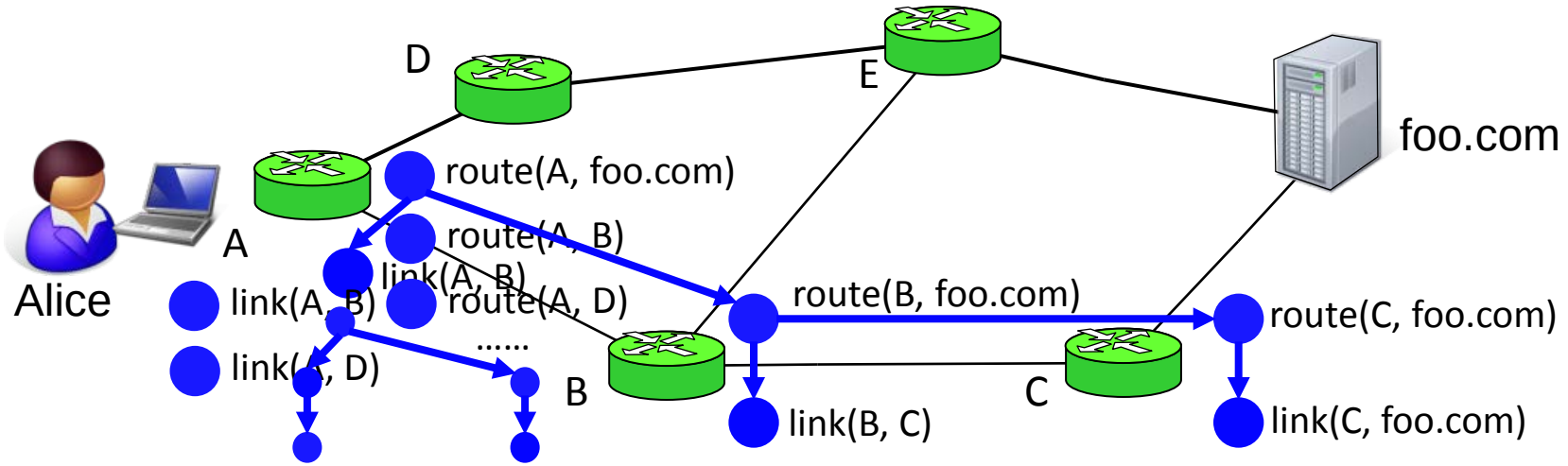
- **A simple task that requires collective effort: routing**
  - System administrator observes strange behavior
  - Example: the route to foo.com has suddenly changed

An Ideal Solution



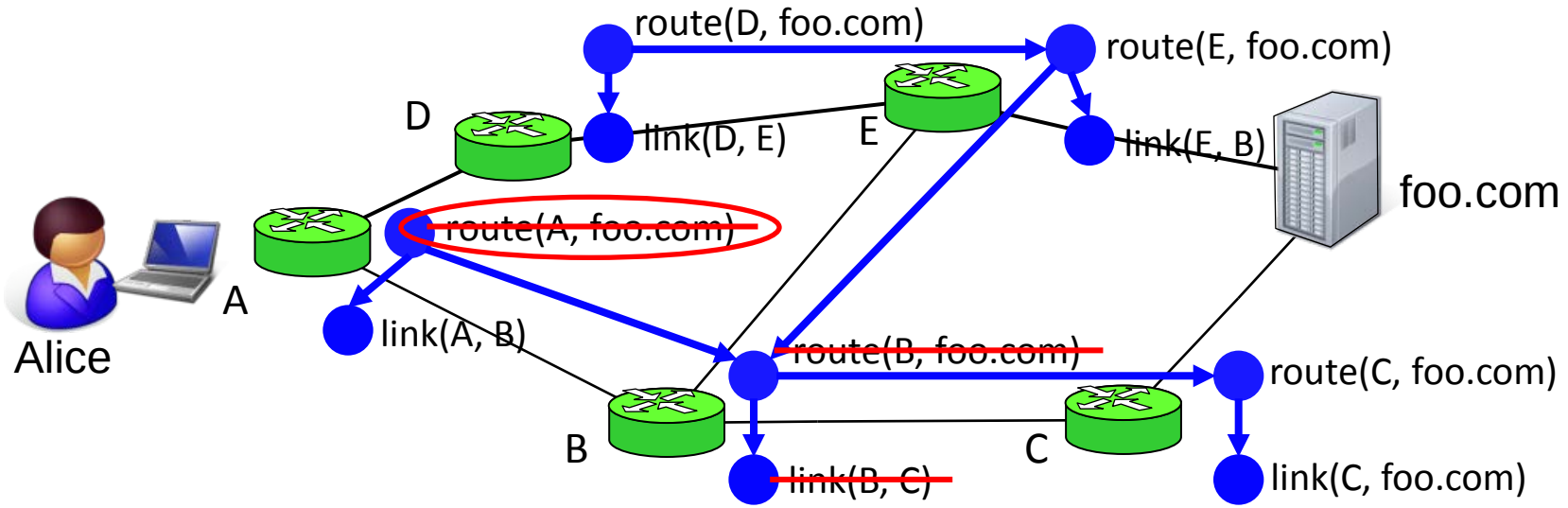
- **What does attribution look like?**

A Data-centric Perspective



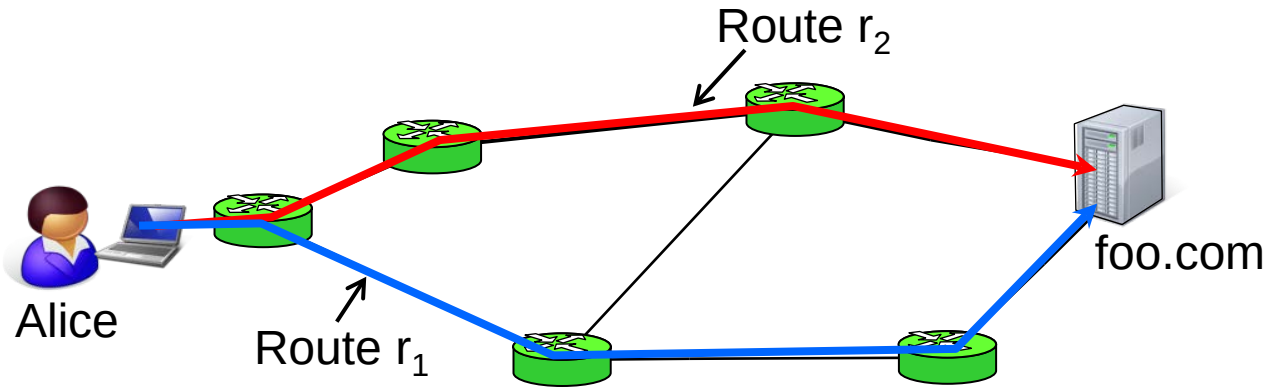
- **We assume a general distributed system**
  - A network consisting of nodes (e.g., VMs)
  - The state of a node is a set of tuples (routes, config, ...)
  - **Idea**: Attribution as reasoning of state dependencies
    - Base tuples: boundary of the reasoning, considered as *facts*

