Hypothesis Testing for Network Security

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We need a science of security

- Practice of doing cyber-security research needs to change
  - Attempts based on reaction to known/imagined threats
  - Too often applied in ad-hoc fashion
- SoS program: move security research beyond ad-hoc reactions
  - Need a principled and rigorous framework
  - Need a *scientific* approach

What is science?

sci·ence *noun* \ˈsī-ən(t)s\

: the systematic study of the structure and behavior of the natural and physical world through observation and experiment

The scientific method

1. Ask a question
2. Formulate a hypothesis
3. Design and conduct an experiment
4. Analyze results

Towards a science of security

- Can we apply the scientific method to the domain of cybersecurity?
  - Challenges: complex, large scale+dynamic environments, many protocols/mechanisms
  - Opportunities: isolation, rigorous analyses, formal models, automation

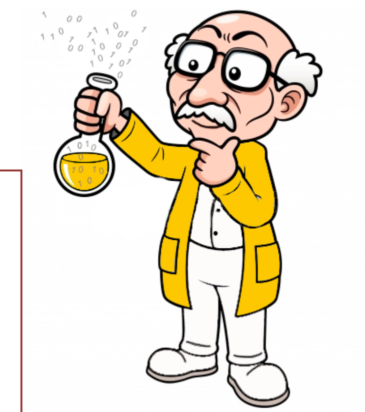
- Can we develop a methodology for science of security?

Our work

- NetHTM: a methodology for science of security
  - Techniques for performing/integrating security analyses to rigorously answer hypotheses about end to end security of a network
- Core: hypothesis evaluation engine
  - Input: testable hypotheses, formal model of system
  - Automatically designs and conducts experiments to evaluate veracity of hypotheses
- Our focus: Network data flow security
  - Builds upon our prior work in formal network modeling

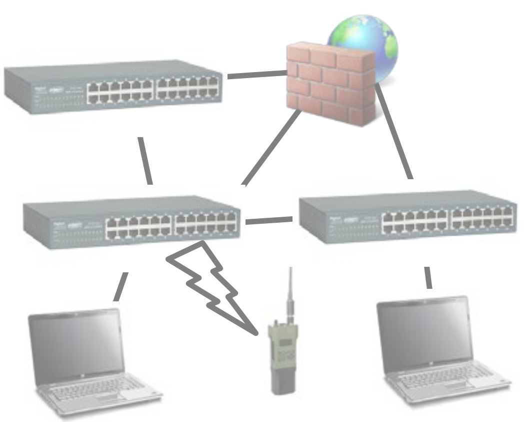
Overall System Architecture

Security Scientist



Hypotheses

- "All network paths traverse a firewall"
- "Fraction of CRE vulnerabilities in network, given set of deployed ACLs, is less than 1%"



