EECS 489
Computer Networks

Software Defined Networking

Agenda

- Software-defined networking
- Programmable networks

The field of networking

- CS networking today is largely the study of the Internet
  - Perhaps the only history class many will take in CS

Building an artifact, not a discipline

- Other fields in “systems”: OS, DB, etc.
  - Teach basic principles
  - Are easily managed
  - Continue to evolve
- Networking:
  - Teach big bag of protocols
  - Notoriously difficult to manage
  - Evolves very slowly
- Networks are much more primitive and less understood than other computer systems

A tale of two planes

- **Data plane**: forwarding packets
  - Based on local forwarding state
- **Control plane**: computing that forwarding state
  - Involves coordination with rest of system

Original goals for the control plane

- **Basic connectivity**: route packets to destination
  - Local state computed by routing protocols
  - Globally distributed algorithms
- **Inter-domain policy**: find policy-compliant paths
  - Done by globally distributed BGP
- What other goals are there in running a network?

Extended roles of the control plane

- Performs various network management tasks
  - For example,
    - Where to route?
    - How much to route?
    - At what rate to route?
    - Should we route at all?
    - …

Bottom line

- Many different control plane mechanisms
- Each designed from scratch for their intended goal
- Encompassing a wide variety of implementations
  - Distributed, manual, centralized,…
- None of them particularly well designed
- Network control plane is a complicated mess!

“The Power of Abstraction”

- “Modularity based on abstraction is the way things get done”
  - Barbara Liskov
- Abstractions → Interfaces → Modularity

Analogy: Mainframe to PC evolution

- Vertical integration, closed
- Specialized application
- Specialized operating system
- Specialized hardware

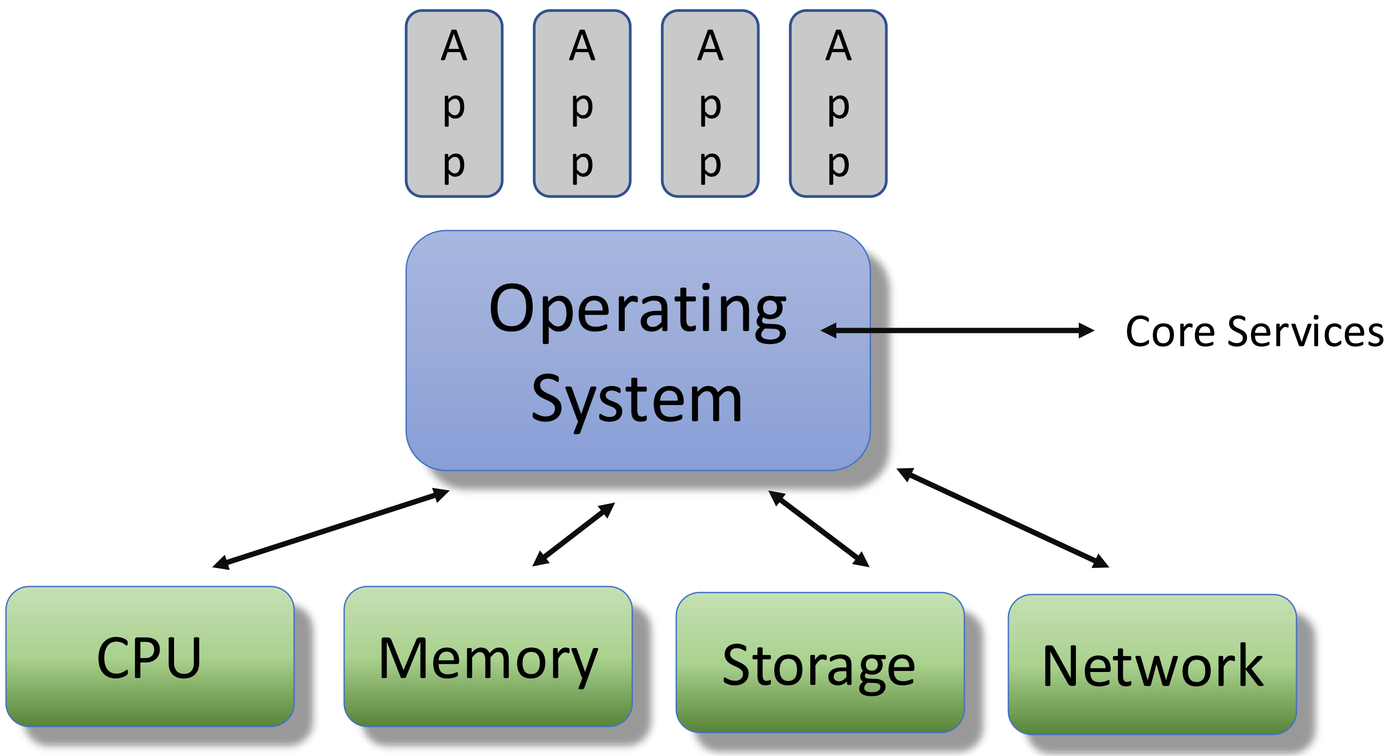
- Open interfaces
- Arbitrary applications
- Commodity operating systems
- Microprocessor

We want the same for networking!