Provenance for Attribution



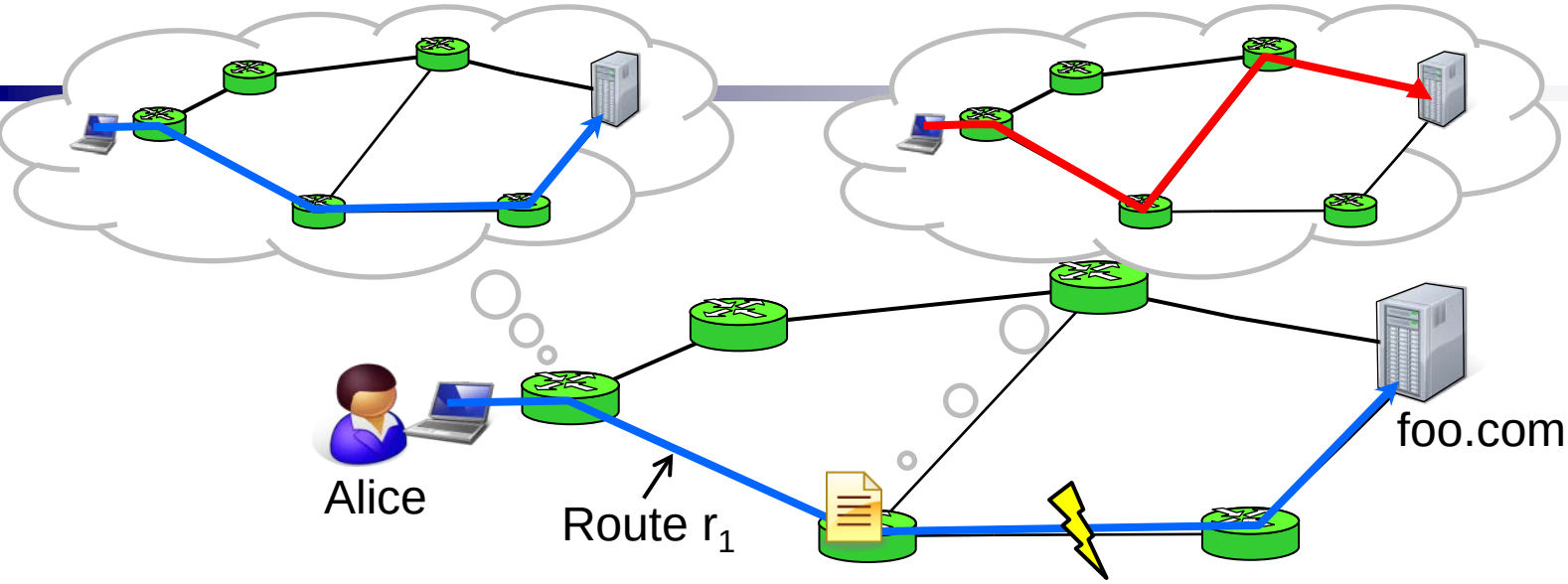
- **Provenance for encoding state dependencies**
  - Explains the derivation of tuples
  - Captures the dependencies between tuples as a graph
  - Attribution of a tuple is a tree rooted at the tuple
    - Route r1 disappeared as B removes the link between B and C

Challenges



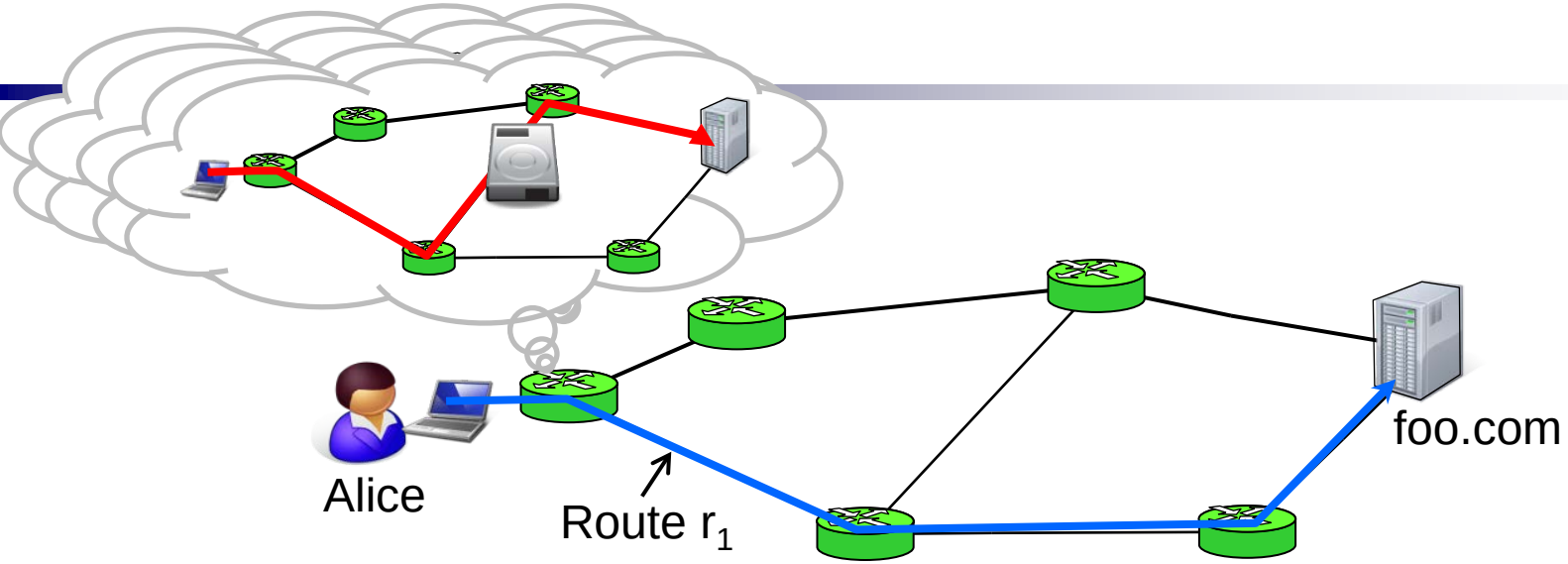
- **Historical information about distributed state**

Challenges



- **Historical information about distributed state**
- **Correct and complete provenance in transient state**

Challenges



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- **Distributed maintenance – performance tradeoffs**

