Securing SDNs with App Provenance

UIUC/R2 Monthly Group Meeting

Presented by Ben Ujcich

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Motivation

SYSTEMS ATTACKS AND DEFENSES

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Security Challenges and Opportunities of Software-Defined Networking

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ogy benefit the attackers. Attacks against SDN controllers and the introduction of malicious controller apps are probably the most severe threats to SDN.[3,7]

nies such as Nokia, Cisco, Dell, HP, Juniper, IBM, and VMware have developed their own SDN strategies. Major switch vendors as well as many promising start-ups offer SDN-enabled switches.

Background

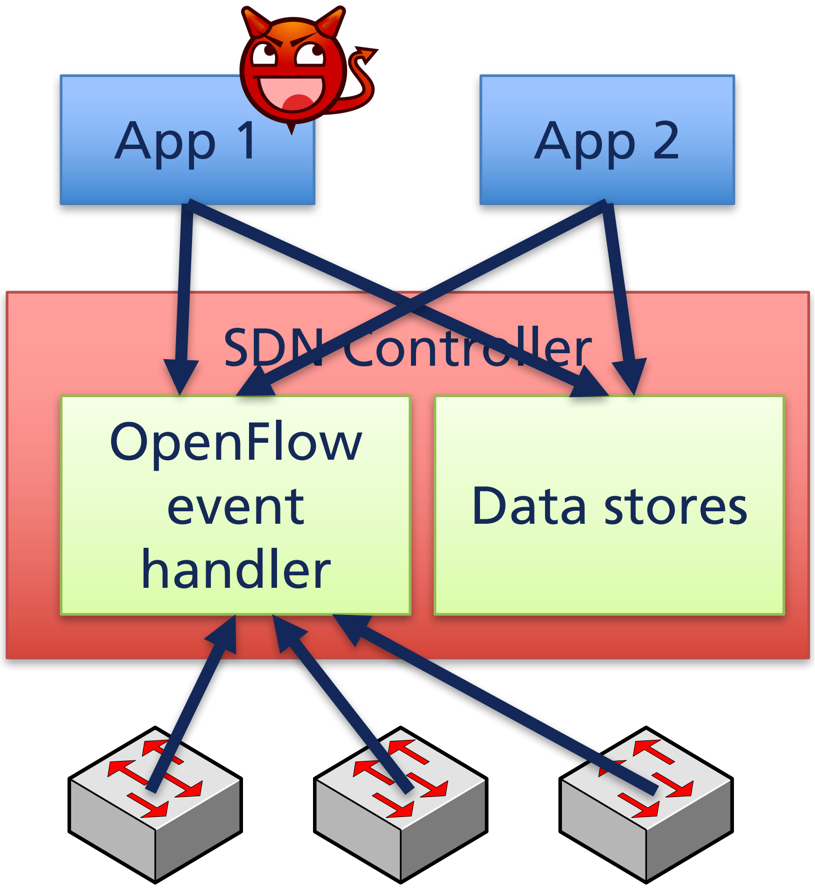
icies, another key advantage of SDN is that it allows routing choices to be defined at a much finer granularity level, that is, per flow rather than at the usual IP-prefix level. For instance, OpenFlow 1.5 supports 44 different types of header fields against which to match a packet in order to choose

the underlying technology and protocols. In addition, flexibility makes it hard to define meaningful SDN network policies, such as which flows are affected by a specific network application and modified in a specific way. The flexibility SDNs

Dynamic configurations make it more difficult for defenders to tell whether the current or past configuration is intended and correct. The

Challenges

- Network applications can modify:
  - OpenFlow control protocol messages (e.g., `PACKET_IN`)
  - Shared data structures (e.g., topology data store)
- Northbound API boundary between apps and controller is complicated
- Apps bundled with controller have risks depending on language