System under evaluation

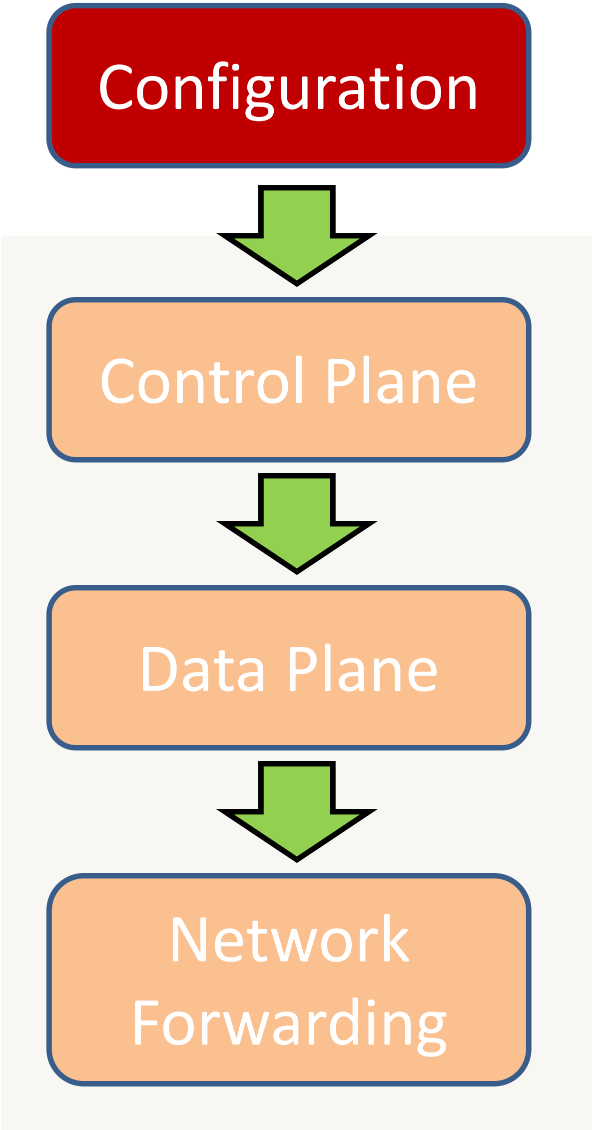
NetHTM Hypothesis Testing Platform

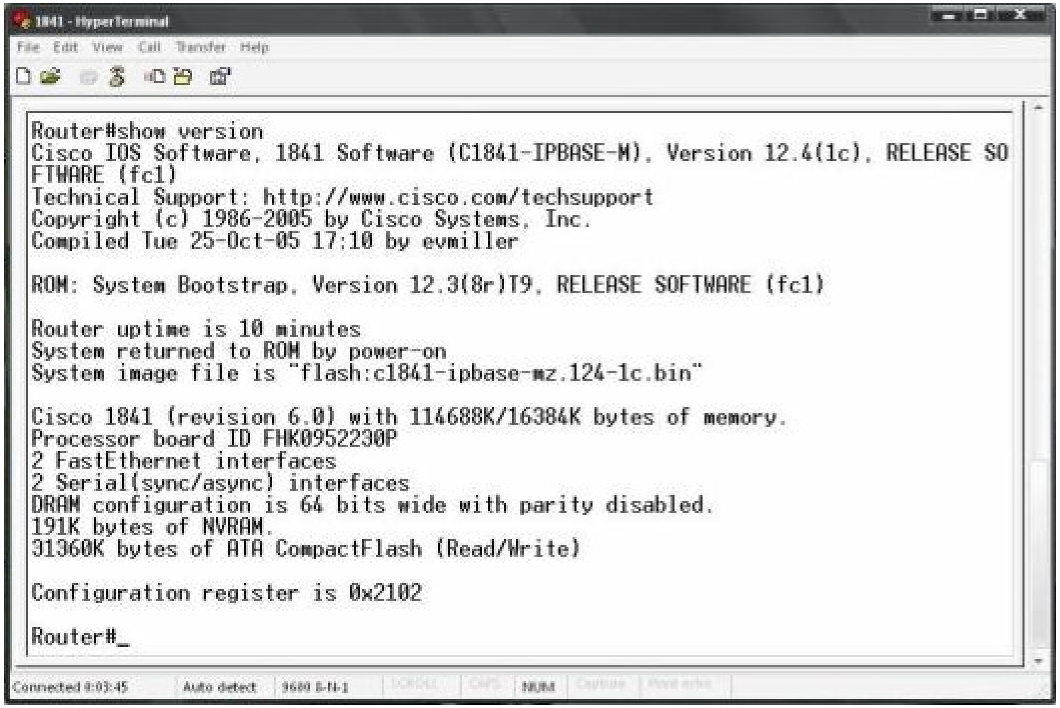
Results

Active sub-tasks and Status

- Task 1: Methodologies for modeling and analyzing networks
  - Core Network Model
  - Modeling virtualized networks [best paper award, HotSDN 2014]
- Task 2: Automated techniques for hypothesis testing
  - Automated experiment construction algorithm
  - Database model of network behavior
- Task 3: Realizing a practical system
  - Modeling dynamic behaviors [NSDI 2015]

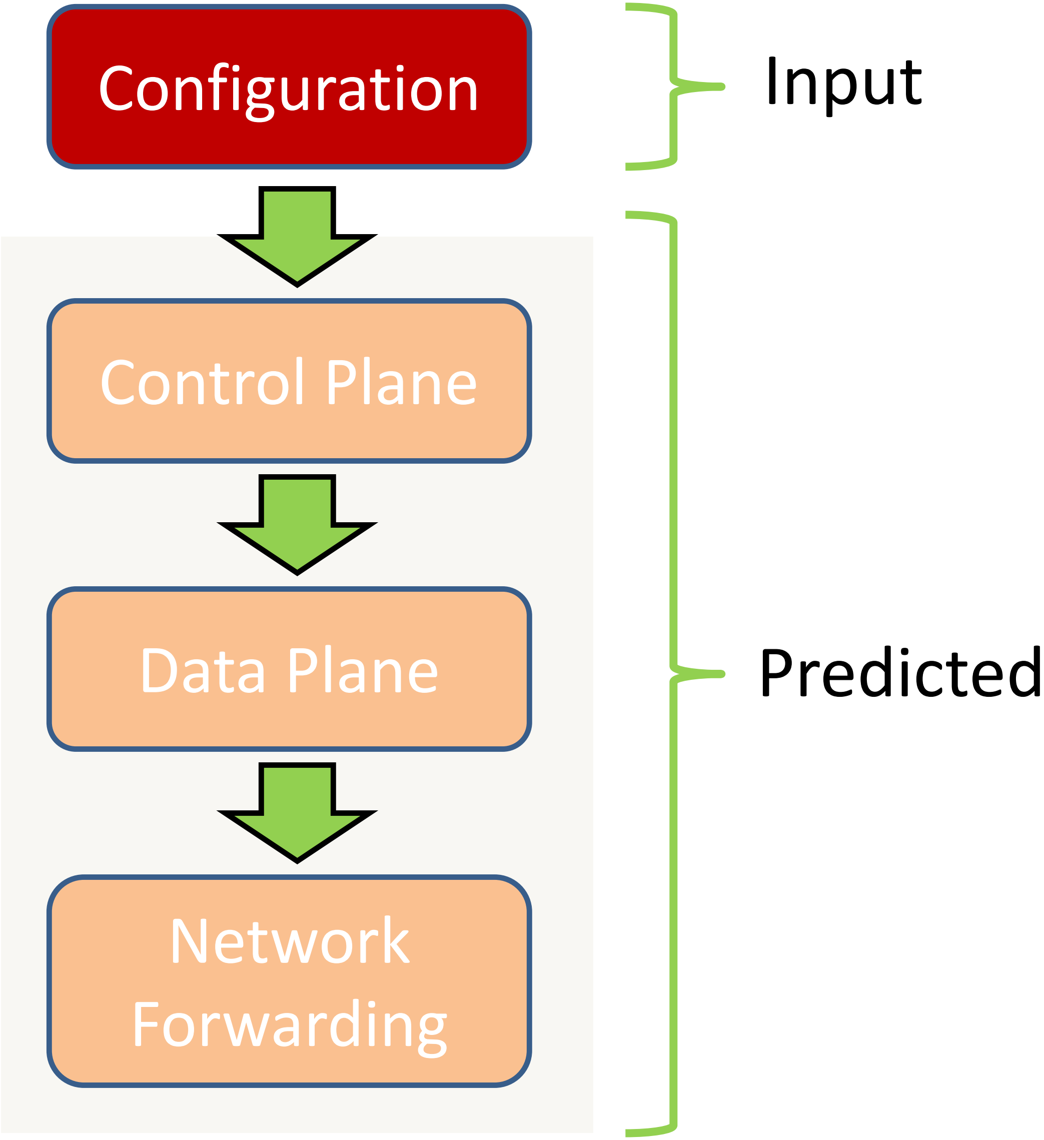
Let's start with a router





```
Router#show version
Cisco IOS Software, 1841 Software (C1841-IPBASE-M), Version 12.4(1c), RELEASE SO
FTWARE (fc1)
Technical Support: http://www.cisco.com/techsupport
Copyright (c) 1986-2005 by Cisco Systems, Inc.
Compiled Tue 25-Oct-05 17:10 by evmiller

ROM: System Bootstrap, Version 12.3(8r)T9, RELEASE SOFTWARE (fc1)

Router uptime is 10 minutes
System returned to ROM by power-on
System image file is "flash:c1841-ipbase-mz.124-1c.bin"

Cisco 1841 (revision 6.0) with 114688K/16384K bytes of memory.
Processor board ID FHK0952230P
2 FastEthernet interfaces
2 Serial(sync/async) interfaces
DRAM configuration is 64 bits wide with parity disabled.
191K bytes of NVRAM.
31360K bytes of ATA CompactFlash (Read/Write)

Configuration register is 0x2102

Router#_
```