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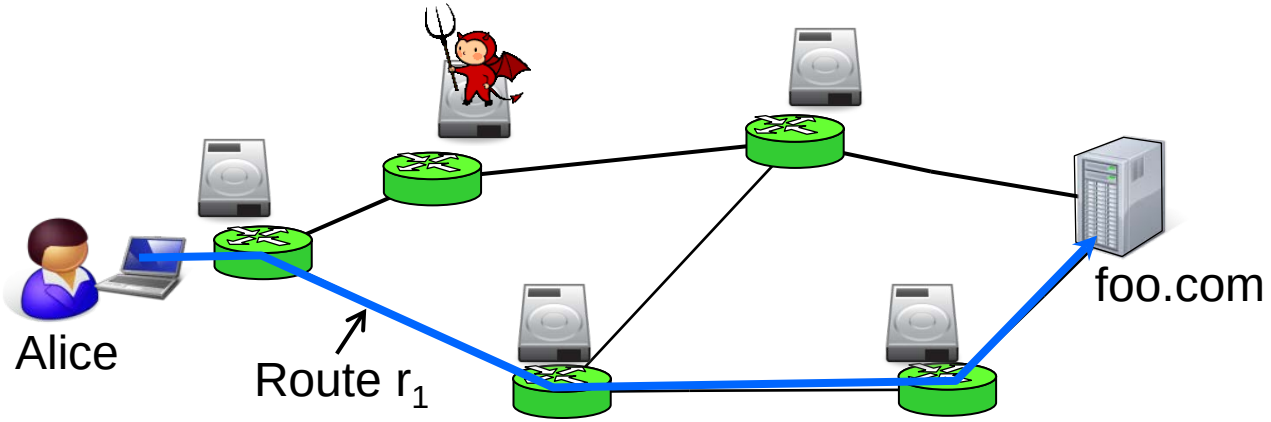
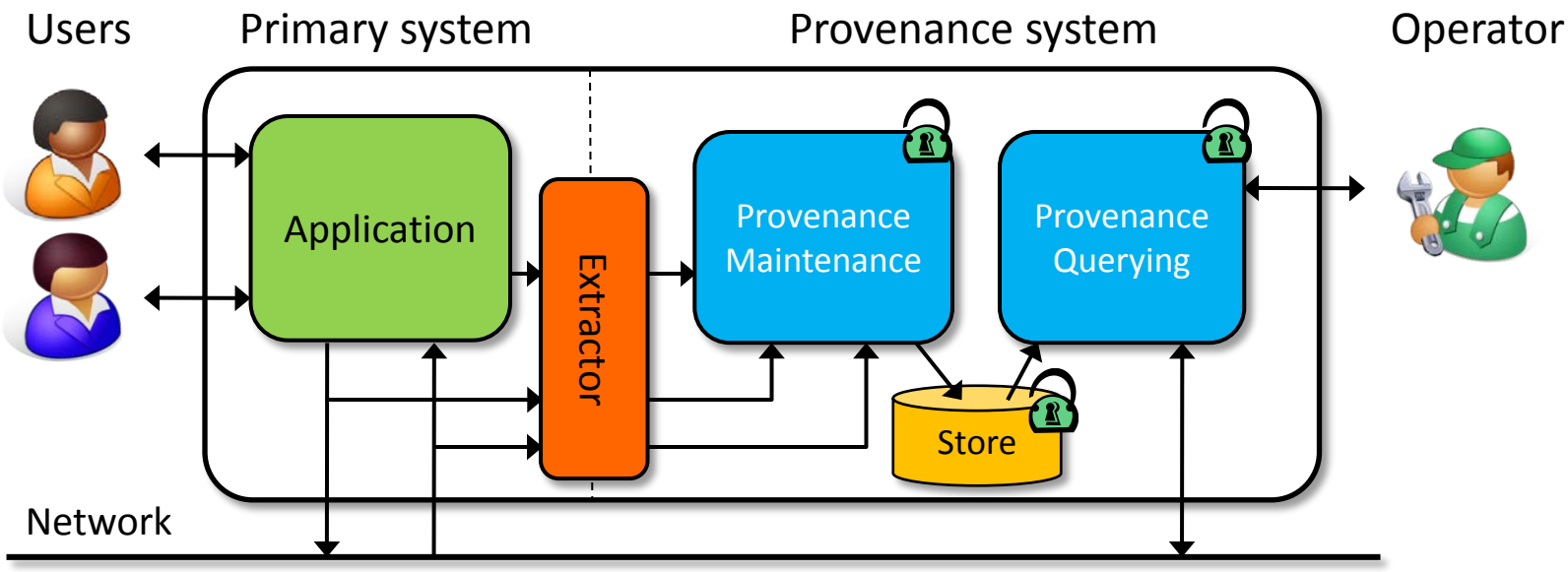


- **Historical information about distributed state**
- **Correct and complete provenance in transient state**
- **Distributed maintenance – performance tradeoffs**
- **Security guarantee in an untrusted environment**

Related Work

- **Provenance for distributed settings**
  - Cloud systems: PA-S3fs [MMS 10], RAMP [IPW 11]
  - Collaborative data sharing systems: Orchestra [GIK+ 07]
- **Provenance for historical system state**
  - PASS [MHB+ 06]
  - workflow systems (Kepler [ABJ 06], VisTrails [CFS+ 06], etc)
- **Provenance security**
  - Sprov [HSW 09], Pedigree [RBT+ 08]

Challenges

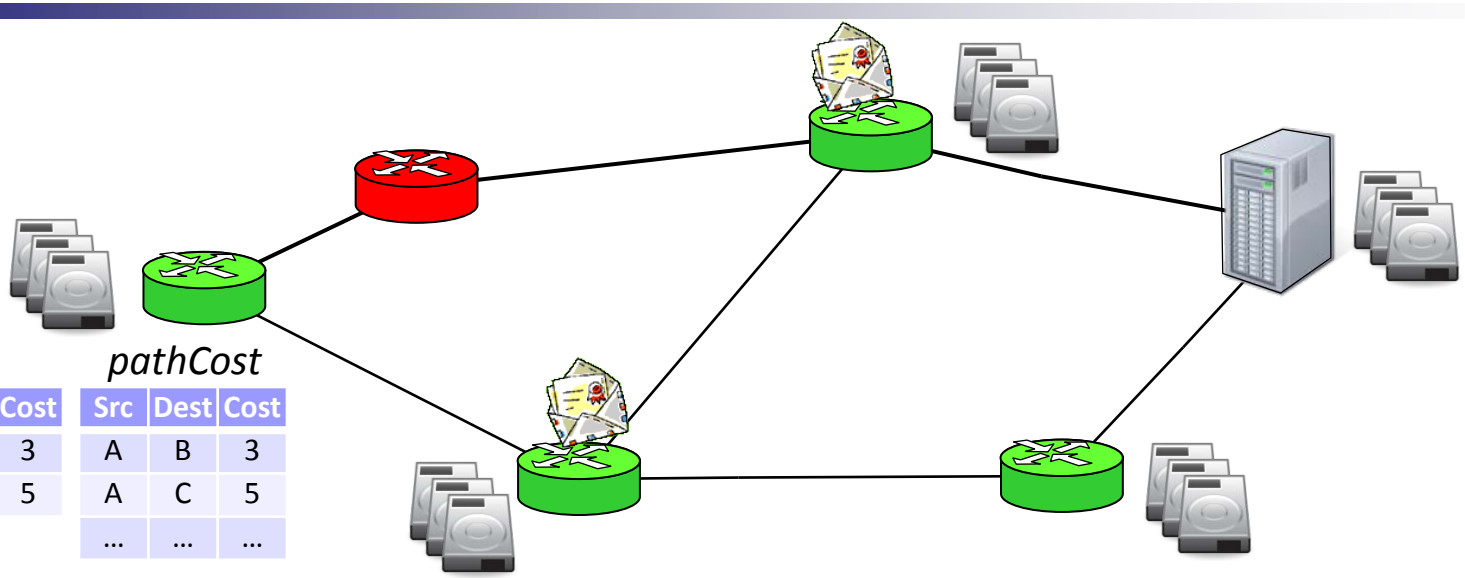


- **Provenance model (distribution + time)**
- **Storage and maintenance at large scale**
- **Distributed provenance querying**
- **Security guarantees in adversarial environment**

Outline

- **Introduction**
  - Motivation: Explain general system anomalies
  - Approach: Secure Time-aware Provenance
- ***Provenance Model [SIGMOD 10, VLDB 13]***
- **Provenance Maintenance and Querying**
- **Securing Network Provenance**
- **Conclusion**

State Transition Systems – State



link

Src	Dest	Cost
A	B	3
A	C	5

pathCost

Src	Dest	Cost
A	B	3
A	C	5
…	…	…

- Node's state captured as tuples
- Message captured as a triplet (src, dest, +/-tuple)
- System state S = (H,M), where H is a set of per-node state, and M is the channel state

Transition Logic as Derivation Rules

- **State transition in general distributed systems**
  - E.g. state machine or event-driven model
  - **Idea**: New state as derivation result of old states

- **Derivation rules: abstract dependency logic**
  - Example: $\tau @ n :- \tau_1 @ n_1 \wedge \tau_2 @ n_2 \wedge ..... \wedge \tau_m @ n_m$