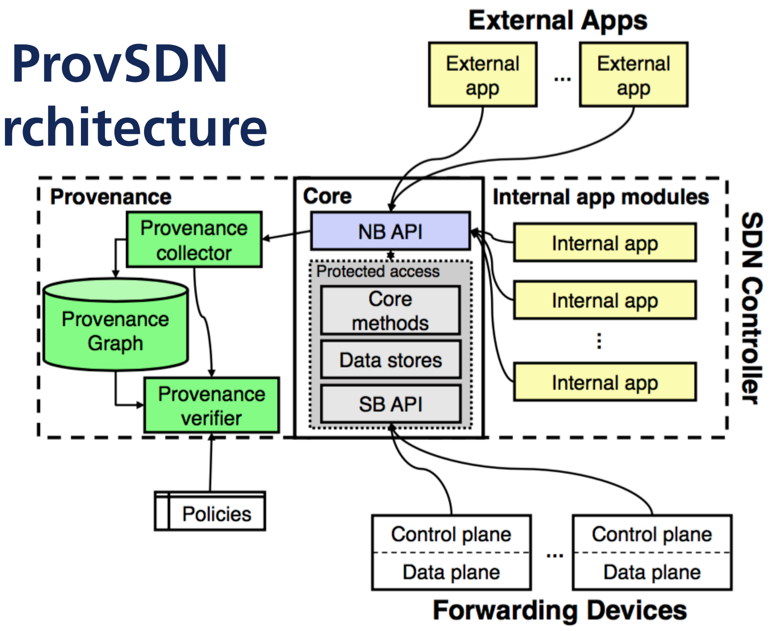
Prior Solutions

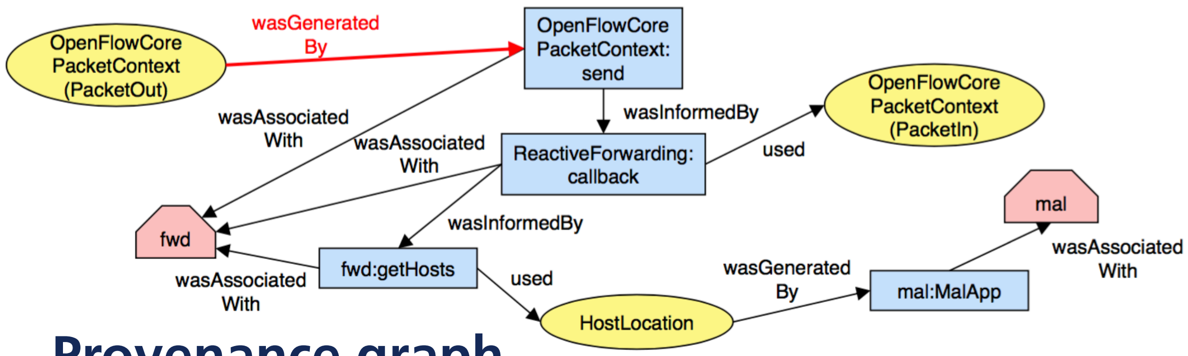
- **Permission-based access control (e.g., Security Mode ONOS)**
  - Pros: easy to implement hierarchical permissions
  - Cons: does not track data once permission has been granted; not expressive for contextual-based systems
- **Taint tracking**
  - Pros: traces how data is used from “sources” to “sinks” for information flow control; minimal additional storage constraints
  - Cons: does not capture which system principal/agent was responsible (i.e., no attribution)

Solution: ProvSDN

- Add data provenance collection to controller activities to create a **provenance-aware control plane**
- Implemented as extension to ONOS SDN controller
- No modifications needed to apps
- Acceptable latency overheads for provenance capture (~100 ms) and online detection/prevention (~300 ms)

