Cross-App Poisoning in Software-Defined Networking

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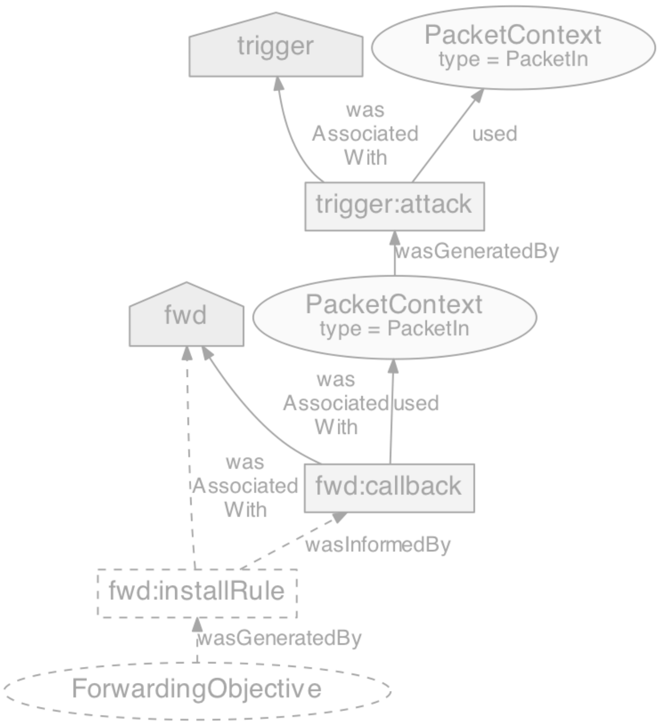

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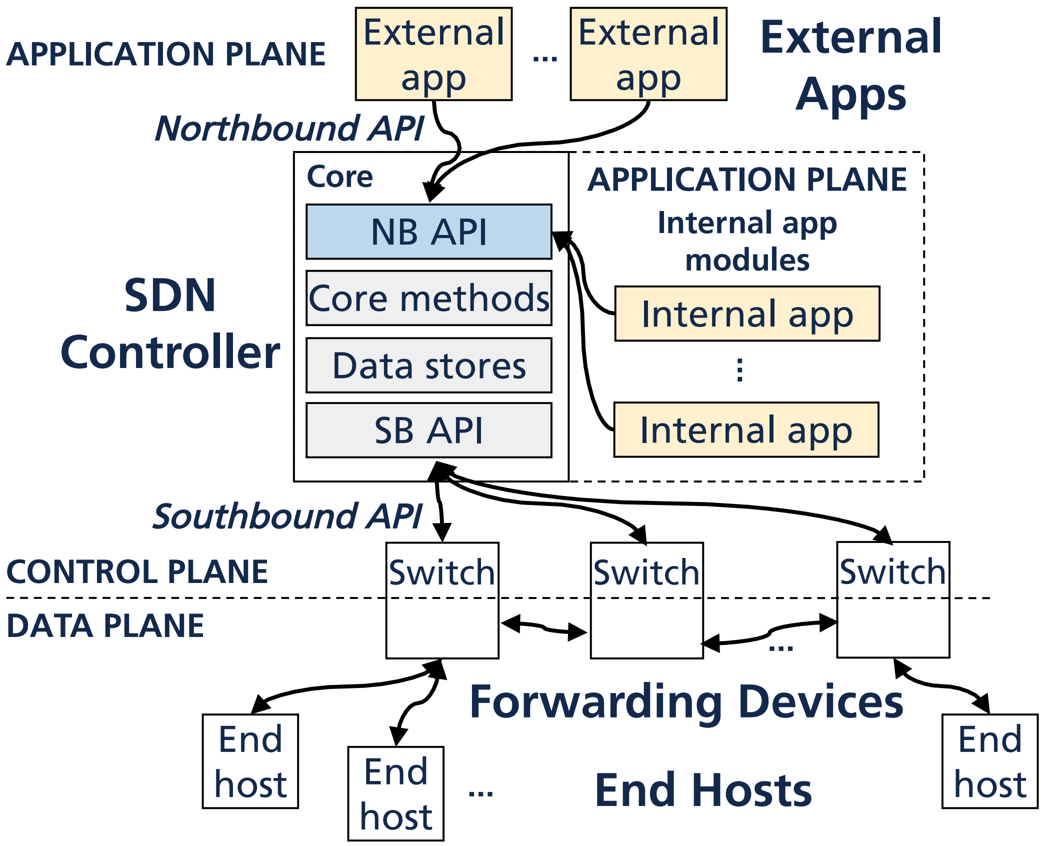
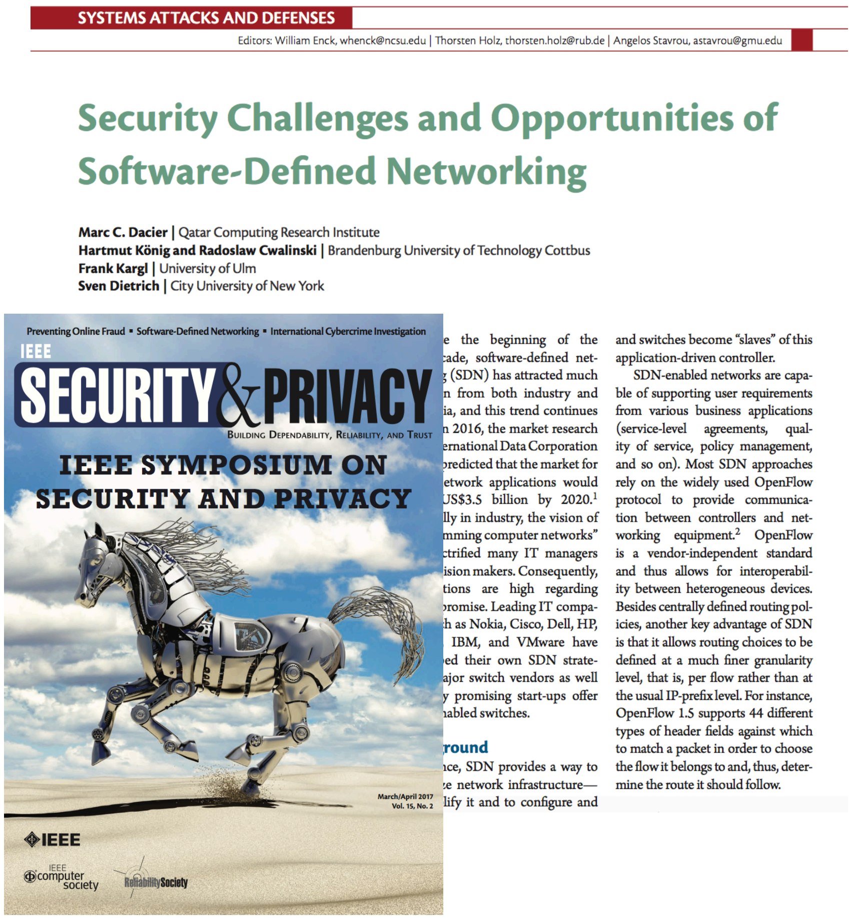
SDN Overview

