Software-Defined Networking:
OpenFlow and Frenetic

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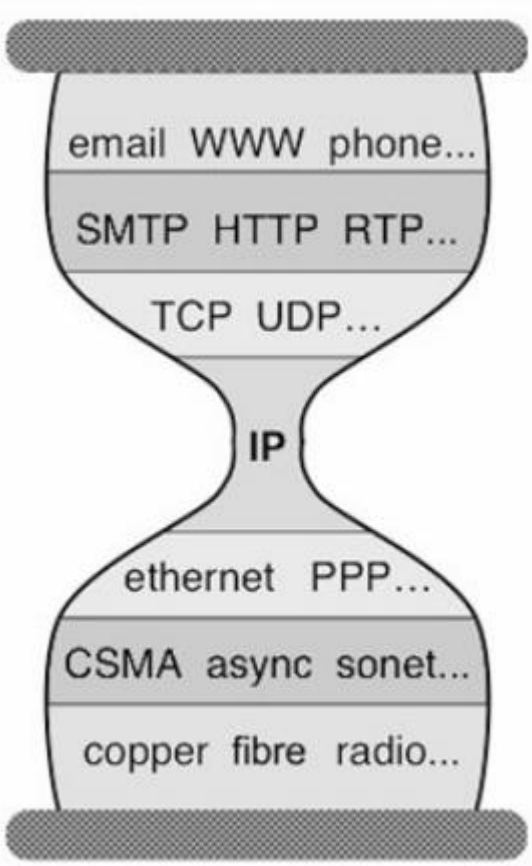
Background

Problem:
Programming Networks is Hard

Network Stack Pros

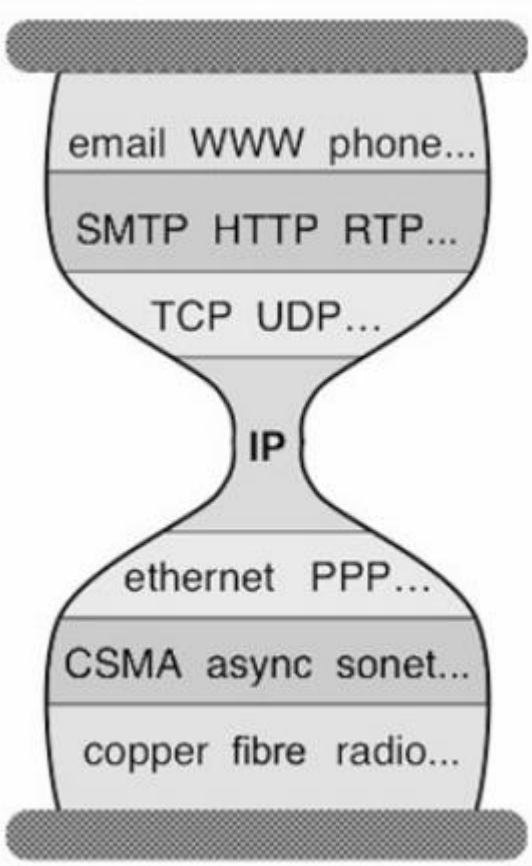
- Key to the success of the Internet
- Layers and layers of abstraction
- Independent innovation at each layer
  - Communication media
  - Ethernet standards
  - Transport layer protocols
- Follows end-to-end argument



(Source: Shenker, 2011)