ProvSDN architecture



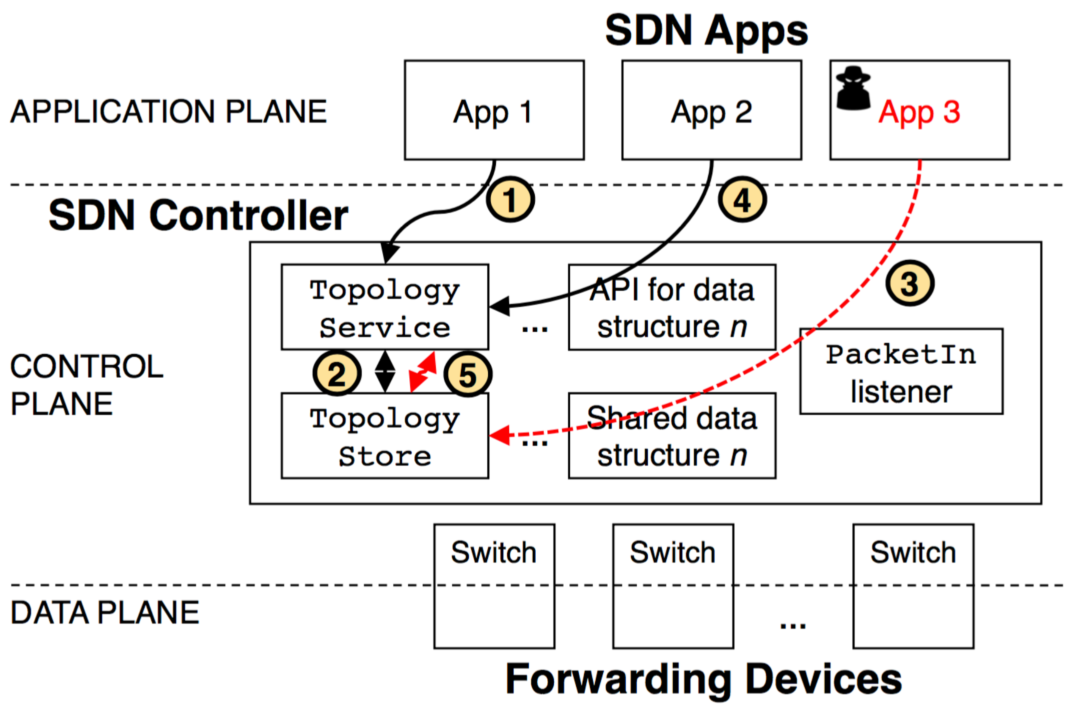


Provenance graph example

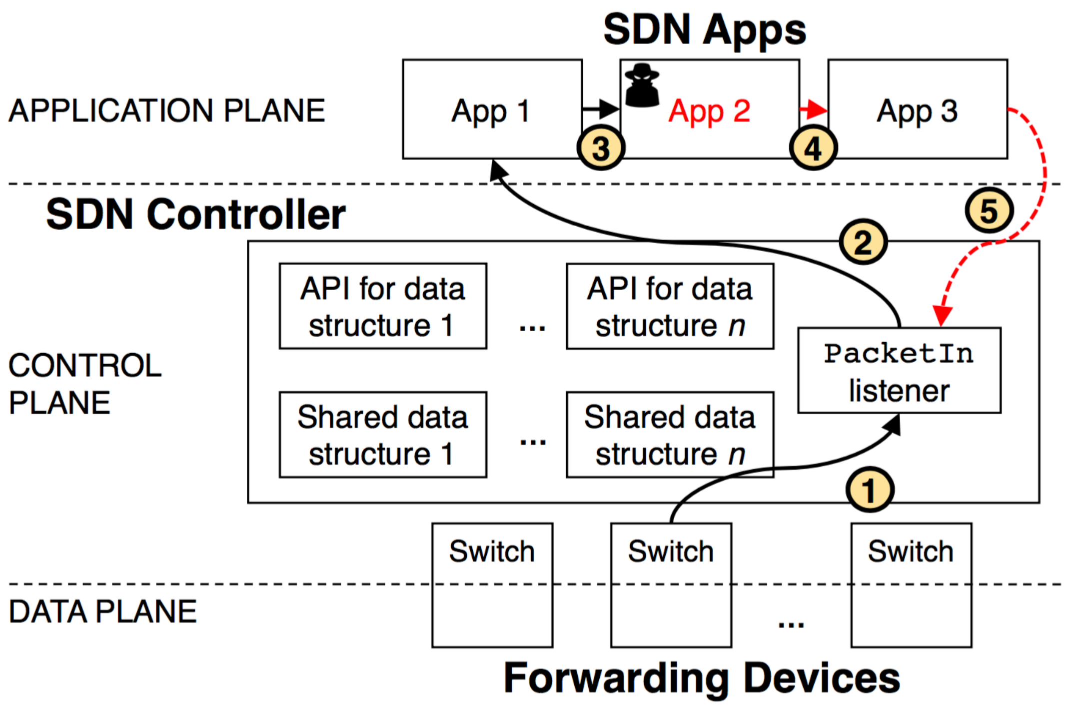
Components

- Cross-app poisoning attacks
- Northbound API semantics
- ProvSDN provenance model
- ProvSDN architecture design
- Implementation
- Evaluation
- Results