- SDN centralizes decisions into an **SDN controller**
- SDN controller acts as a **network operating system**
- **Network applications (apps)** extend functionality



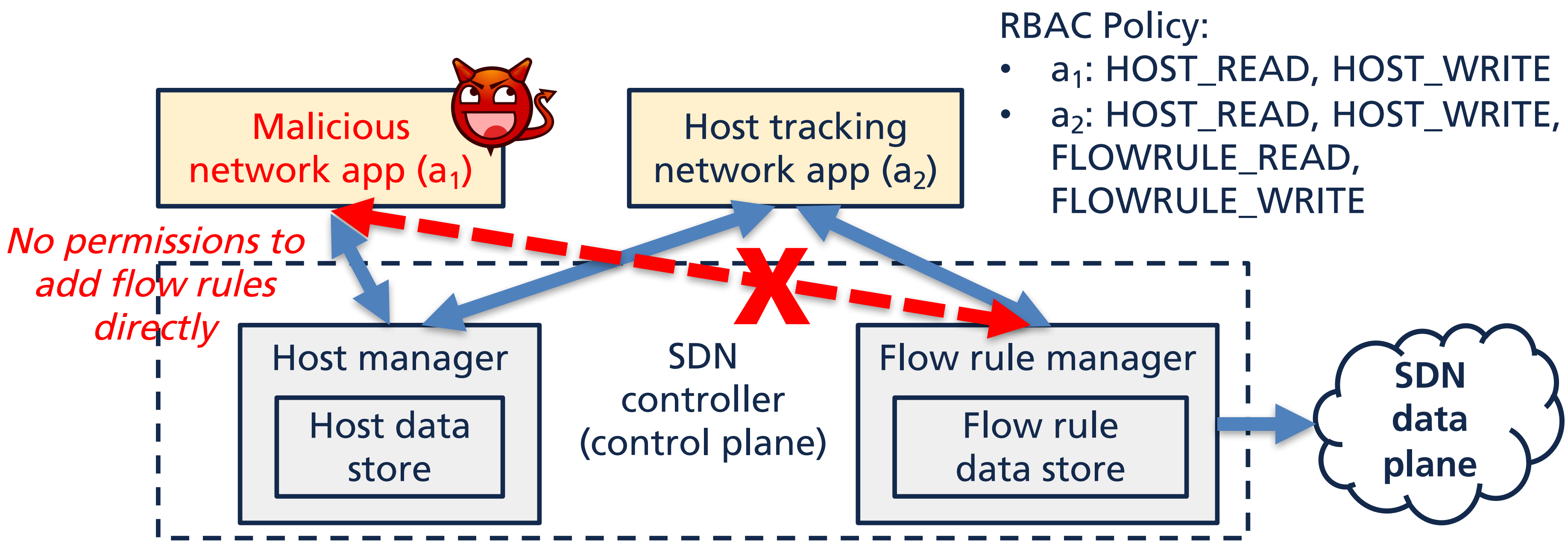
State of SDN Security



- *IEEE S&P* magazine, 2017
  - "Attacks against SDN controllers and … **malicious controller apps** are probably the **most severe threats** to SDN."
  - "**Dynamic configurations make it more difficult** for defenders to tell whether the current or past configuration is intended…"