    Rule head — *Rule body*
  - Rule head is derived, if all the predicates in rule body hold
  - Written as *Network Datalog (NDlog)* rules [LCG+ 06]

Extracting Dependency Logic

- **Option 1: Inferred provenance** **Declarative Chord DHT**
  - Declarative specifications explicitly capture provenance
  - E.g. Declarative networking, SQL queries, etc.
- **Option 2: Disclosed provenance** **Hadoop MapReduce**
  - Modified source code reports provenance
- **Option 3: Observed provenance** **Quagga Software Router**
  - Defined on observed I/Os of a black-box system

Example: Pairwise Minimal Cost

```
sp1: pathCost(@S,D,C) :- link(@S,D,C).
sp2: pathCost(@Z,D,C1+C2) :- link(@S,Z,C1),
                             minCost(@S,D,C2).
sp3: minCost(@S,D,MIN<C>) :- pathCost(@S,D,C).
```

link(@Src,Dst,C) – "a direct link from node *Src* to *Dst* with cost *C*"

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pathCost(@Src,Dst,C) – "a path from node *Src* to *Dst* with cost *C*"

Example: Pairwise Minimal Cost

sp1: pathCost(@S,D,C) :- link(@S,D,C). ← *One-hop paths*

sp2: pathCost(@Z,D,C1+C2) :- link(@S,Z,C1), minCost(@S,D,C2). ← *Multi-hop paths*

sp3: minCost(@S,D,MIN<C>) :- pathCost(@S,D,C). ← *Aggregation for min cost*

link(@Src,Dst,C) – "a direct link from node *Src* to *Dst* with cost *C*"

pathCost(@Src,Dst,C) – "a path from node *Src* to *Dst* with cost *C*"

minCost(@Src,Dst,C) – "best path from node *Src* to *Dst* with minimal cost *C*"

Execution Model

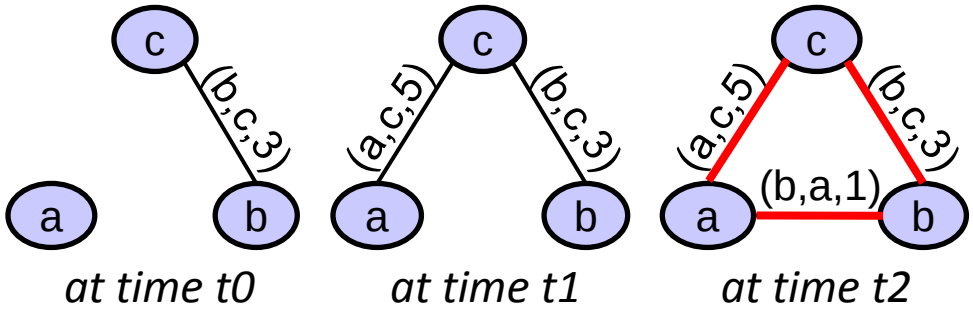
- **Pipeline Semi-naïve evaluation** [LCG+ 06]

  sp2a: ΔpathCost(@Z,D,C1+C2) :- Δlink(@S,Z,C1), minCost(@S,D,C2).

  sp2b: ΔpathCost(@Z,D,C1+C2) :- link(@S,Z,C1), ΔminCost(@S,D,C2).

  - Rewrite into event-condition-action rules
  - Consume updates, and generate new updates

Execution Traces



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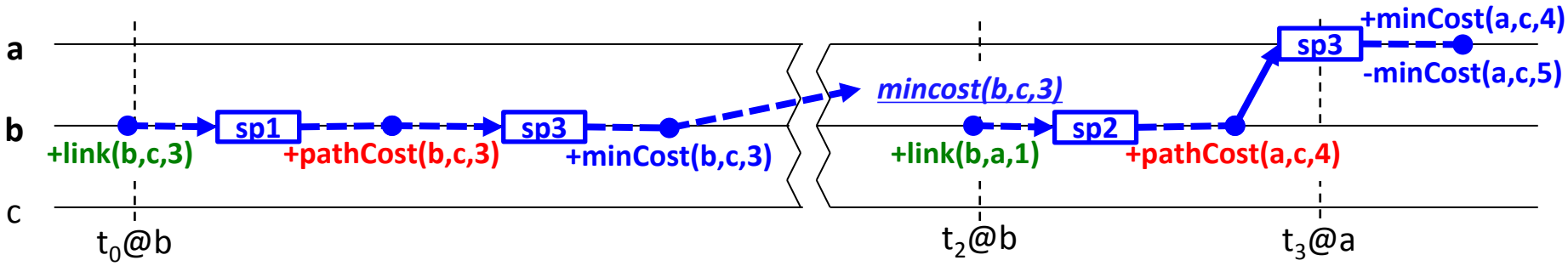
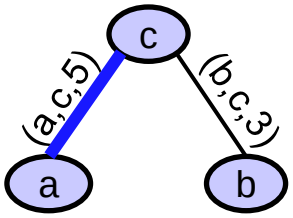
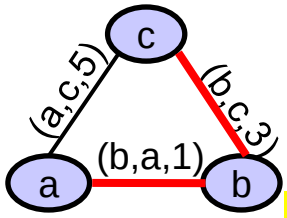


- **Execution trace as an ordered sequences of events**
  - Encode the execution of a state transition system

Provenance Model



at time t1



at time t2

pathCost(@a,c,4)

- INSERT/DELETE: Tuple τ was inserted (deleted) on node n at time t
- DERIVE/UNDERIVE: Tuple τ was derived ved) via rule R on node n at time t
- SEND/RECV: Update +/- τ was sent (received) by node n at time t

Constraints

DELETE(t3, a, minCost(@a,c,5))

INSERT(t3, a, minCost(@a,c,4))

DERIVE(t3, a, minCost(@a,c,4), sp3@a)

INSERT(t3, a, pathCost(@a,c,4))

Communication

RECV(t3, a, pathCost(@a,c,4), b, t2)

SEND(t2, b, pathCost(@a,c,4), a)

Rule triggering

DERIVE(t2, b, pathCost(@a,c,4), sp2@b)

EXIST(t2, b, minCost(@b,c,3))

INSERT(t2, b, link(@b,a,1))

INSERT(t0, b, minCost(@b,c,3))

……

Snapshot

Correctness

- **Provenance should be "consistent" with the trace**
  - Both are artifact from a system execution
  - **Idea: Extract a subtrace from provenance graph**
    - Extracting subtrace using topological sort
    - Edges in provenance graph represents dependencies
  - **Question: how do we define "consistency"**

Provenance Properties

- **Provenance is valid**
  - The extracted subtrace should be a viable trace
- **Provenance is sound**
  - The extracted subtrace has same event orders as actual trace
  - Problem: order of concurrent events (no synchronized clocks)
  - **Idea:** per-node perspective (indistinguishable executions)
- **Provenance is complete**
  - Provenance includes complete explanation of state (changes)
  - **Idea:** state (changes) are reproducible based on provenance
- **Provenance is minimal**
  - Provenance is exactly the explanation and nothing more