Cross-App Poisoning Attacks



Method 1: Shared data structure access via controller API



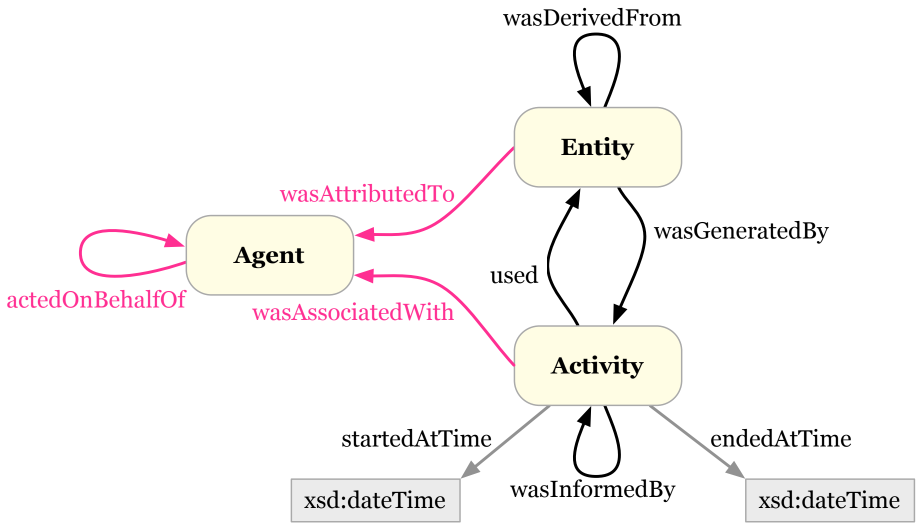
Method 2: `PacketIn` processing via callbacks.

Northbound API Semantics

- Unlike traditional operating systems, SDNs do not (yet) have well-defined semantics
- Prerequisite for defining provenance model
- Approach: static analysis of controller functions/methods
  - Class with high number of references in other classes (3 or more) is considered public-facing and thus part of the northbound API
  - **ONOS "Public": 63 classes, 721 methods**
  - **ONOS "Internal": 194 classes, 1,405 methods**

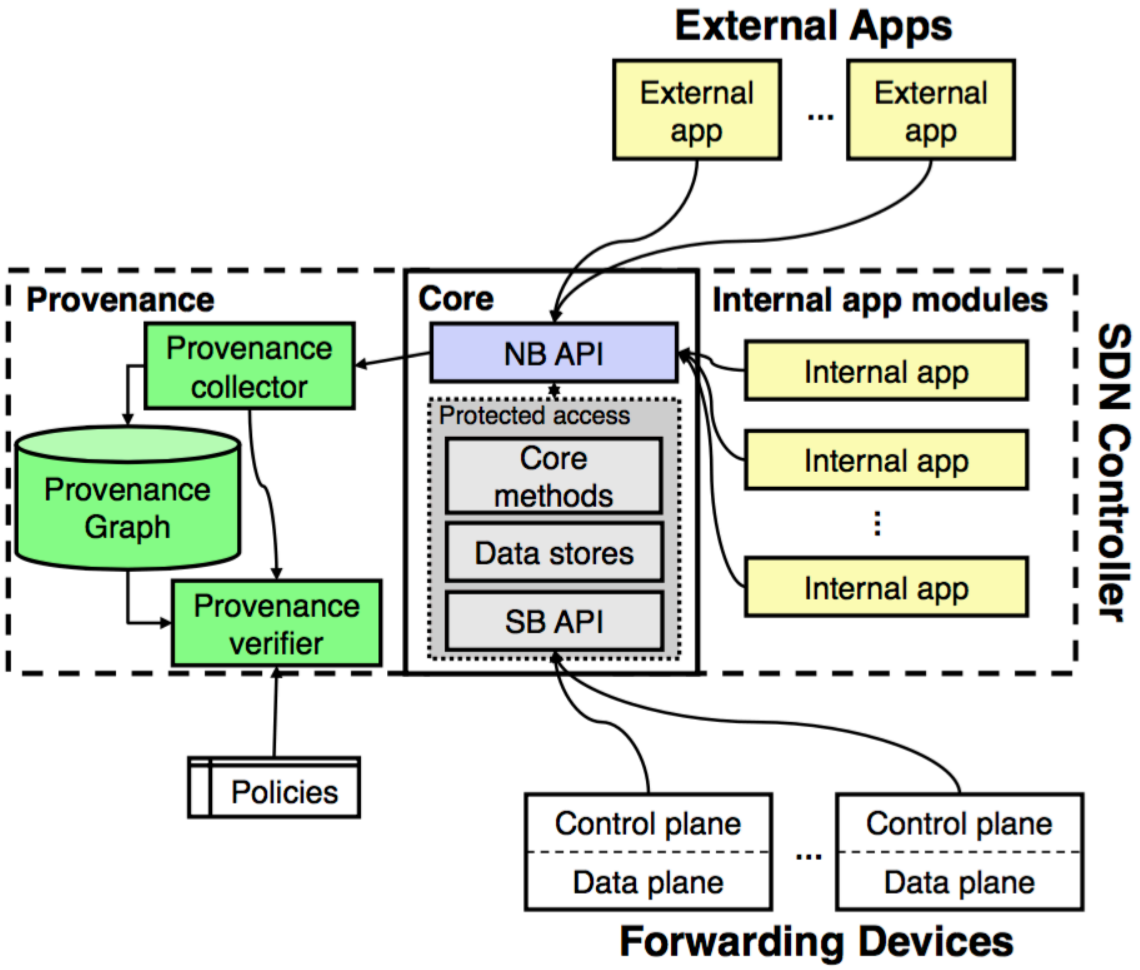
ProvSDN Provenance Model (W3C PROV-DM)