Need for **greater insight** into network decision-making **among apps**

RBAC in Control Plane

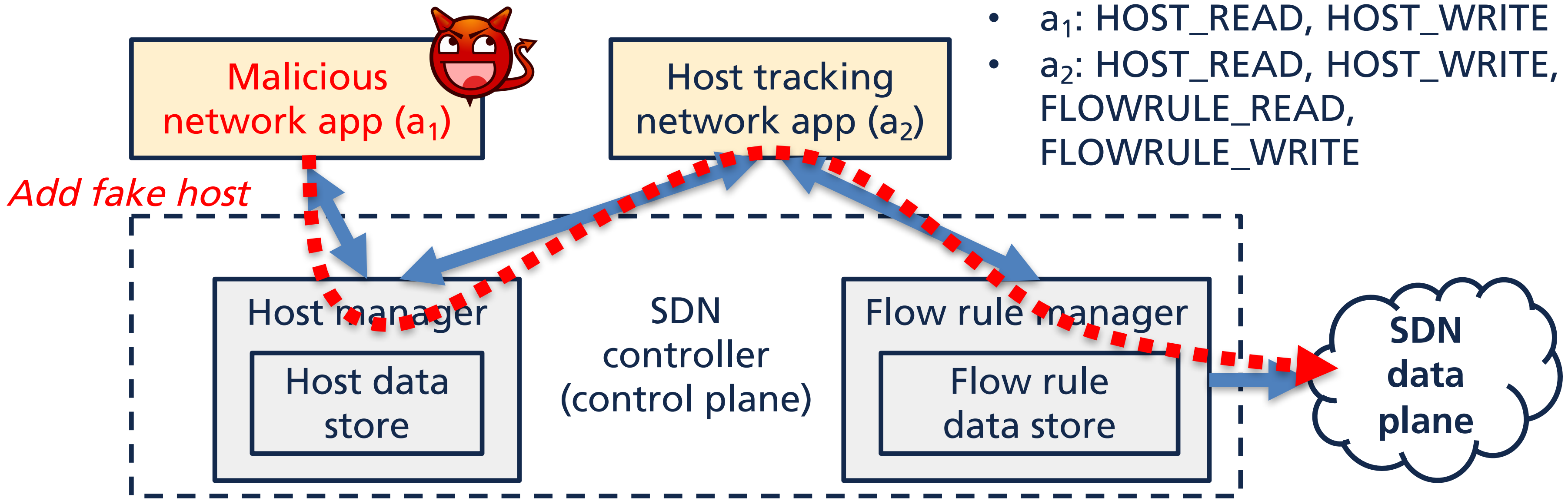


Current solutions rely on **role-based access control** (RBAC)

RBAC Limitations

RBAC Policy:

- a_1: HOST_READ, HOST_WRITE
- a_2: HOST_READ, HOST_WRITE, FLOWRULE_READ, FLOWRULE_WRITE



RBAC is insufficient because it does not track **information flow**

Approach

High level goal: Track information flow within the SDN control plane

- Formalize **cross-app poisoning** (CAP)
- Perform static analysis of apps to find **CAP gadgets**
- Incorporate **information flow control** (IFC) in control plane
- Apply **data provenance** techniques to track information flow and **enforce IFC** with minimal additional latency (**ProvSDN**)

Threat Model

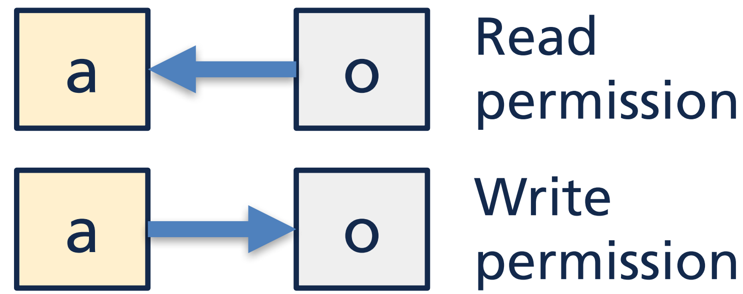
- <u>Attacker objective</u>: arbitrarily **install flow rules** to affect data plane **connectivity**
- <u>Defender objective</u>: prevent CAP attacks **even after RBAC** has been applied
- System assumptions:
  - SDN controller is **trusted** and adequately **secured**
  - Apps may originate from third parties; **untrusted**
  - Attacker controls a **least-privileges** app

Cross-App Poisoning (CAP)

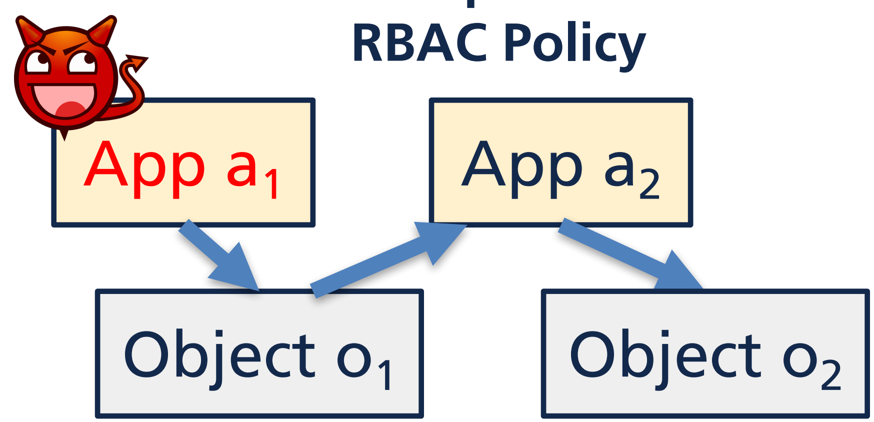
- **IFC integrity problem**
- Model RBAC policy with **apps**, control plane's **data structures (objects)**, and **read** and **write permissions (edges)**