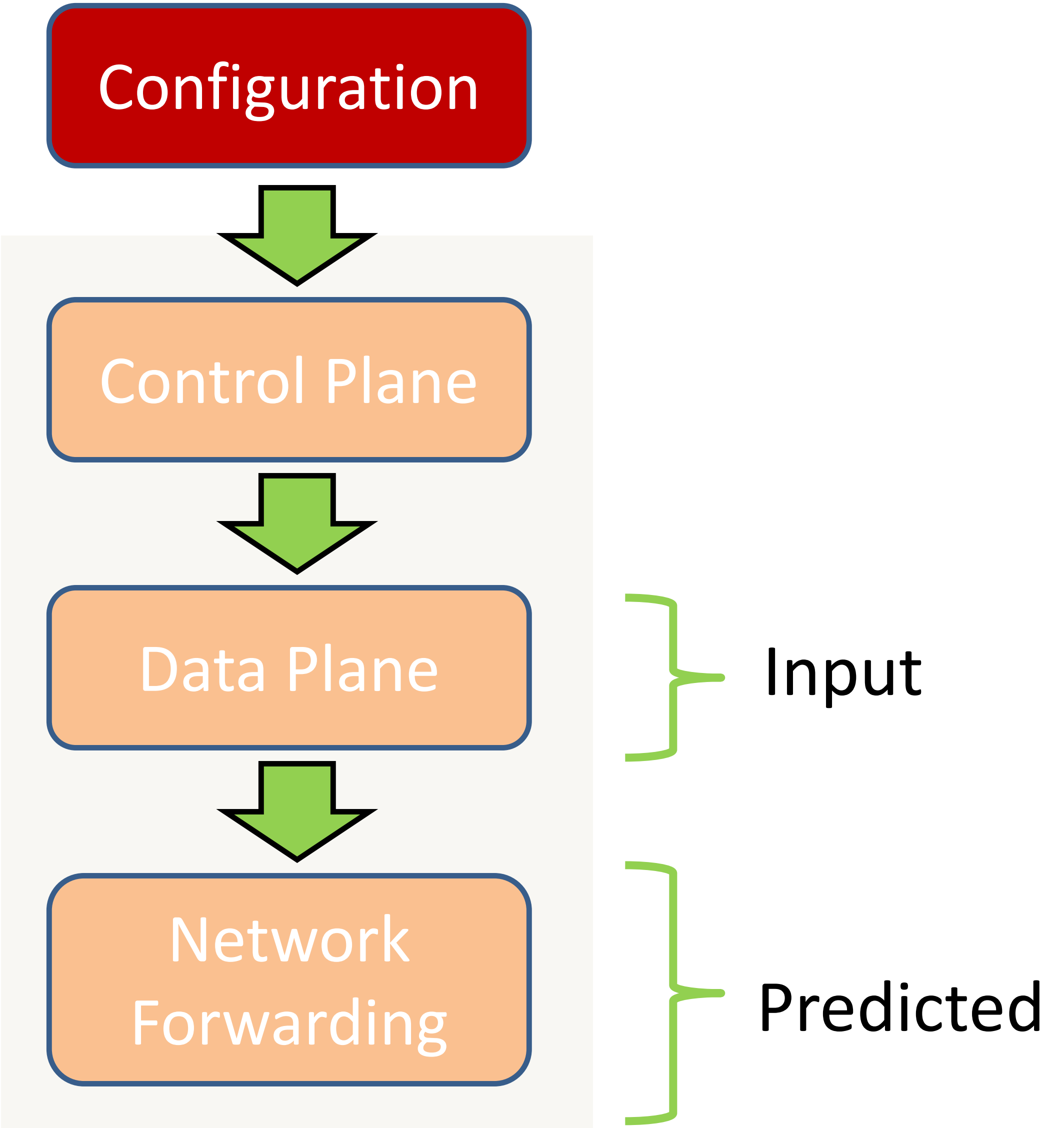
One approach: Build a model of the router