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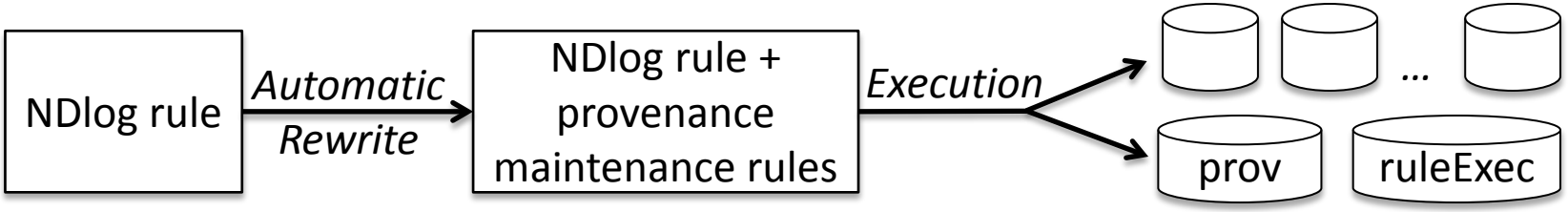
- ***Maintenance and Querying [VLDB 13]***
- **Securing Provenance**
- **Conclusion**

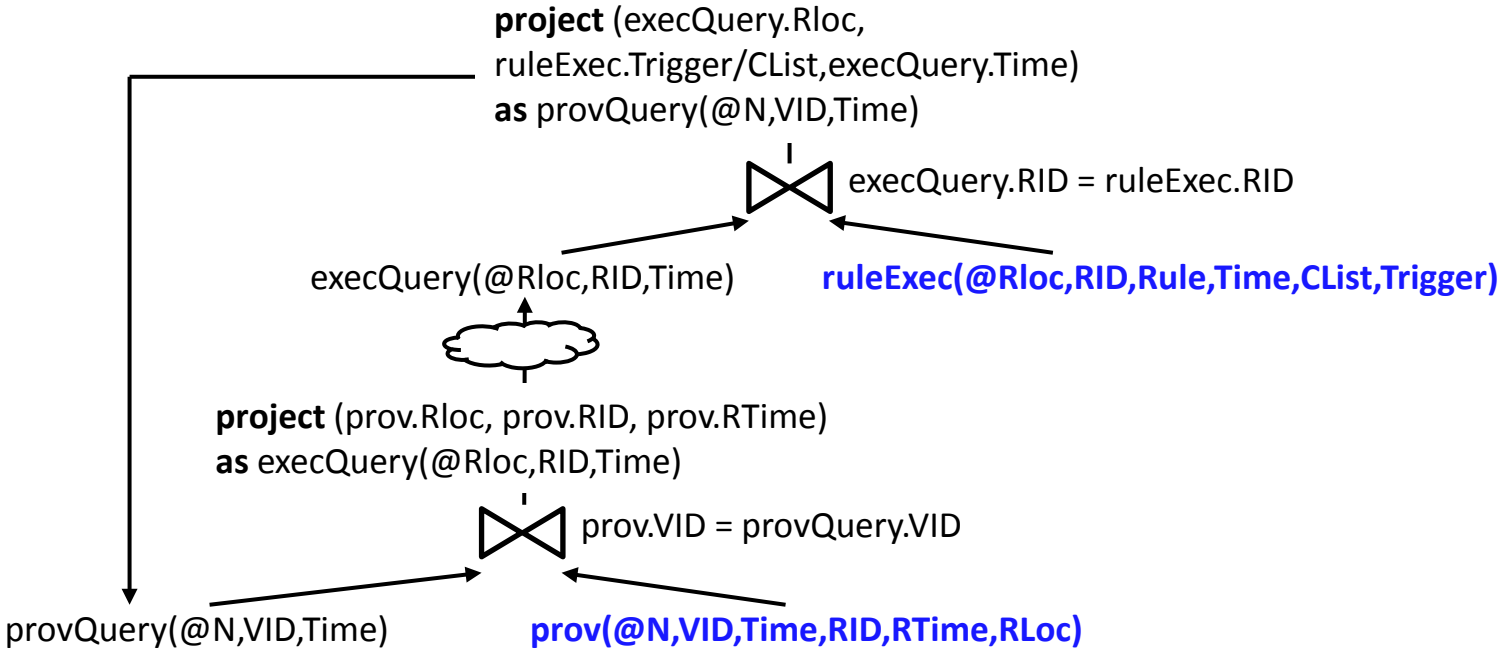
Provenance Maintenance [SIGMOD 10]

- **Provenance as views of network state** [GIK+ 07]
  - Maintain in relational tables (prov, ruleExec, send, recv)
  - Incremental view maintenance
  - Pipelined Semi-Naïve (PSN) [LCG+ 06] evaluation
- **Automatic rewrite of derivation rules**
  - Additionally maintain provenance data
  - Does NOT affect the scalability of the base protocol



Recursive Provenance Querying

- **Traversal of the provenance graph**
  - Step 1: Retrieve rule execution instances
  - Step 2: Expand dependent derivations



Recursive Provenance Querying

- **Traversal of the provenance graph**
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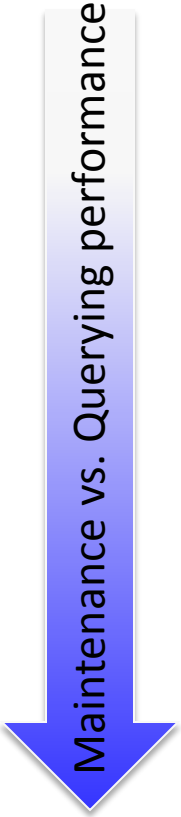
- **Generic framework for provenance querying**
  - Formulated in declarative networking engine
  - Allows customization (annotation defined in provenance semiring [GKT 07]) and optimization (caching, etc)

Performance Tradeoffs

- **Proactive maintenance**
  - Provenance deltas – deltas between adjacent versions
  - Incrementally applied in querying
- **Reactive maintenance**
  - **Idea**: sufficient data for reconstructing provenance
  - Input logs – communications and update of base tuples
  - Reconstruct provenance by deterministic replay
  - Long-running systems? Periodic snapshots
- **Analogous to log-structured versioning systems**



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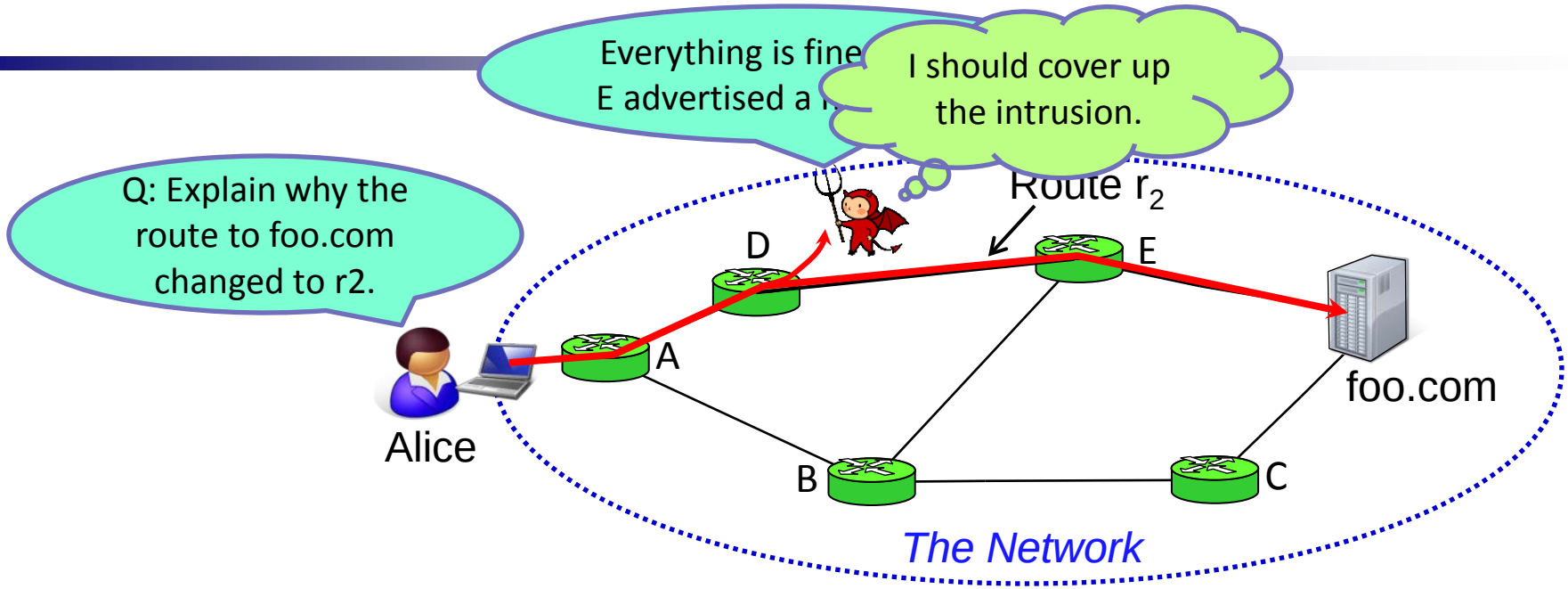
- **Provenance Maintenance and Querying**
- ***Securing Network Provenance [SOSP 11]***
- **Conclusions**