Network Stack Cons

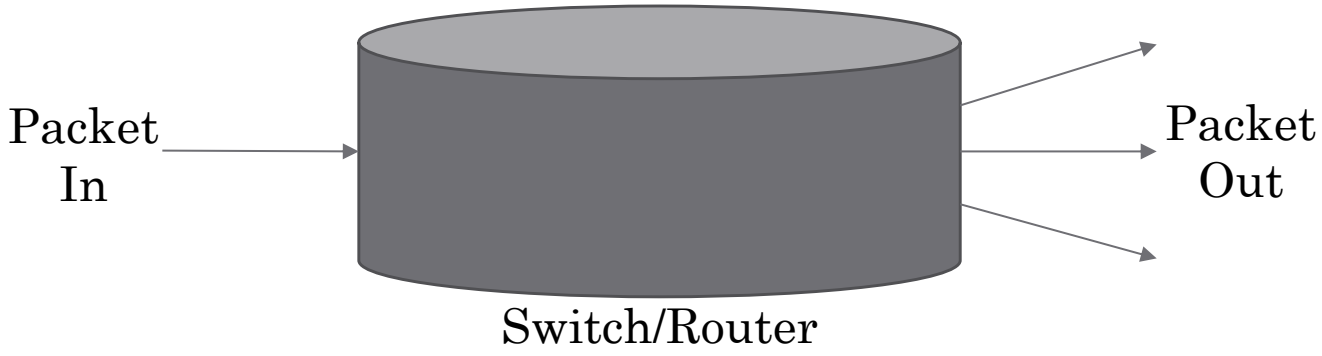
- Network switches and routers built and optimized for internet traffic
- Network components and internet protocols set in stone
  - Difficulty to switch from IPv4 to IPv6
- Difficult to perform research on Internet



Problem:
Network infrastructure has "ossified"

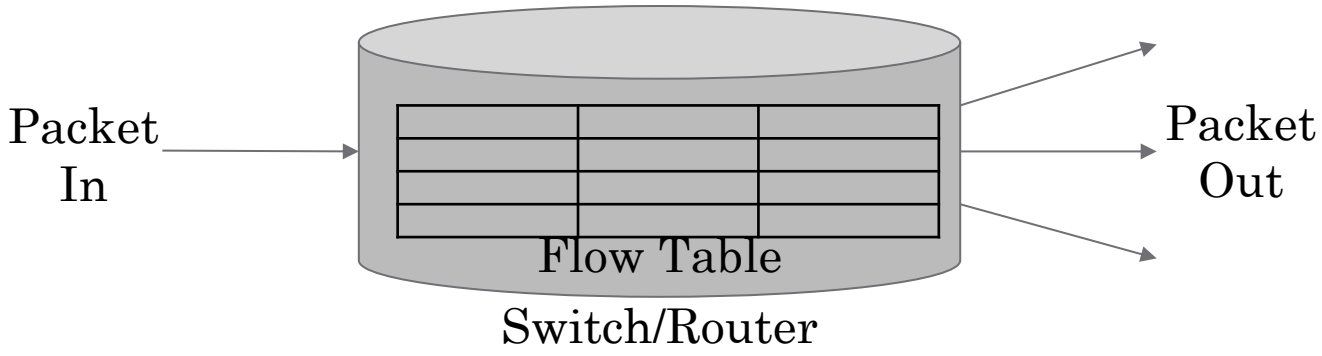
(Source: Shenker, 2011)

Functions of a switch/router



- Receive a packet and send to appropriate destination
- Prevent a packet from reaching a certain destination

Programming a switch/router



- Use a limited API to program the switch/router flow table
- Must program each network device separately
- Programming dependent on topology
- Does not scale

Problem: No generalized API for programming scalable networks

Data Plane vs. Control Plane

Data Plane

- Receive a packet
- Forward packet based on flow table
- Network stack abstractions are data plane abstractions

Control Plane

- Update flow table to specify where packets should go
- Update flow table to specify where packets should not go
- No abstractions for updating the control plane

Programming networks is hard because…

- Network stack is an abstraction for the data plane
- Network infrastructure has "ossified" due to the success of the internet
- Switch and router internals vary by manufacturer and there is no standard API for the control plane
- Without any abstractions for control plane, research and innovation in network programming is near impossible
  - Must compute configuration of each device
  - Can only work with given network-level protocol (i.e. IP)

OpenFlow

Authors

- Nick McKeown
  - ‘95 PhD UC Berkeley
  - Co-founded Nicira Networks, ONF
  - Faculty at Stanford
- Tom Anderson
  - ‘91 PhD Univ. of Wash.
  - UC Berkeley ‘91-’97
  - Faculty at Univ. of Wash.
- Hari Balakrishnan
  - ‘98 PhD UC Berkeley
  - Faculty at MIT
- Guru Parulkar
  - ‘87 PhD Univ. of Deliware
  - Many network-related startups
  - Executive director of Clean Slate Internet Design Program