- Pros:
  - Can test prior to deployment

- Cons:
  - Modeling is complex
  - Prediction misses bugs in control plane
  - Requires vendor support

Our approach: Just model the data plane



- Pros:
  - Checks as close as possible to network behavior
  - Unified analysis for multiple protocols
  - Catches implementation bugs

Our approach: Data-plane modeling

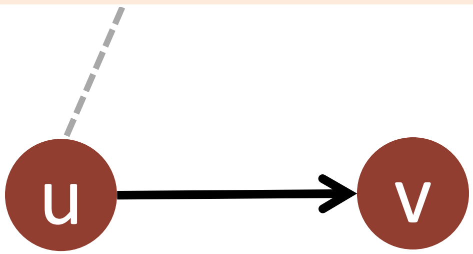
- Challenge: need some general way to express complex forwarding behavior

- Solution: Represent data plane as boolean functions
  - Can leverage well-understood approaches to SAT solving, to check hypotheses against data plane
  - Translate SAT results to report hypothesis veracity along with diagnostic information

Examples

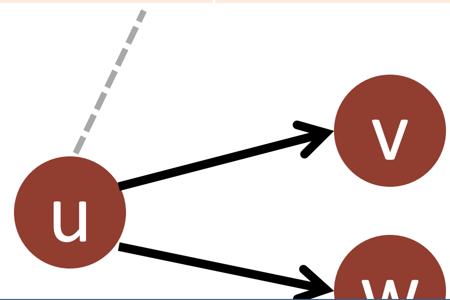
Packet Filtering

Destination	Interface
10.1.1.0/24	v
Drop port 80 to v	



Longest Prefix Matching

Destination	Interface
10.1.1.0/24	v
10.1.1.128/25	w



Similar approaches to handle NAT, multicast, ACLs, encapsulation, MPLS label swapping, OpenFlow, etc.

$P(u,v) = IP_{dest} \in 10.1.1.0/24$

$\wedge\ Port_{dest} \neq 80$

$P(u,v) = IP_{dest} \in 10.1.1.0/24$

$\wedge\ IP_{dest} \notin 10.1.1.128/25$

Automating Hypothesis Testing

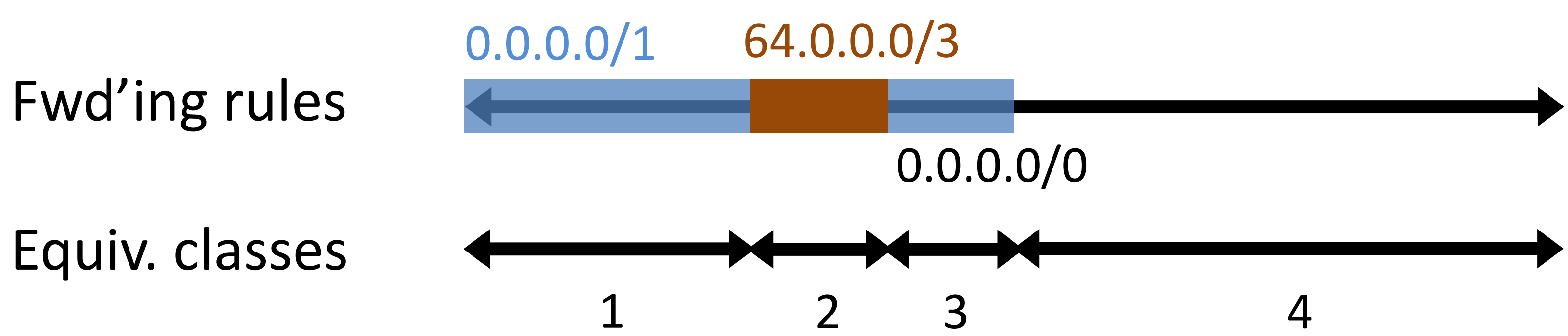
- Could directly extend existing techniques (e.g., SAT solvers)
  - Problem: not very scalable
- Alternative solution: represent and test Boolean functions as graph traversals
- Main idea:
  - Represent network state as a forwarding graph
  - Translate hypothesis tests into graph traversals