Many control plane mechanisms

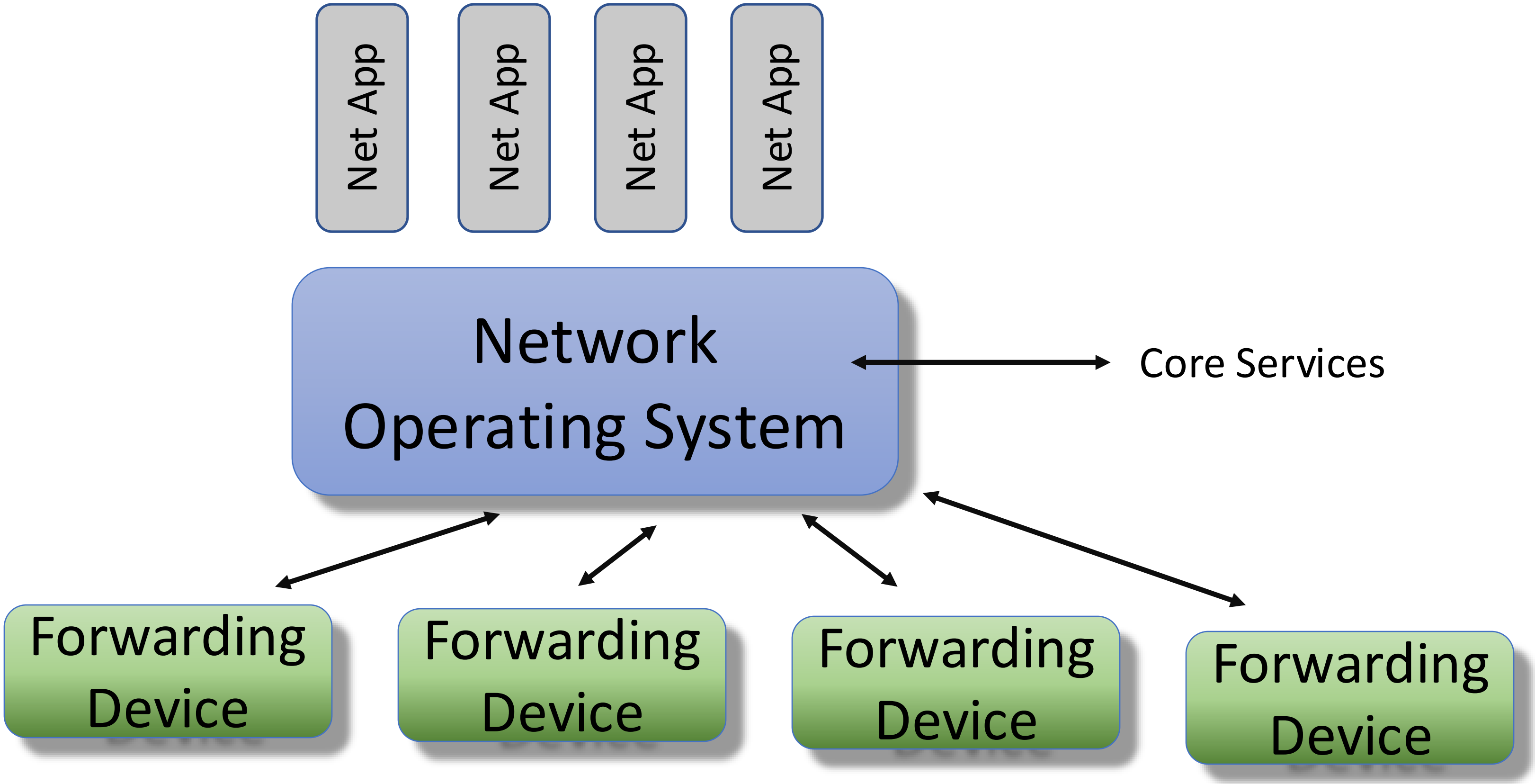
- Variety of goals, no modularity
  - Routing: distributed routing algorithms
  - Isolation: ACLs, Firewalls,…
  - Traffic engineering: adjusting weights,…
- Control Plane: mechanism without abstraction
  - Too many mechanisms, not enough functionality