Challenge: Adversaries Can Lie



- **Problem: adversary can …**
  - … fabricate plausible (yet incorrect) response
  - … point accusation towards innocent nodes

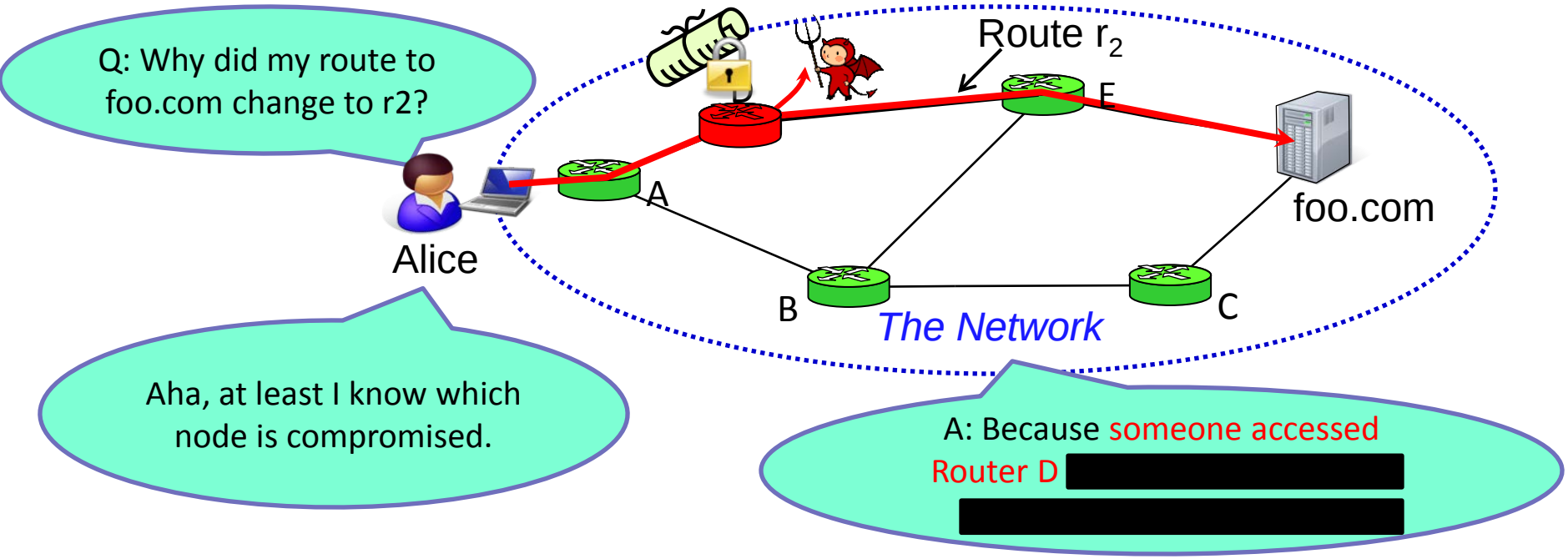
Threat Model

- **Existing work**
  - Trusted kernel, monitor, or hardware
    - E.g. Backtracker [OSDI 06], ReVirt [OSDI 02], A2M [SOSP 07]
  - These components may have bugs or be compromised
  - *Alternatives that do have require such trust?*
- **No trusted components**
  - Adversary has full control over an arbitrary subset of the network (Byzantine faults).
    - E.g. Compromised nodes can tamper, drop, or replay information
  - Pessimistic threat model gives strong guarantees

Ideal Guarantees

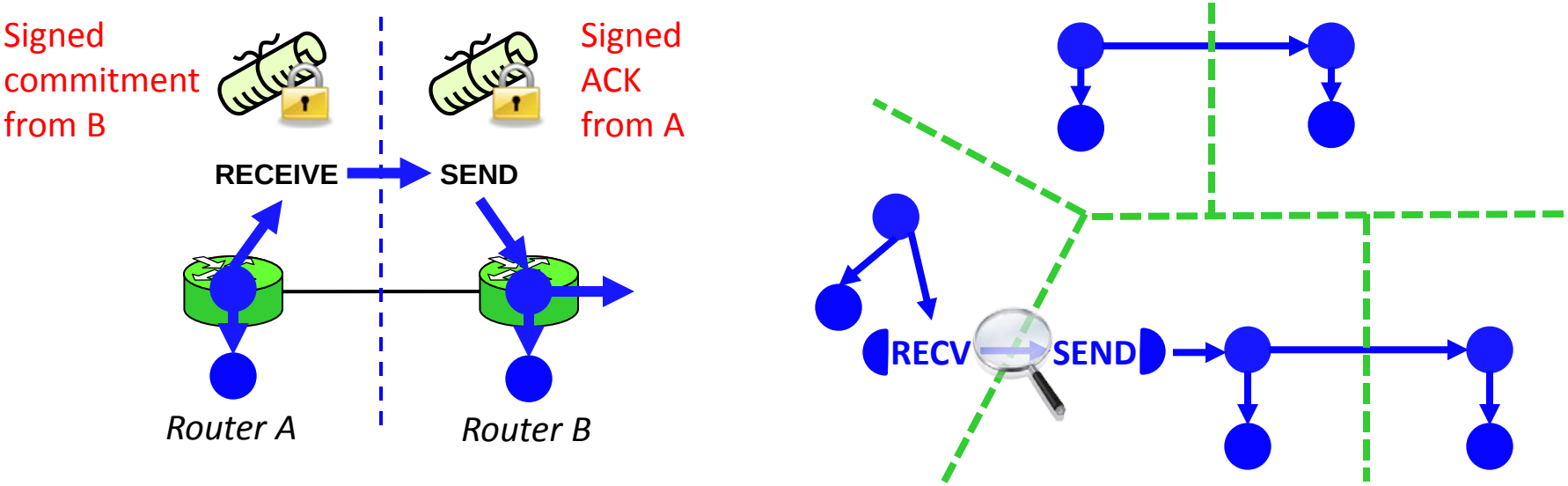
- **Ideally: explanation is always complete and accurate**
- **Fundamental limitations**
  - E.g. Faulty nodes secretly exchange messages
  - E.g. Faulty nodes communicate outside the system
- ***What guarantees can we provide?***

Realistic Guarantees [SOSP 11]



- **No faults: Explanation is complete and accurate**
- **Byzantine fault: Explanation identifies at least one faulty node**