Limiting the Search Space

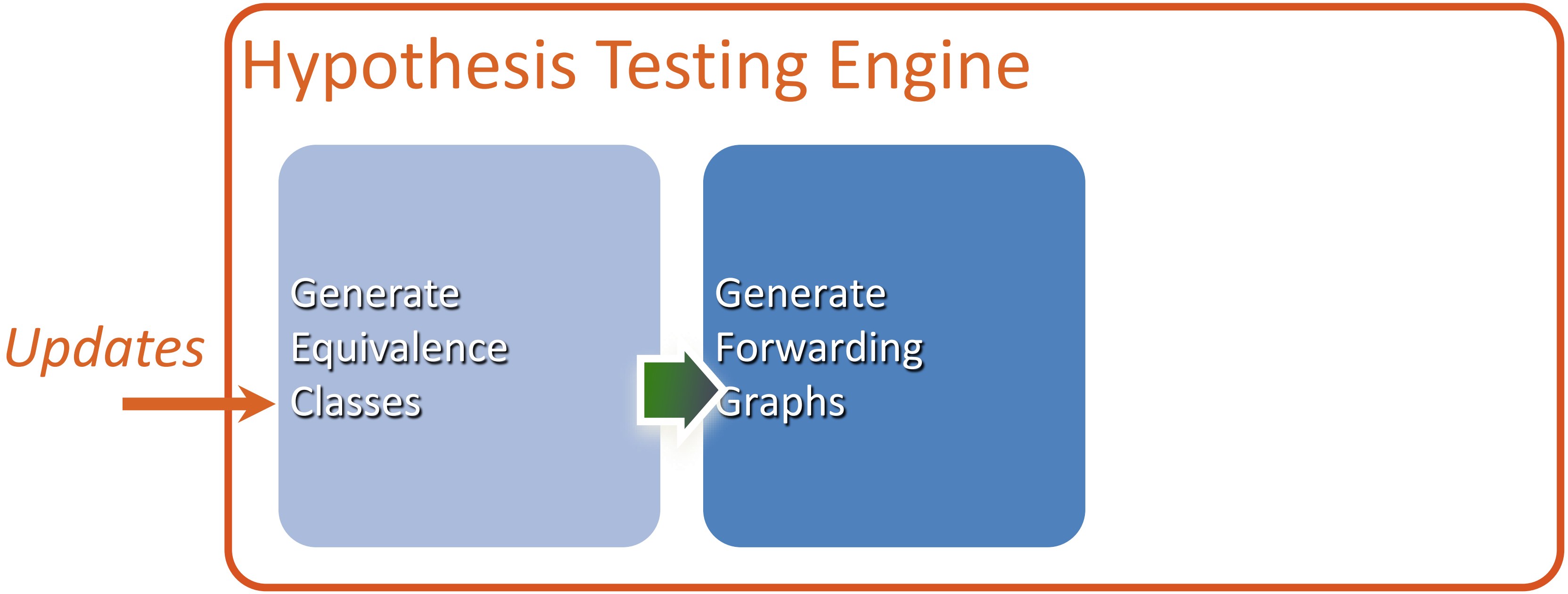
Hypothesis Testing Engine

Updates → Generate Equivalence Classes

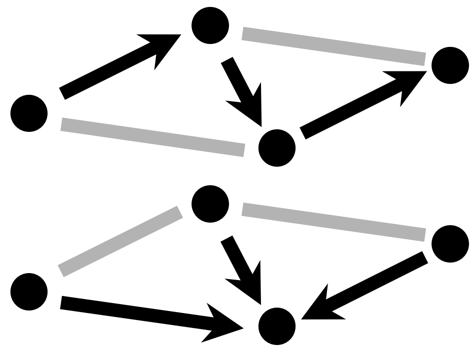
Equivalence class:
Packets experiencing the same forwarding actions throughout the network.



Limiting the Search Space



Forwarding graphs:



All the info to answer hypotheses

Limiting the Search Space

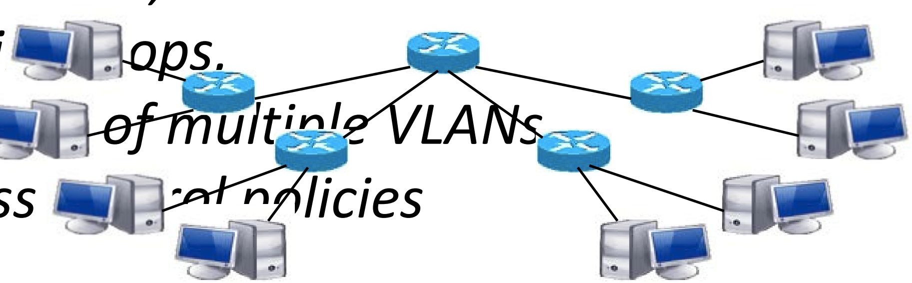
Hypothesis Testing Engine

Updates → Generate Equivalence Classes → Generate Forwarding Graphs → Run Experiments