Goal: Find paths from apps to objects that are **not directly connected**

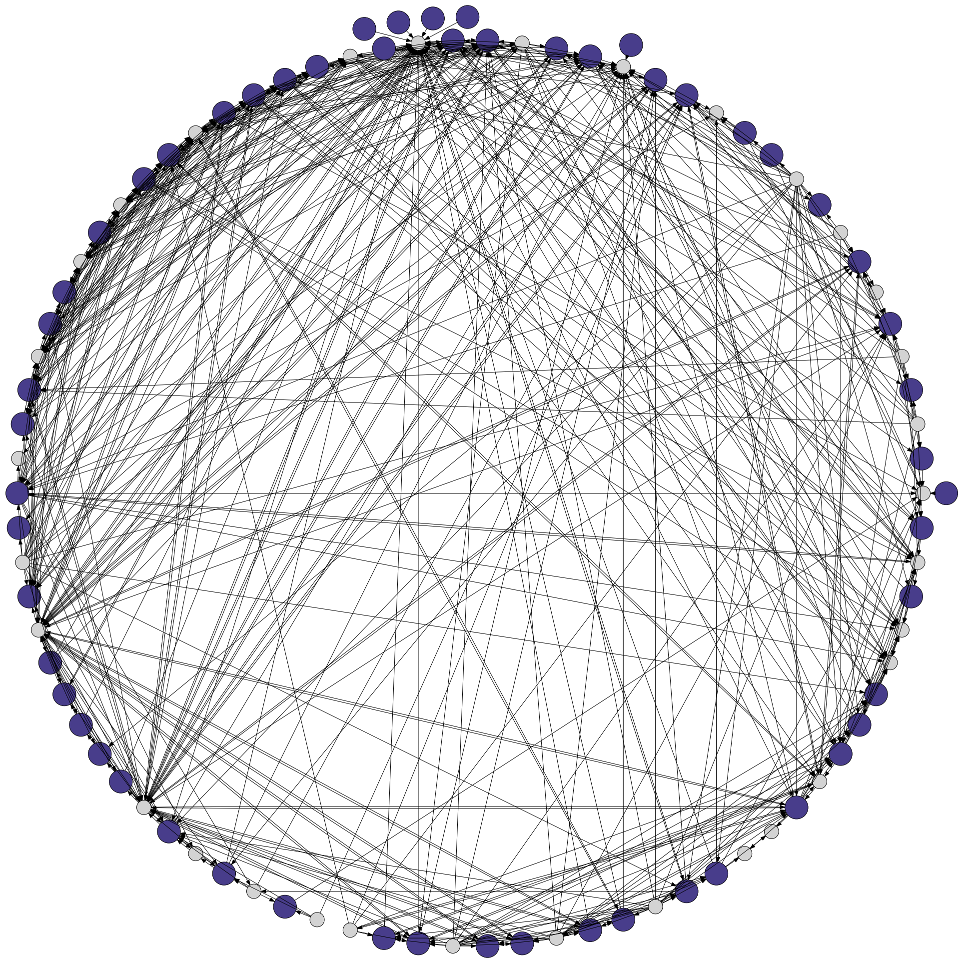
CAP Semantics



Example with RBAC Policy



CAP in ONOS



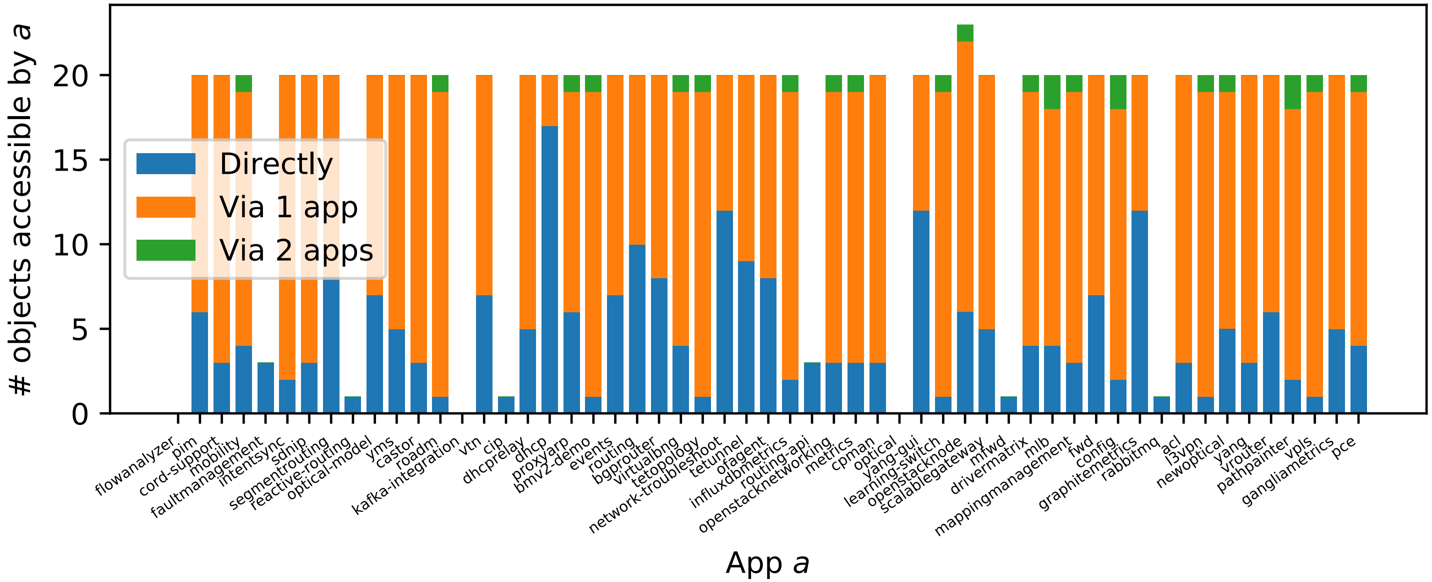
CAP for (Security-Mode) ONOS with Least-Privileges RBAC Policy