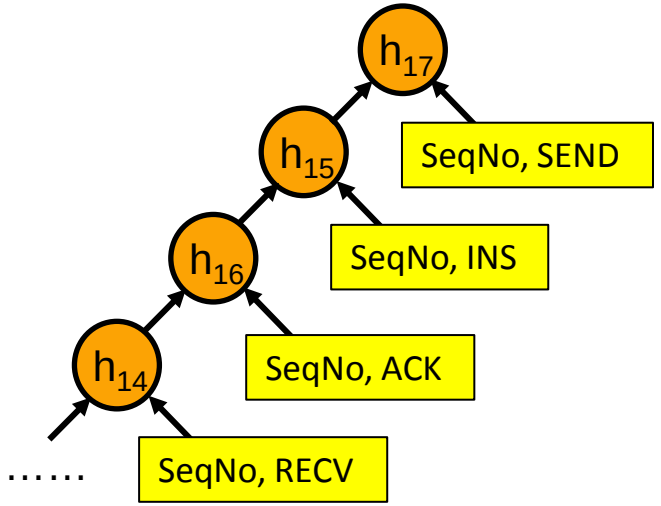
Securing Cross-Node Edges

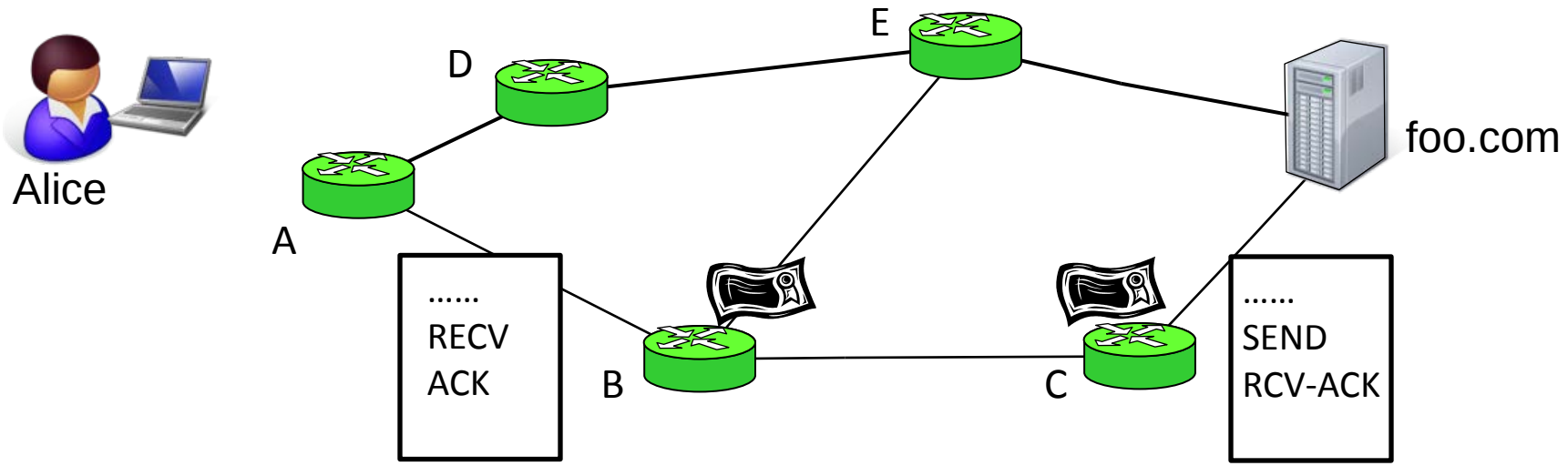


- **Idea 1: Each node keeps vertices about local actions**
  - TAP model cleanly partition the provenance graph
- **Idea 2: Make the graph tamper-evident**
  - Secure cross-node edges (evidence of omissions)

Secure Provenance Maintenance

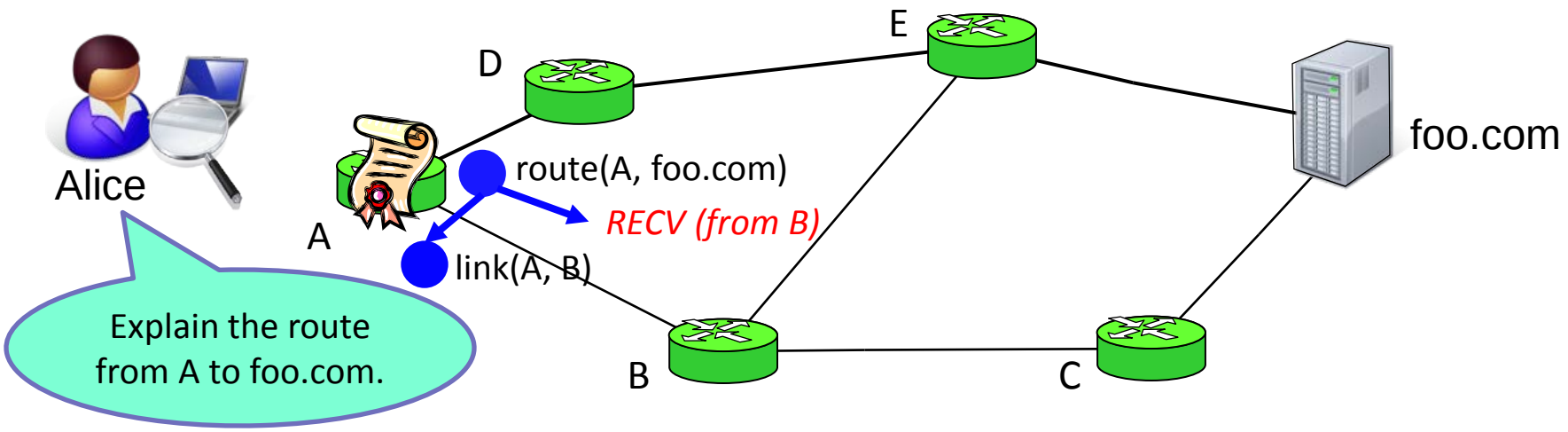
- **Tamper-evident logs** [HKD 07]
  - Linear append-only list of events
  - Recursively-defined hash chain
  - Include top-level hash in messages
  - Any tampering breaks the chain!





Secure Provenance Querying

- **Recursively construct the provenance graph**
  - Retrieve secure logs from remote nodes
  - Check for tampering, omission, and equivocation
  - Replay the log to regenerate the provenance graph



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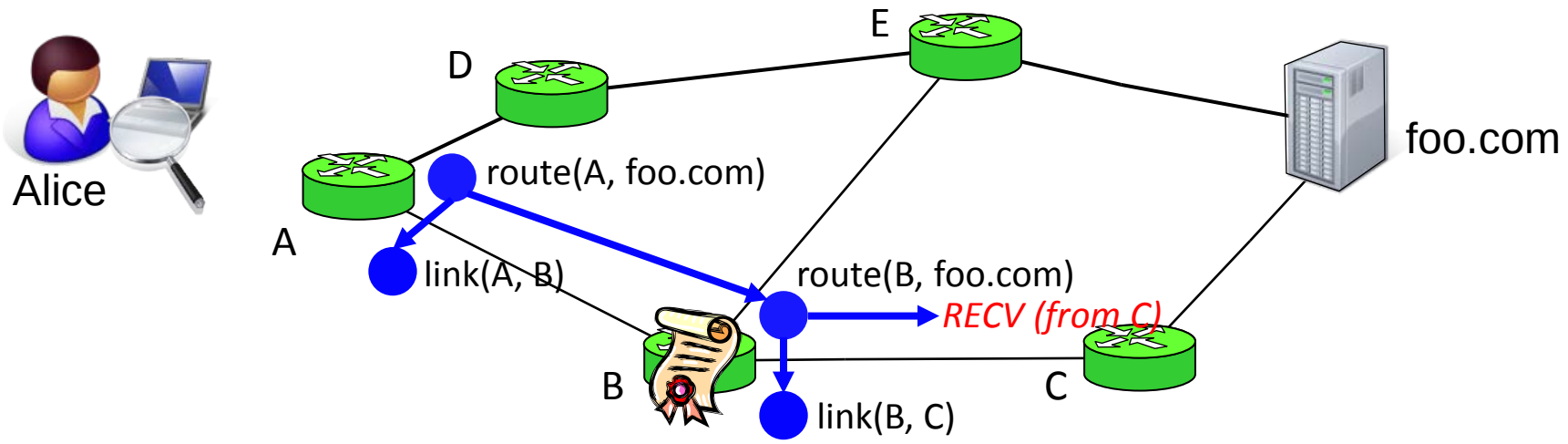