Correct Hypotheses

Incorrect Hypotheses

Black holes,
Routi … ops,
Isol… of multiple VLANs
Access … rol policies



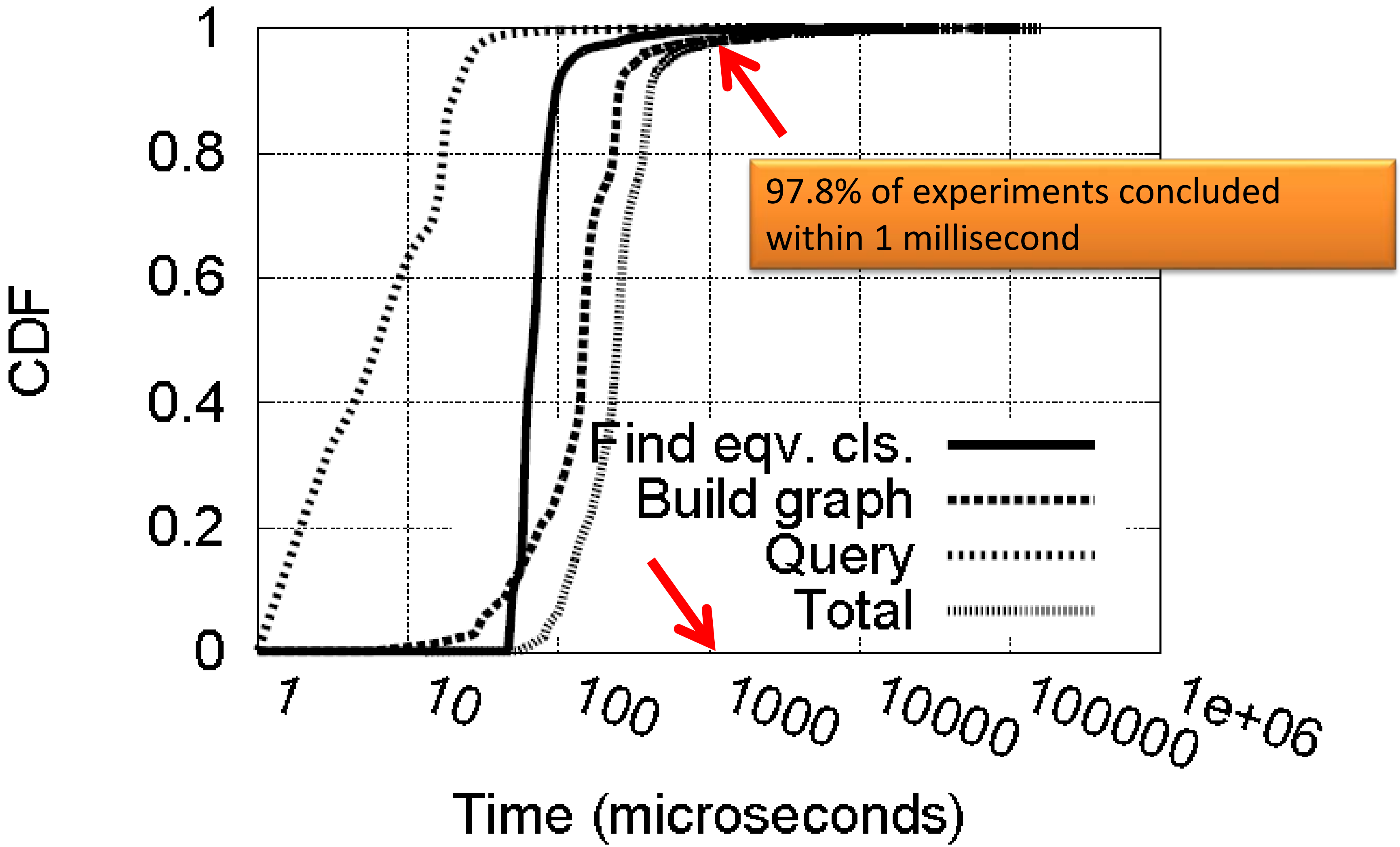
Result report

- Experimental step that violates hypothesis
- Affected set of packets

Evaluation

- Simulated an IP network using a Rocketfuel topology
  - Replayed Route Views BGP traces
  - 172 routers, 90K BGP updates
  - Microbenchmarked each phase of HTE's operation