- ONOS app
- ONOS object (data structure)

Strong connectivity shows potential **highly dependent data**

CAP in ONOS

onos
Open Network Operating System



- **63** apps (excluding test app)
- **212** protected methods in **39** manager classes

Strong connectivity shows potential **highly dependent data**

CAP Gadgets

- **Writes may not always causally depend on reads**
- Use static analysis
- Identify **CAP gadgets** that allow flow from a permissioned data **source** to a permissioned data **sink**
- Assume the attacker uses a **triggering app** to start

Sources and sinks in ONOS forwarding app `fwd`

```
public class ReactiveForwarding {
  public void activate(...) {
    ...
    appId = coreService.registerApplication("org.onosproject.
         ↪ fwd");
    packetService.addProcessor(processor, PacketProcessor.
         ↪ director(2));
    ...
  }
  private class ReactivePacketProcessor implements
       ↪ PacketProcessor {
    public void process(PacketContext context) {
      ...
      installRule(context,...);
    }
  }
  private void installRule(PacketContext context,...) {
    ...
    ForwardingObjective forwardingObjective =
         ↪ DefaultForwardingObjective.builder().withSelector(
         ↪ selectorBuilder.build()).withTreatment(treatment).
         ↪ withPriority(flowPriority).withFlag(
         ↪ ForwardingObjective.Flag.VERSATILE).fromApp(appId).
         ↪ makeTemporary(flowTimeout).add();
    flowObjectiveService.forward(context.inPacket().
         ↪ receivedFrom().deviceId(), forwardingObjective)
  }
}
```

Source

Sink

CAP Gadgets in ONOS

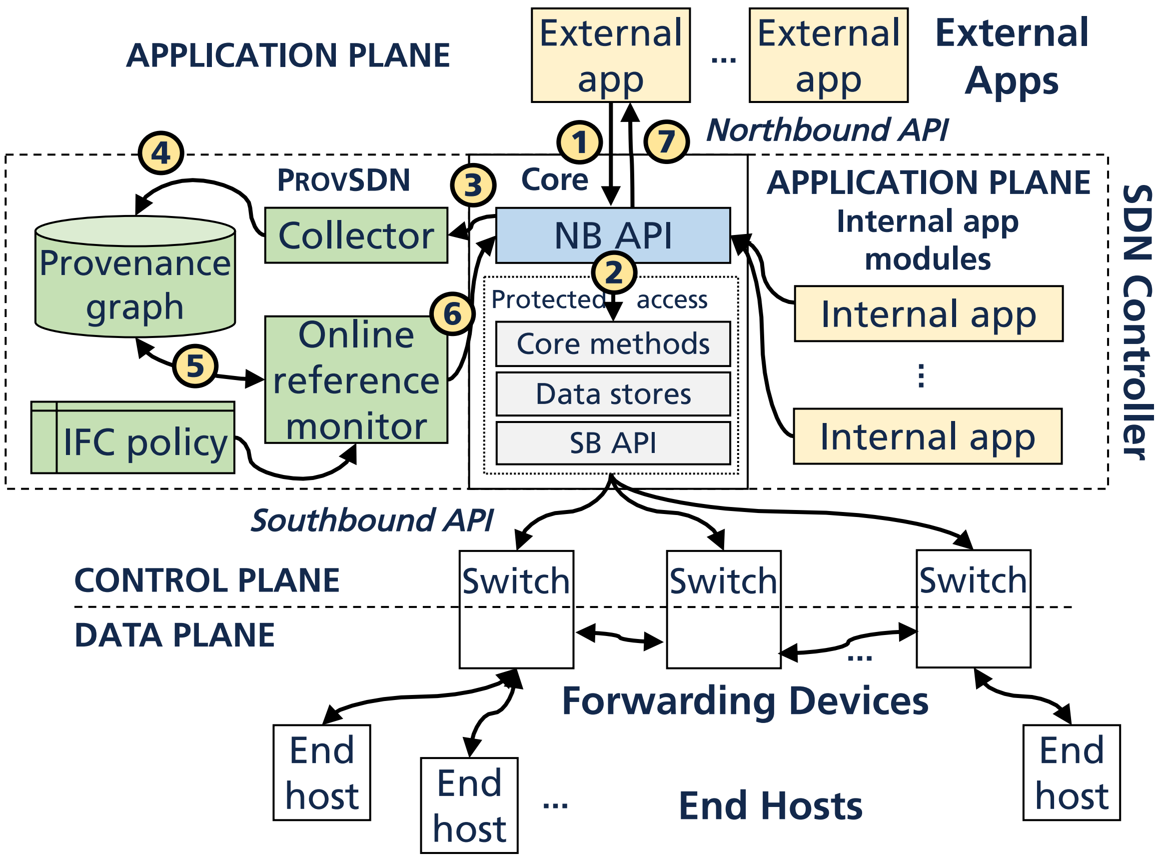
Table 1: Static Analysis Results of CAP Gadgets for Security-Mode ONOS Apps.