- Larry Peterson
  - ‘85 PhD Purdue University
  - GENI project chair
  - Faculty at Princeton
- Jennifer Rexford
  - ‘96 PhD Univ. of Mich.
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  - Broader Gateway Protocol
  - Faculty at Princeton
- Scott Shenker
  - ‘83 PhD Univ. of Chig.
  - XEROX Parc
  - Co-founder of Nicira Networks, ONF
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Goals

- Run experiments on campus networks
- Software-based approach
- Low cost

Goals and Challenges

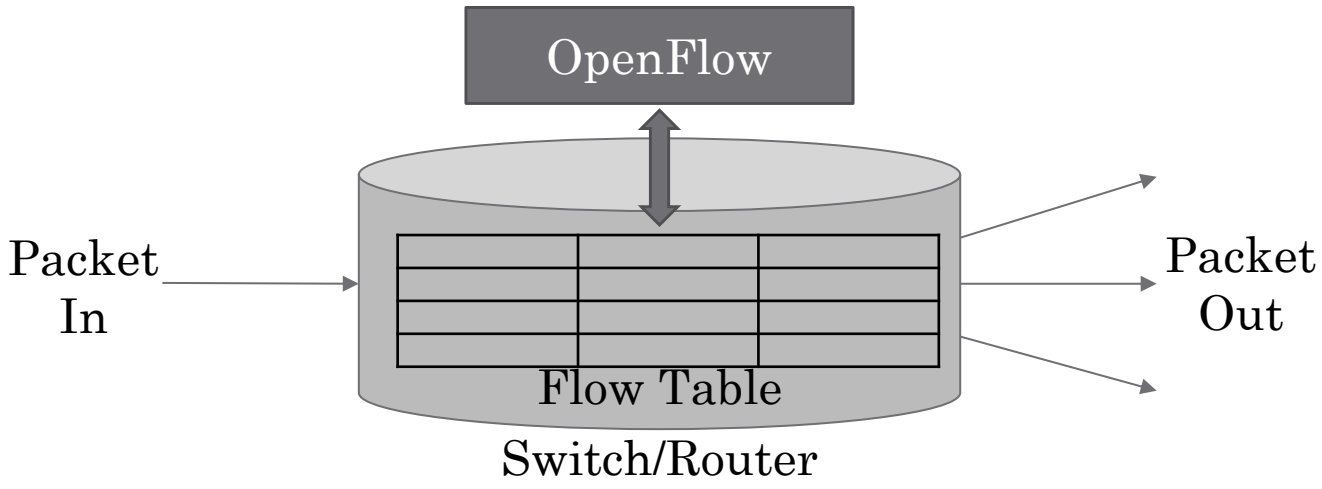
- Run experiments on campus networks
  - Reluctance by admins to using experimental equipment on college network
  - Isolation: Control over network without disruptions to normal traffic
  - What functionality is needed for experiments?
- Software-based approach
  - Software-based solutions have low performance
  - Software-based solutions support low port density
- Low cost
  - Take advantage of existing infrastructure
  - Closed platforms from vendors

Take Aways

- OpenFlow allows network devices to decouple the data plane from the control plane
- Data plane processing done by network device
- Data plane abstraction is the network stack
- Control plane processing done by controller
- New control stack for OpenFlow devices provides standardized API and abstractions necessary to innovate in field of network management

Design

- Separate data plane from control plane
- Data plane
  - High performance forwarding
- Control plane
  - Flow table is programmable
  - Accessed through controller using OpenFlow Protocol



OpenFlow API

- Forward packets to given port (or ports)
- Forward packets to controller
  - Usage: Can analyze and process packets
- Drop the packet
  - Usage: Protect against attacks by removing suspicious packets

Flow Table Entry

- Packet header to define flow
- Action to be performed
- Statistics

OpenFlow-enabled Network Device

Flow Table comparable to an instruction set

MAC src	MAC dst	IP Src	IP Dst	TCP dport	...	Action	Count
*	10:20:.	*	*	*	*	port 1	250
*	*	*	5.6.7.8	*	*	port 2	300
*	*	*	*	25	*	drop	892
*	*	*	192.*	*	*	local	120
*	*	*	*	*	*	controller	11