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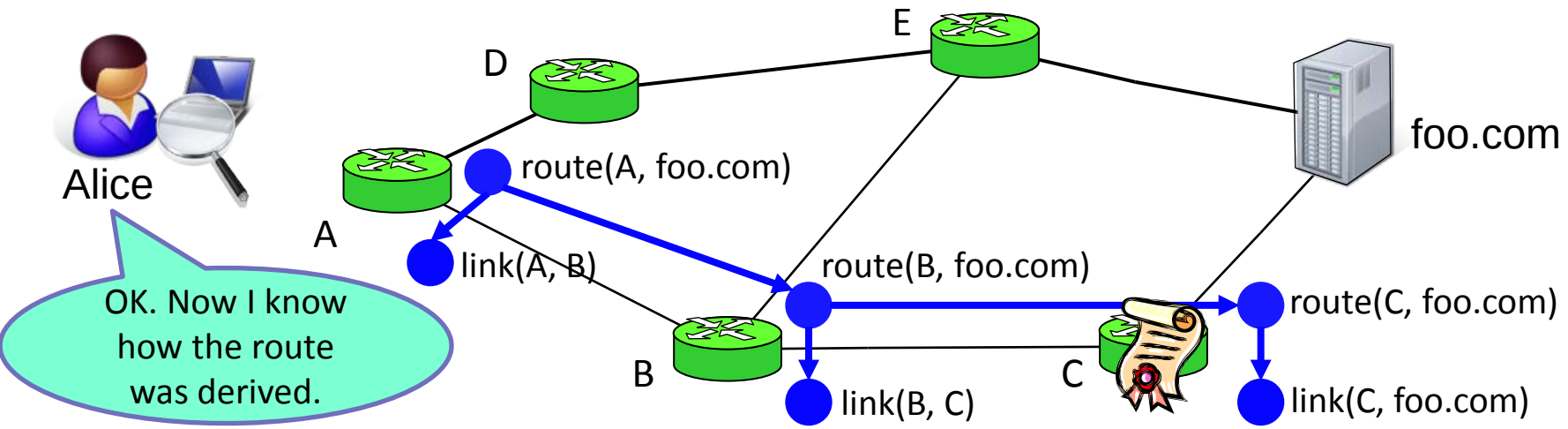
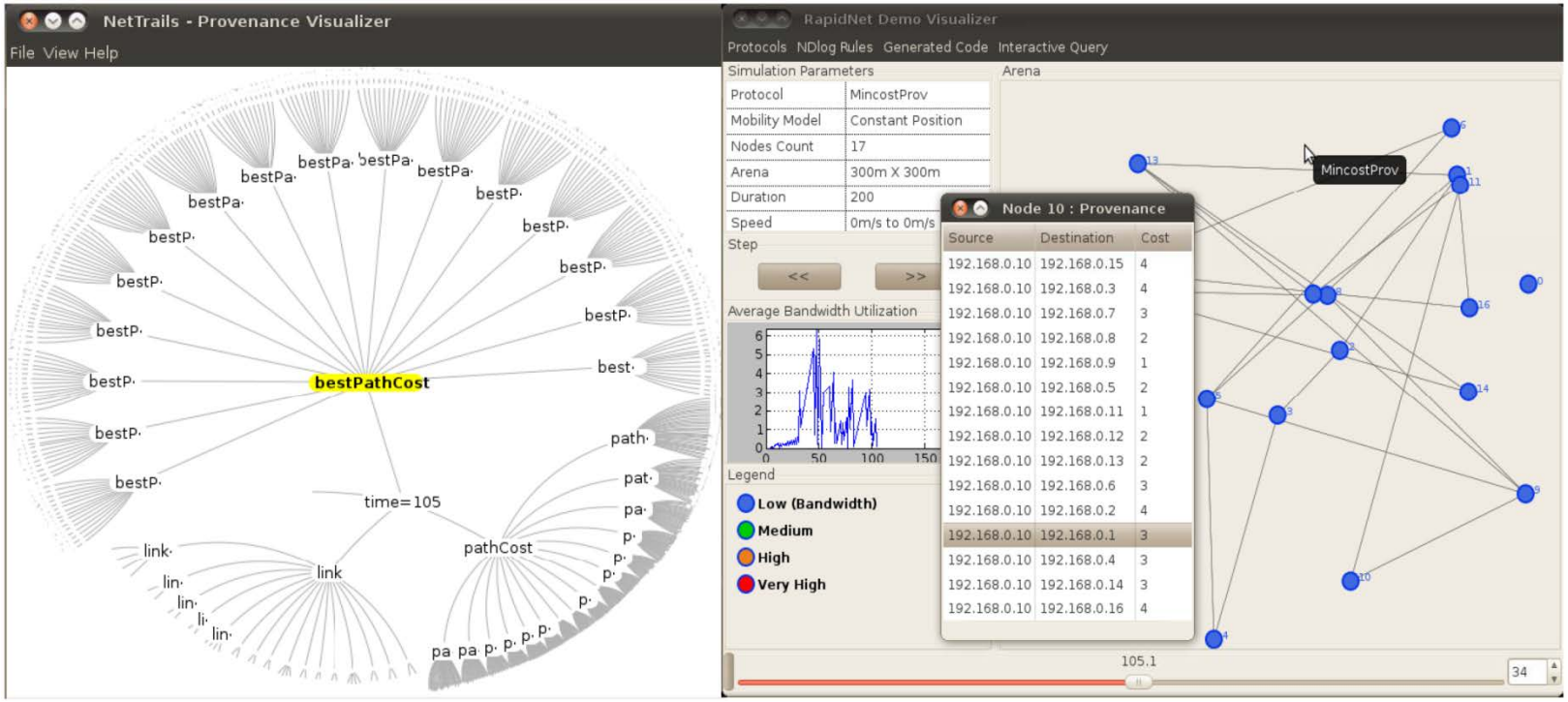


NetTrails [SIGMOD-demo 11]

- **Based on the RapidNet declarative networking engine** *http://netdb.cis.upenn.edu/rapidnet/*
- **System available for download.**



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Ongoing and Future Directions

- **Privacy concerns of provenance**
  - Tension between attribution and privacy
  - Results in Interdomain routing [HotNets 11, SIGCOMM 12]
- **Better use of provenance data**
  - Provenance-based recovery and damage assessment
  - Feedback for invariant refinement. Deduce invariants (desired properties) by mining reported provenance.
- **Answer why-not questions**

Project website: http://snp.cis.upenn.edu/