W3C PROV type	SDN objects of interest	Additional attributes
Entity	• Switches • Hosts • Network Links • Flow Rules • OpenFlow messages	• RUUID • DUUID • Creation time • Class name
Activity	• OpenFlow message processing • Flow rule management • Host tracking • Link and topology management • Storage management	• UUID • Creation time • Method name • Class name
Agent	• Apps • Controller • Switches	• UUID • App name



Source: "A Walk Through PROV-O", Tim Lebo, https://www.w3.org/2011/prov/wiki/ISWCProvTutorial

ProvSDN Architecture Design



- Security goals
  - Non-bypassable
  - Complete
- Threat model
- Northbound API enforcement
- Optimizations

Implementation

- Controller: **ONOS (Java-based)**
  - ProvSDN provenance collector: 1,100 LOC
- Provenance graph database: **Neo4j**
  - Separate Neo4j server instance
- Provenance query language: **Neo4j Cypher**

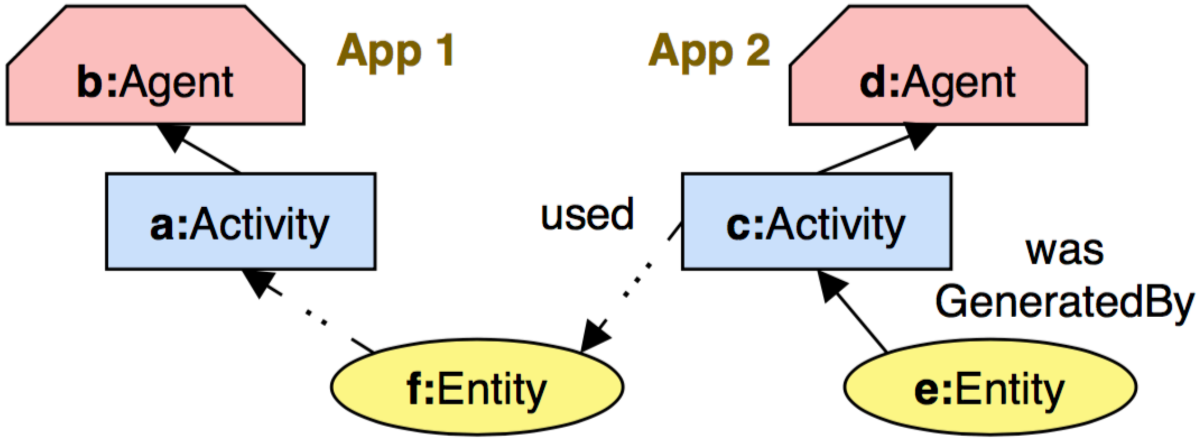
Evaluation

- **Policy:** only allow apps to use data that was
  1. generated from previous activity by app,
  2. genereted by controller, or
  3. generated by switches
- Enforcing application isolation