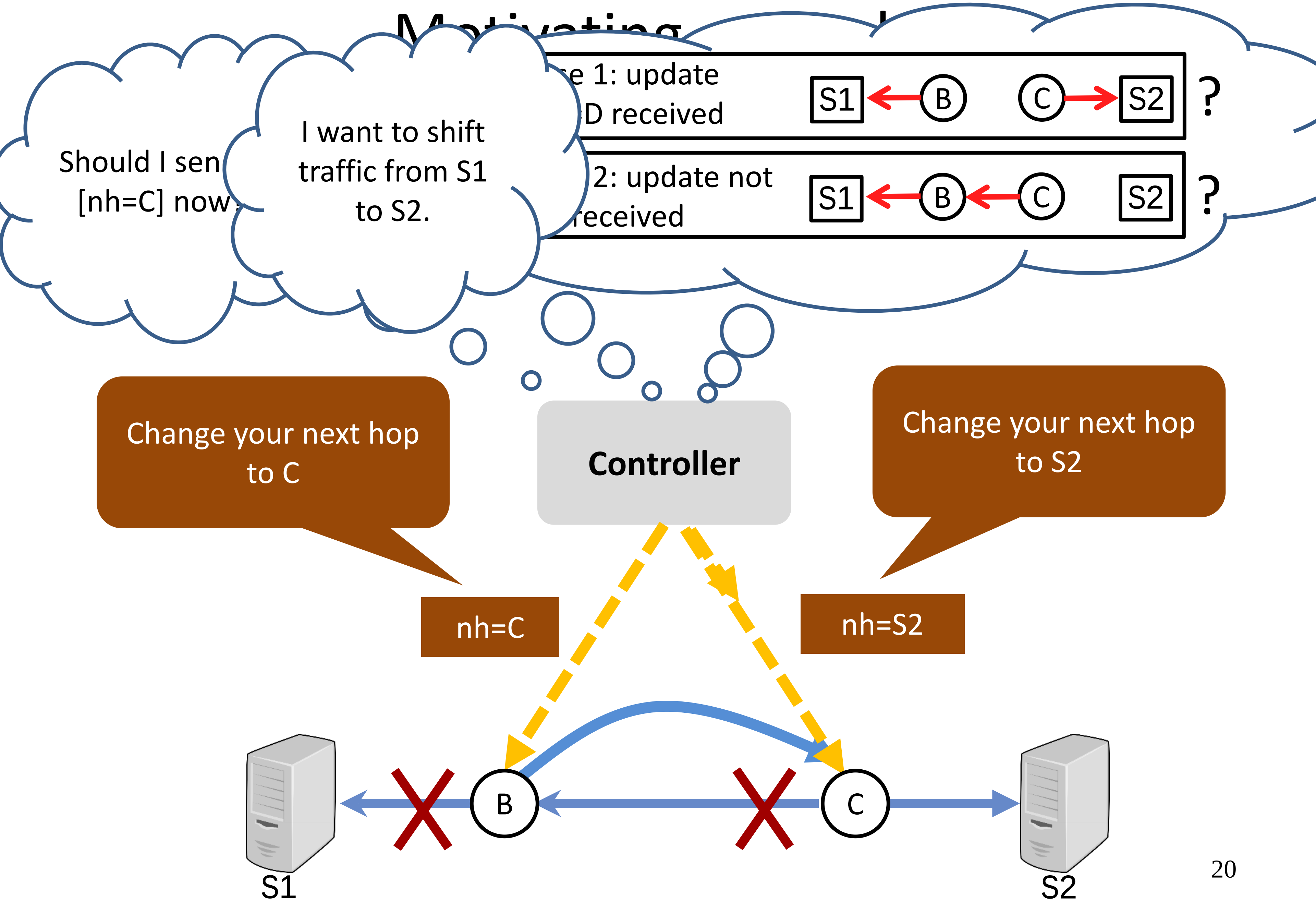
Single-Hypothesis Testing Speed



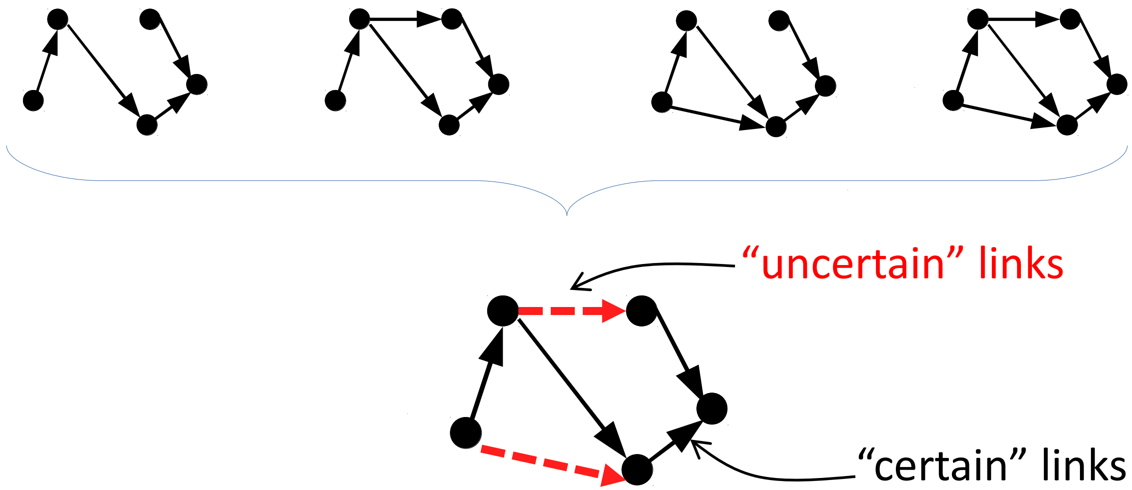
Dealing with System Dynamics

- Challenge: Networks are Dynamic and Nondeterministic
  – May not always know what will happen given an input
  – May not always have up to date state
  – May not be fully deployed

- Solution approach: dealing with “uncertainty”
  – Explicitly model uncertainty in network’s current state