(Source: ONF, 2012)

Isolation

Two Options:

- Add another action to the OpenFlow API
  - Forward packets through normal pipeline

OR

- Define separate VLANs
  - No overlap over production and experimental traffic

Discussion

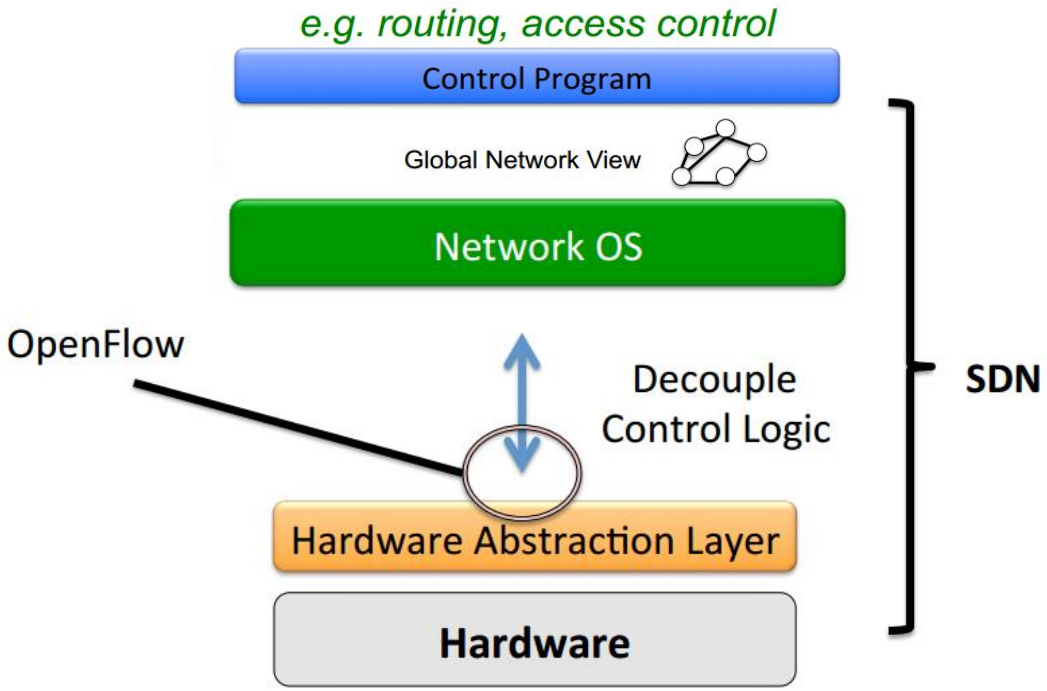
- What is easy to accomplish with the OpenFlow solution?

- What is still hard to do with OpenFlow?

Controllers

- Must communicate using OpenFlow protocol
- Individual controllers for multiple switches or single controller for all switches
- Use with Network OS
  - NOX
- Should provide some permissions to prevent mixing of traffic or unauthorized flow table changes
- Implementation details left unspecified

Control Stack



- OpenFlow is only a means to achieve the decoupling needed for Software-Defined Networking
- Network OS provides common control functionality that can be used by multiple applications

(Sources: Casado, 2011; Shenker, 2011)

Discussion

- What functionality should the Network OS have?

- What layers or abstractions are missing from the control stack?

Google B4

- Provides connectivity among Google datacenters
- Use SDN and OpenFlow
- Centralized traffic engineering application
  - Resource contention
  - Multipath forwarding/tunneling to leverage network capacity according to application priority
  - Dynamically relocate bandwidth
- Many links run at near 100% utilization for extended periods of time

(Source: Jain, 2013)

Open Network Foundation

- Promote adoption of Sotware-Defined Networking through open standards such as OpenFlow
- Partners:

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Frenetic

Authors

- Nate Foster
  - ‘09 PhD Upenn
  - Faculty at Cornell

- Rob Harrison
  - ‘11 Masters Princeton
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- Matthew L. Meola
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- Michael J. Freedman
  - PhD NYU
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  - Faculty at Princeton

- Jennifer Rexford
  - ‘96 PhD Univ. of Mich.
  - AT&T Labs ‘96-’05
  - Broader Gateway Protocol
  - Faculty at Princeton