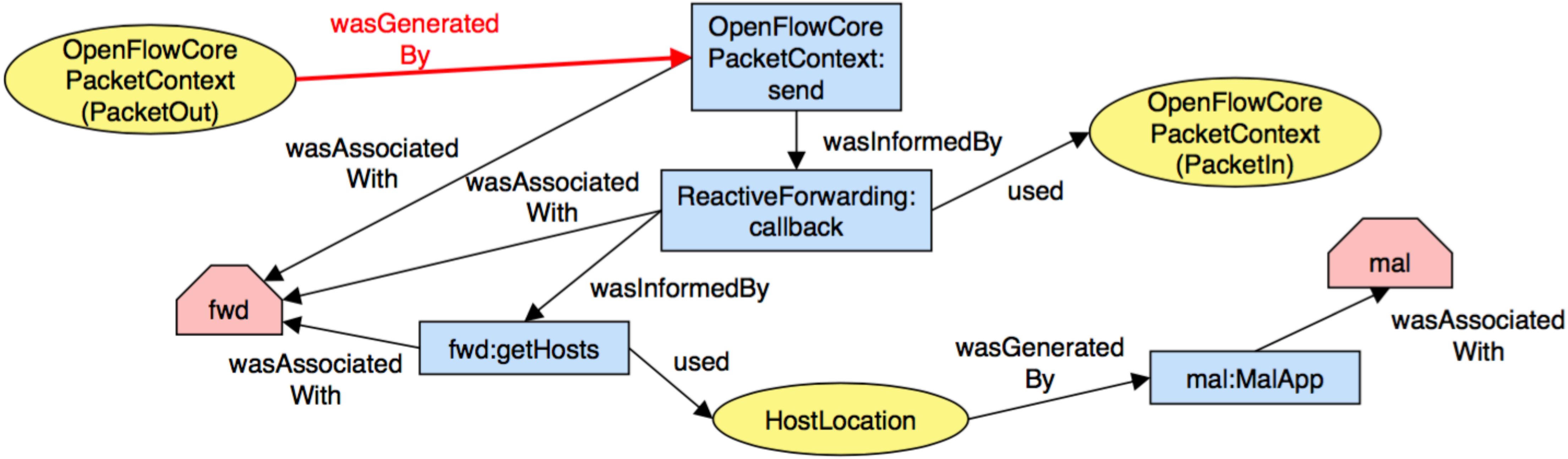
Neo4j Cypher query for policy

```
MATCH p=(b:AGENT)<--(a:ACTIVITY),
  q=(a:ACTIVITY)<-[*]-(f:ENTITY)<-[:USED]-()<-[*]-(c:
       ACTIVITY)-->(d:AGENT),
  r=(c:ACTIVITY)<-[:WAS_GENERATED_BY]-(e:ENTITY)
WHERE e.time_create > currentTime() - 2 seconds
  AND b.name <> d.name AND e.name <> f.name
  AND b.name <> "openflow" AND d.name <> "openflow"
  AND b.name <> "controller" AND d.name <> "controller"
RETURN p,q,r LIMIT 1;
```

Subgraph pattern represented by query

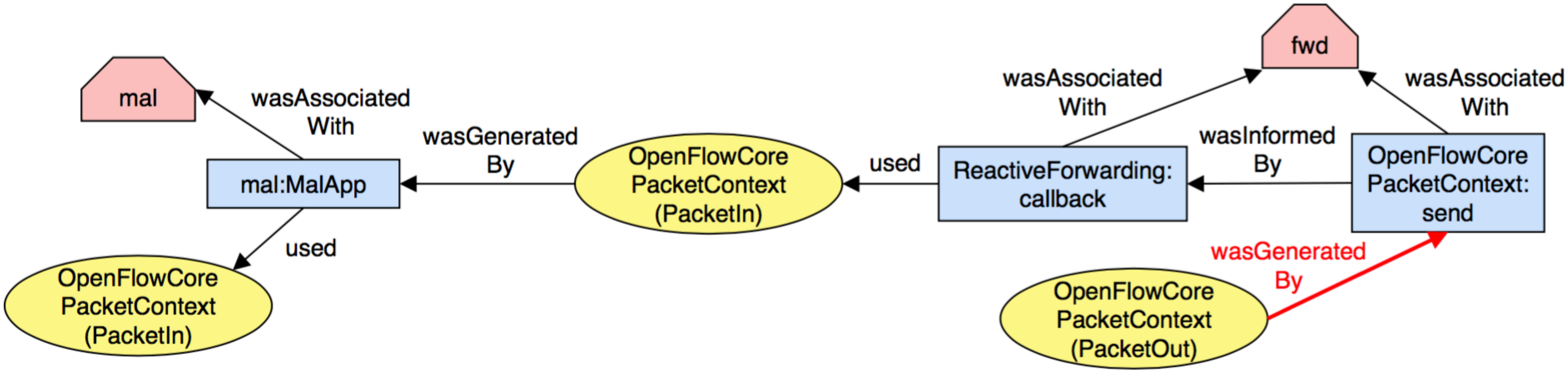


Evaluation: Host Location Change Attack



- Prevent forwarding app from using `HostLocation` data that was previously tampered with by malicious app `mal`