Source ($p \in P_R$)	App ($a \in A$)	Sink ($p \in P_W$)	Attacker's capabilities if source data have been compromised by attacker
APP_READ	openstacknetworking	FLOWRULE_WRITE	Attacker modifies the app ID to remove all flows with a given app ID
APP_READ	openstacknode	CLUSTER_WRITE	Attacker modifies the app ID to make an app run for leader election in a different ONOS topic (*i.e.*, an app using ONOS's distributed primitives)
APP_READ	openstacknode	GROUP_WRITE	Attacker modifies the app ID to associate an app with a particular group handler
APP_READ	routing	CONFIG_WRITE	Attacker modifies the app ID to misapply a BGP configuration
APP_READ	sdnip	CONFIG_WRITE	Attacker modifies the app ID to misapply an SDN-IP encapsulation configuration
DEVICE_READ	newoptical	RESOURCE_WRITE	Attacker misallocates bandwidth resources based on a connectivity ID
DEVICE_READ	vtn	DRIVER_WRITE	Attacker misconfigures driver setup for a device (*i.e.*, switch)
DEVICE_READ	vtn	FLOWRULE_WRITE	Attacker misconfigures flow rules based on a device ID
HOST_READ	vtn	FLOWRULE_WRITE	Attacker misconfigures flow rules based on a host with a particular MAC address
PACKET_READ	fwd	FLOWRULE_WRITE	Attacker injects or modifies an incoming packet to poison a flow rule
PACKET_READ	learning-switch	FLOWRULE_WRITE	Attacker injects or modifies an incoming packet to poison a flow rule

Attackers can leverage other data structures to affect flow rules **without flow rule permissions**

ProvSDN

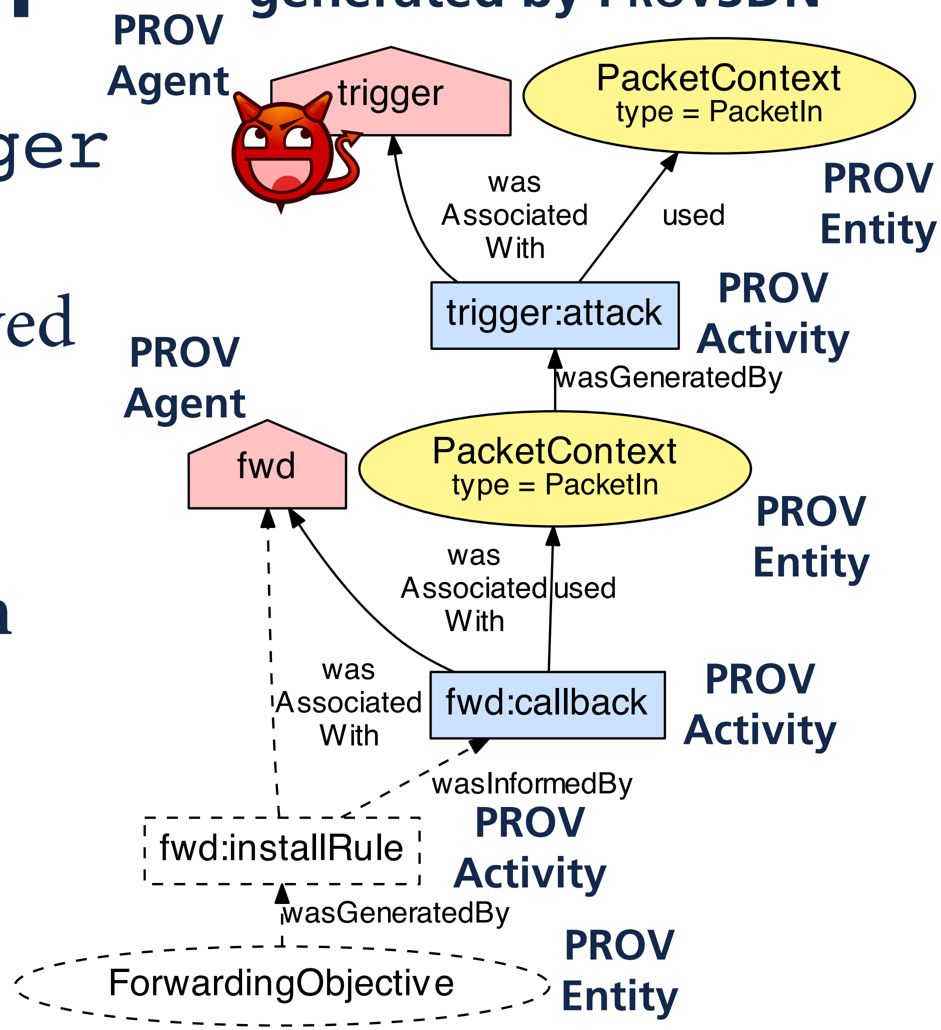
- Use **data provenance** to record control plane state
- Online reference monitor enforces **IFC**
- **Implemented on ONOS**