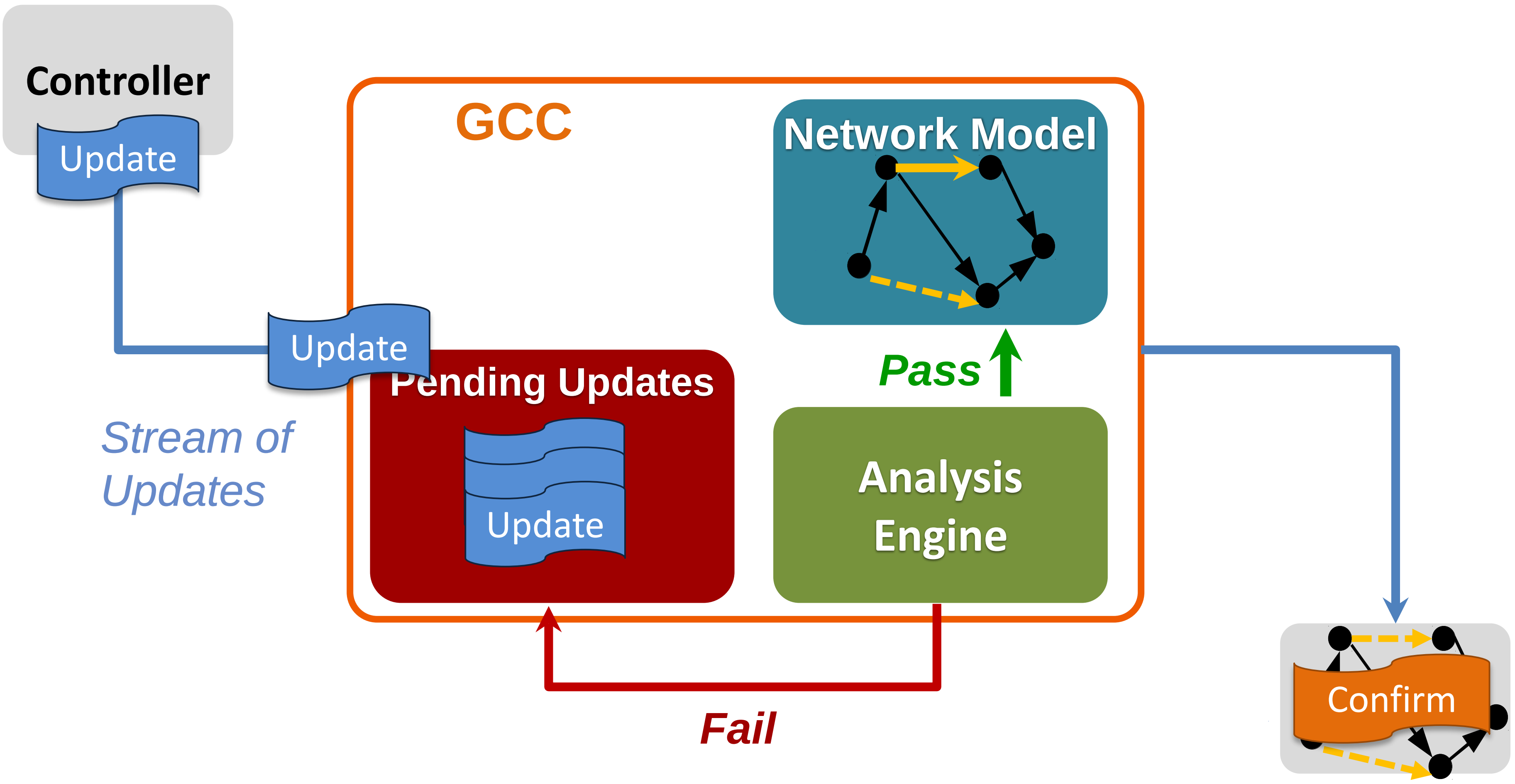

Motivating
e 1: update
D received
S1
B
C
S2
?
2: update not
received
S1
B
C
S2
?
Should I sen
[nh=C] now
I want to shift traffic from S1 to S2.
Controller
Change your next hop to C
Change your next hop to S2
nh=C
nh=S2
B
C
S1
S2

Uncertainty-aware modeling: Approach

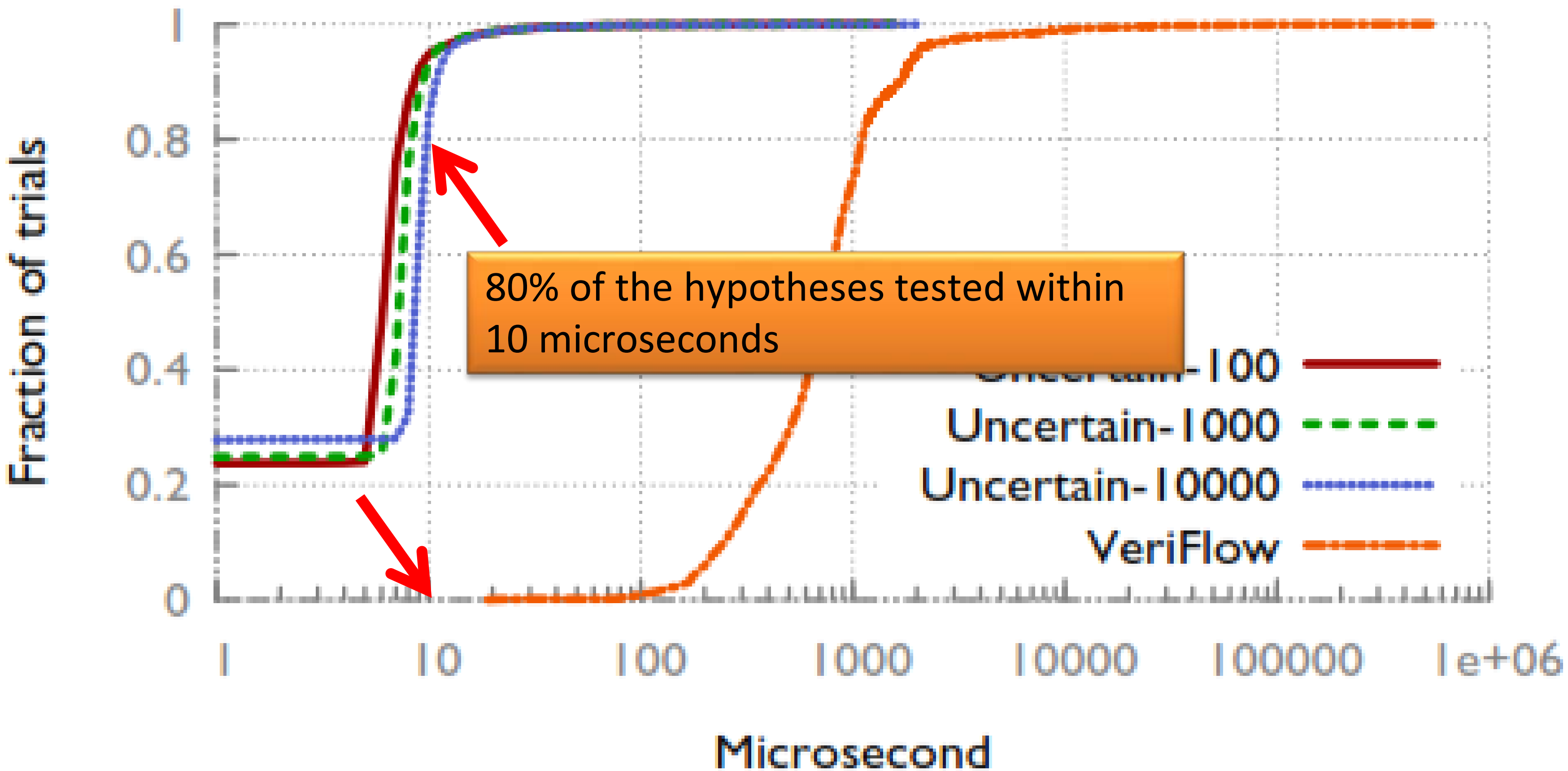


1. Derive possible network states, given inputs
2. Represent possible states using symbolic “uncertainty graph”
3. Traverse graph to test hypotheses
4. Update graph as information comes in
   - Network changes, acks from network, certain delays pass

Technical approach



Hypothesis Testing Time in Dynamic Networks



Conclusion

- We are constructing a hypothesis testing engine for SoS
  - Analysis methodology for reasoning about science of security of networks
  - Adds to theoretical underpinnings of SoS, supports practice of SoS
- Early results indicate feasibility
  - Experiments run in milliseconds on complex networks
- Interested in working with you
  - My contact info: caesar@illinois.edu