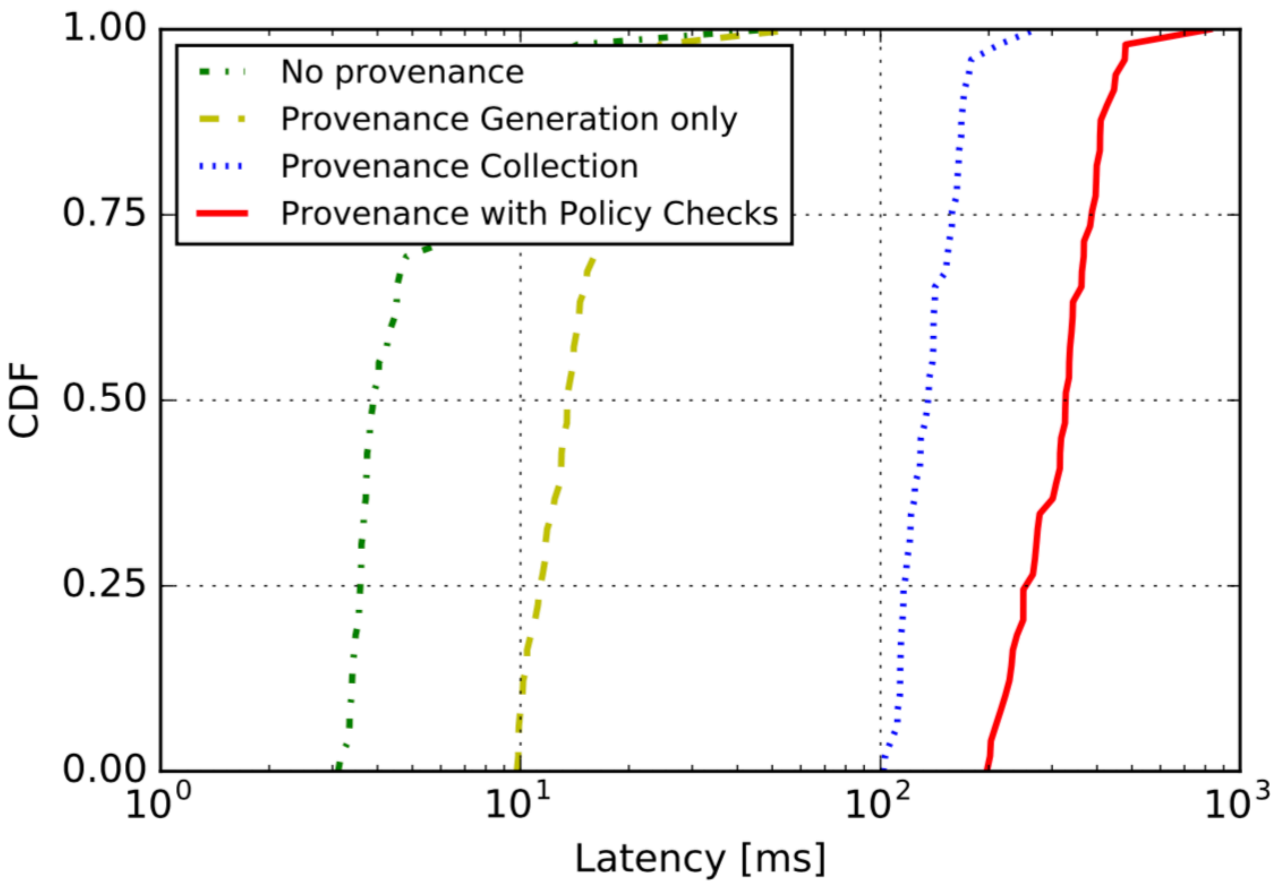
Evaluation: ARP Spoofing Attack



- Prevent forwarding app from using an OpenFlow `PacketIn` message that was tampered with by malicious app `mal`