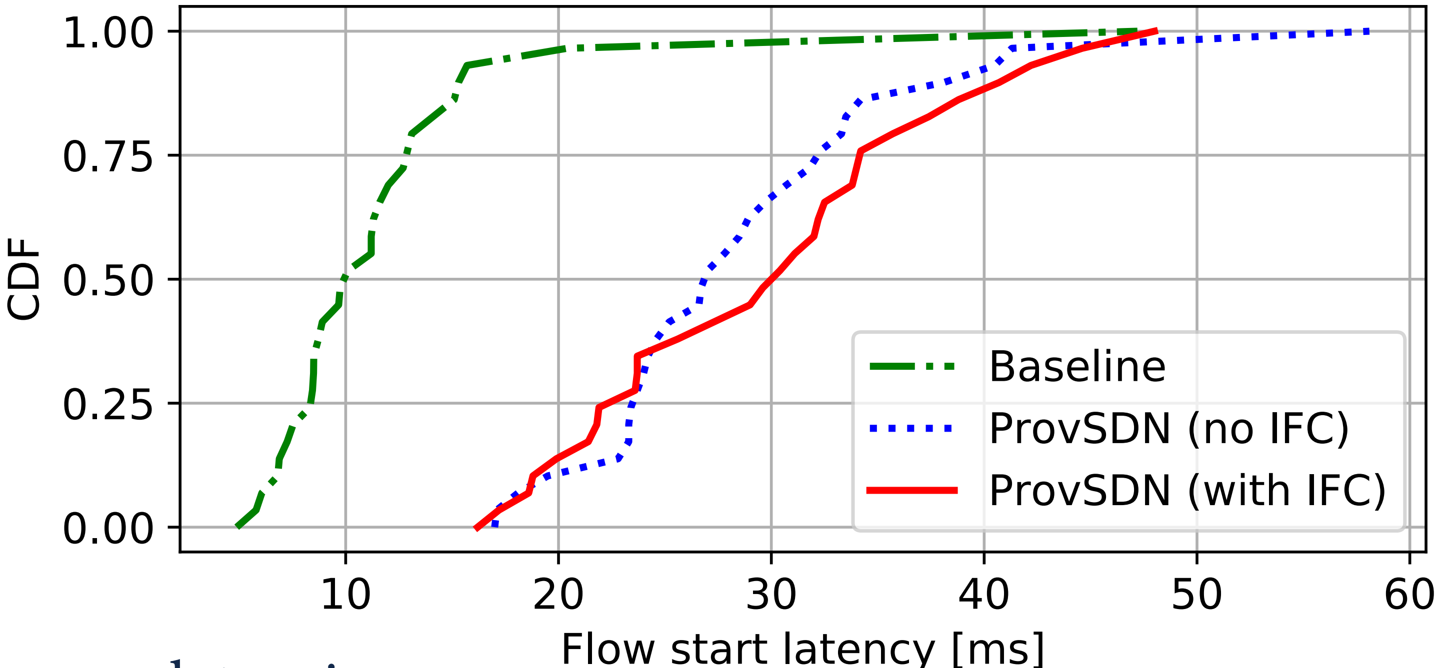
Attack Evaluation

- Use triggering app `trigger` to modify an incoming packet before being received by forwarding app `fwd`
- <u>Label</u>: `trigger` as **low integrity** and `fwd` as **high integrity**
- <u>Policy</u>: prevent **low** from flowing to **high**

Provenance graph generated by ProvSDN



Performance Evaluation



- Average latencies:
  - Without PROVSDN: **11.66 ms**
  - PROVSDN, no IFC: **28.51 ms**
  - PROVSDN with IFC: **29.53 ms**

Acceptable latency when amortized over long flows

Summary

- We analyzed the **IFC integrity problem** in SDN control planes by investigating information flow
- We proposed a model to identify **cross-app interactions as vectors for potential attacks** and found where they existed in ONOS as a case study
- We proposed a **data provenance** approach with ProvSDN to record control plane state evolution and **enforce IFC** in an online reference monitor
- We **implemented ProvSDN** in the **ONOS controller**

Questions?

- Thanks for listening!
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CAP Paper