- David Walker
  - ‘01 PhD Cornell (Morrisett)
  - Faculty at Princeton

Problems

- OpenFlow is a "machine language"
  - Directly reflects underlying hardware
  - High level policy may require multiple low-level rules
- Network programs are not isolated from each other
  - No equivalent of virtual memory space
  - Composition of programs is a manual process and error prone
- Controller does not see all traffic, so some information may be hidden
  - Delay in programming switches and routers
  - Must take care of additional corner cases

Hard to effectively program OpenFlow tables using NOX

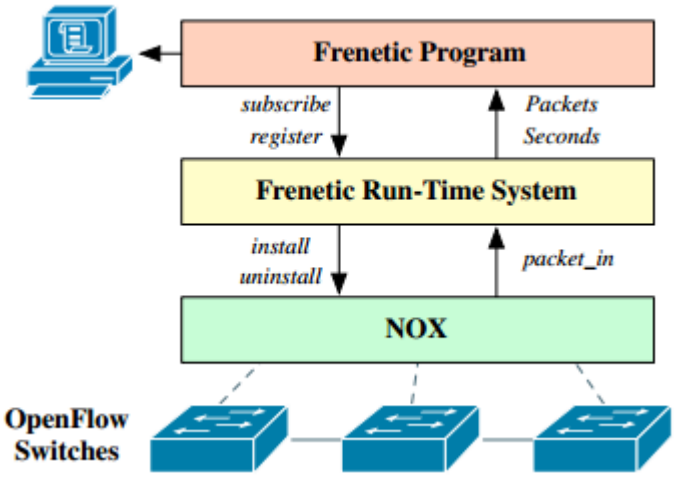
Take Aways

- OpenFlow is the "machine language" of network programming
  - Difficult to program correctly and efficiently
  - Not enough layers of abstraction for programmers

- Frenetic addresses issues with composibility, low-level interaction, and providing a unified view through the Frenetic run-time system and Frenetic programming language

Approach

- Add a layer of abstraction
  - Run-time system converts between high-level program to correct low-level network rules
- Frenetic programming language based on functional reactive programming (FRP)
  - "See every packet" abstraction
  - Composition
  - Rich pattern algebra



(Source: Foster, 2010)

Example w/o Frenetic

```
def repeater(switch):
    p1 = {IN_PORT:1}
    p2 = {IN_PORT:2}
    a1 = [output(2)]
    a2 = [output(1)]
    install(switch, p1, a1, DEFAULT)
    install(switch, p2, a2, DEFAULT)


def monitor(switch):
    p = {IN_PORT:2,TP_SRC:80}
    install(switch, p, [], DEFAULT)
    query_stats(switch, p)
```

```
def repeater_monitor(switch):
    p1 = {IN_PORT:1}
    p2 = {IN_PORT:2}
    p2web = {IN_PORT:2,TP_SRC:80}
    a1 = [output(2)]
    a2 = [output(1)]
    install(switch, p1, a1, DEFAULT)
    install(switch, p2, a2, DEFAULT)
    install(switch, p2web, a2, HIGH)
    query_stats(switch, p2web)
```

Example w/ Frenetic

```
def monitor_sf():
    return(Filter(inport_p(2) & srcport_p(80)) |o|
    GroupByTime(30) |o|
    SumSizes())


rules = [Rule(inport_p(1), [output(2)]),
         Rule(inport_p(2), [output(1)])]

def repeater_monitor():
    register_static(rules)
    stats = Apply(Packets(), monitor_sf())
    print_stream(stats)
```

Discussion

- Are there any issues with OpenFlow that Frenetic could not address?
- How does Frenetic reinforce the idea that innovation in this field will come through abstractions and layering?
- Does Frenetic or OpenFlow help address the issue of "ossification" of the internet?

Take Aways

- OpenFlow is the “machine language” of network programming
  - Difficult to program correctly and efficiently
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- Frenetic addresses issues with composibility, low-level interaction, and providing a unified view through the Frenetic run-time system and Frenetic programming language

References

- OpenFlow: Enabling innovation in campus networks. Nick McKeown et al. (2008-04). ACM Communications Review.
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