Results: End Host Latency

- Provenance generation adds **one order of magnitude** to latency
- Average **140 ms** without checks and **330 ms** with checks
- (Future work: other graph databases)



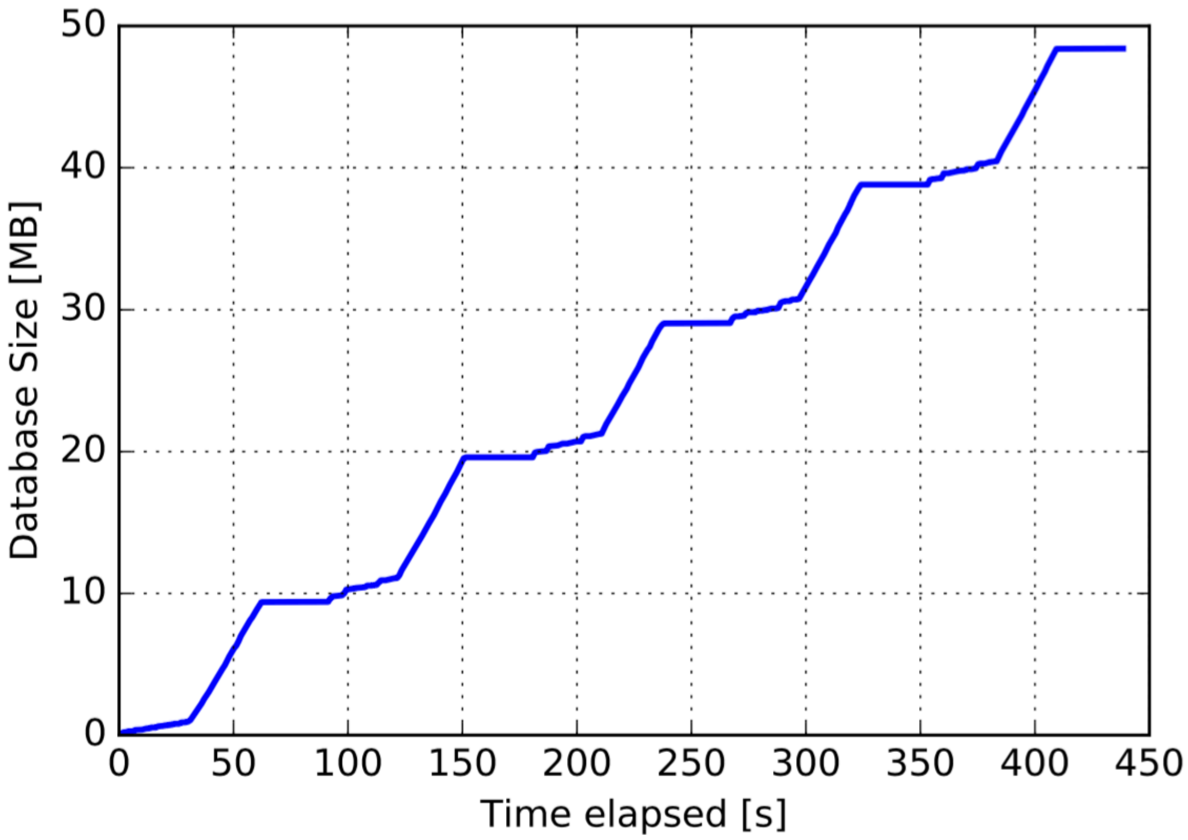
Results: Microbenchmarking

Element	Average time	Number of operations	Total time spent
Internal check	0.027 ms	3,514,962	95.391 s
Provenance collection	0.072 ms	35,299	2.548 s
Provenance recording	1.26 ms	89,757	113.505 s
Online querying	19.26 ms	4,043	77.888 s

- Online querying **was most expensive**
- API boundary check **was most frequent** (and least expensive)

Results: Storage

- Spikes correspond to flow modifications; depends on topology
- (Future work: pruning provenance graph)



Summary

- Provenance-based solution to information flow control for securing SDN controllers and network applications
- Real-time checking for online enforcement of information flow control policies
- Implemented in production-quality ONOS SDN controller
- Future work: exploring other ways we can use provenance (e.g., compliance, forensics)
- Paper submitted to NDSS '18

Questions?

- Thanks for listening!