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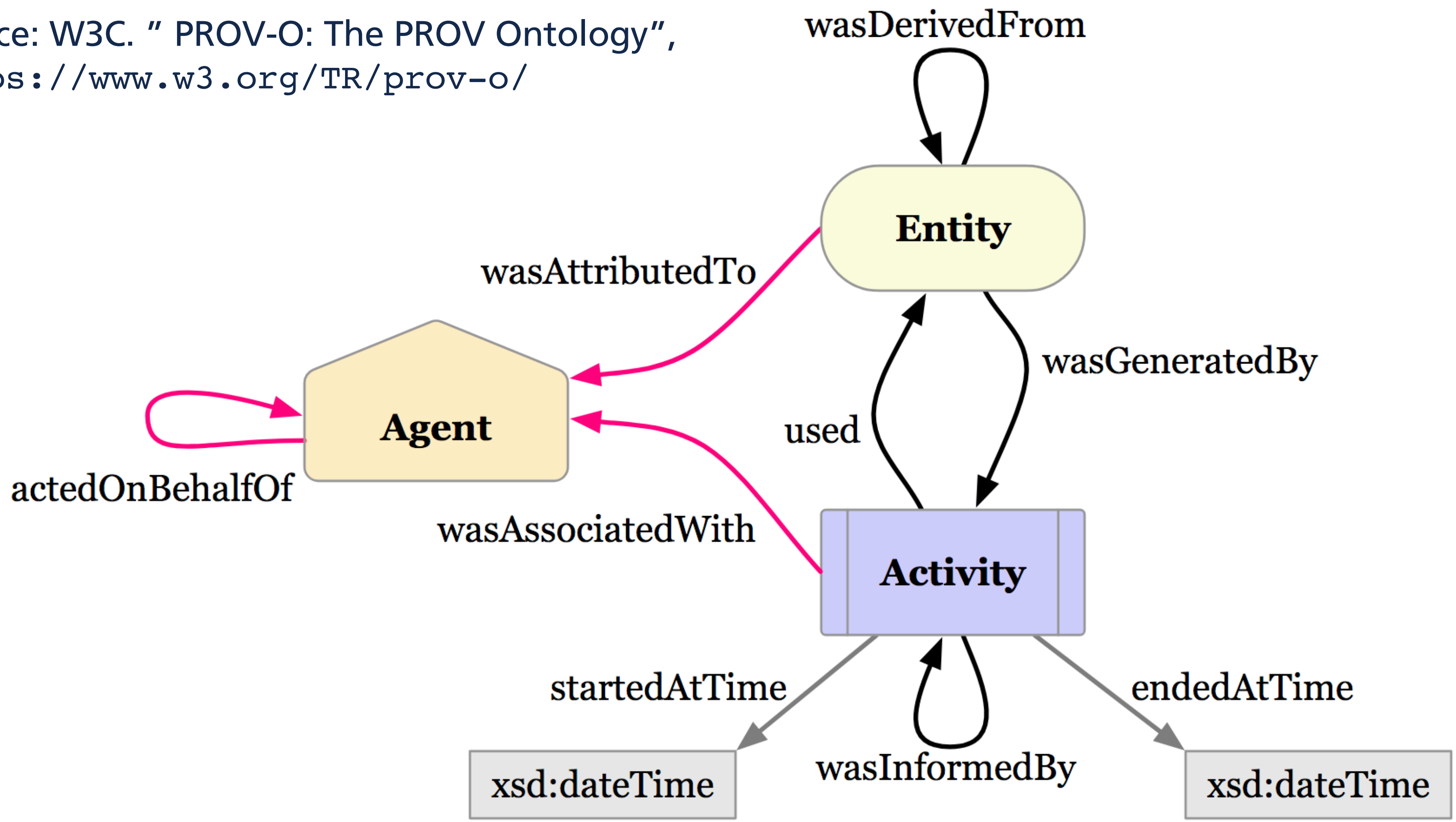
Backup Slides

Static Analysis for ONOS

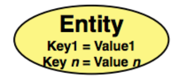
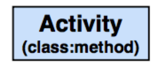
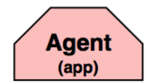
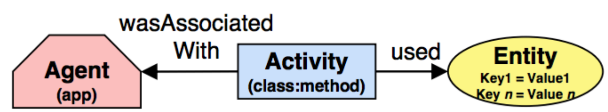
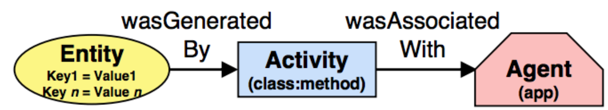
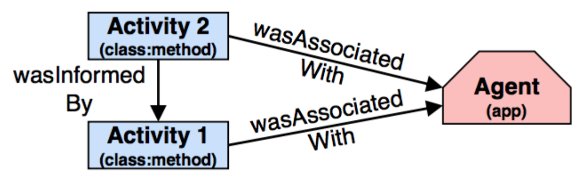
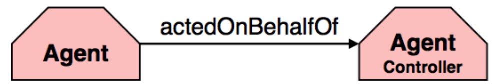
- JavaParser to build abstract syntax tree (AST)
- Sources and sinks derived from analysis of where permissioned methods were called in apps
- Field-sensitive inter-procedural data flow analysis

W3C PROV Data Model

Source: W3C. " PROV-O: The PROV Ontology",
`https://www.w3.org/TR/prov-o/`



W3C PROV Semantics

Object or Event	W3C PROV-DM Representation
Control plane object with attributes	
App method or function call	
App, controller, or switch identity	
App reading object from the shared control plane	
App writing object to the shared control plane	
Intra-app method or callback method	
Internal service on behalf of controller	

ProvSDN Microbenchmarks

Operation	Average time per operation	Number of operations	Percent of total time
Collect	155.66 μs	23 067	1.38%
Write	11.15 μs	57 948	0.25%
IFC check	98.50 μs	544	0.02%
Internal check	44.67 μs	5 692 315	98.34%

Limitations

- Availability-based attacks → can still audit past actions to influence policy-making process
- Separation of memory enforcement → redesign controllers
- Language-based limitations
  - C/C++ controllers
  - Python controllers
  - Java controllers