OS analogy

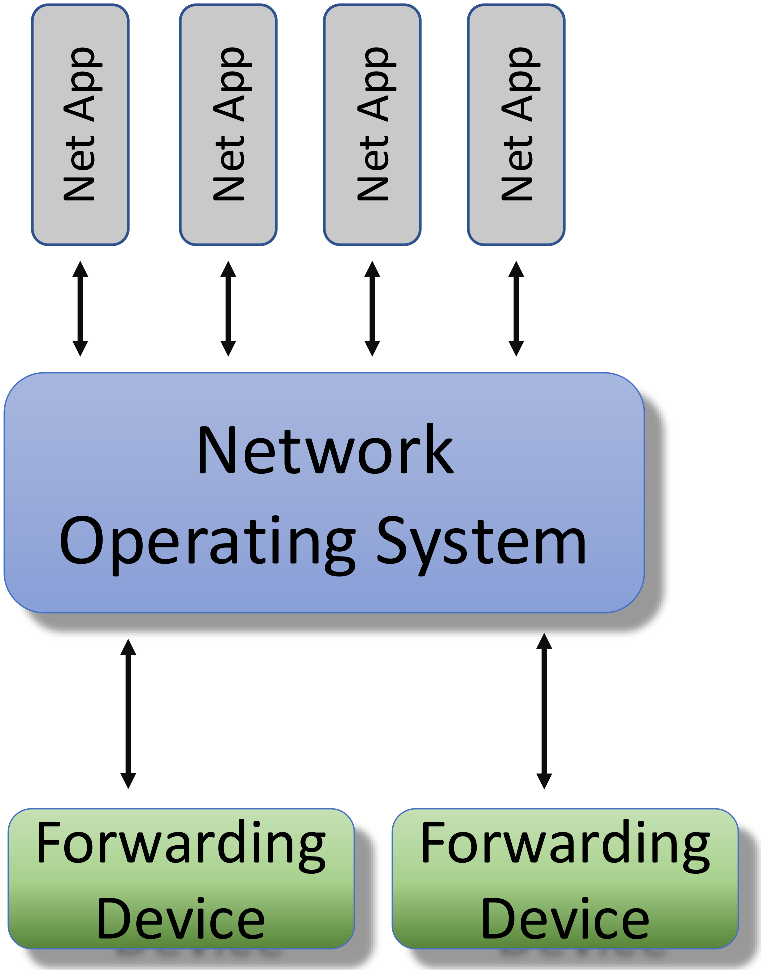


App
App
App
App
Operating System
Core Services
CPU
Memory
Storage
Network

Software Defined Networking



Software Defined Networking



Application Interfaces
- Java API
- Northbound (e.g. RESTConf)

SDN Controller/Control Plane
- Topology Service
- Inventory Service
- Statistics Service
- Host Tracking

SouthBound Interface
- OpenFlow
- OVSDB
- NETCONF
- SNMP

Forwarding Devices/
Data Plane

Task: Compute forwarding state

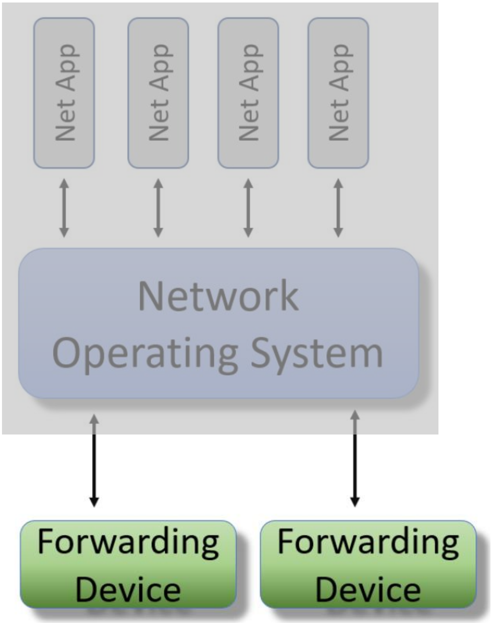
- Consistent with low-level hardware/software
  - Which might depend on vendor
- Based on entire network topology
  - Because many control decisions depend on topology
- For all routers/switches in network
  - Every router/switch needs forwarding state

Separate concerns with abstractions

- Be compatible with low-level hardware/software
  - Forwarding abstraction
- Make decisions based on entire network
  - Network state abstraction
- Compute configuration of each physical device
  - Specification abstraction

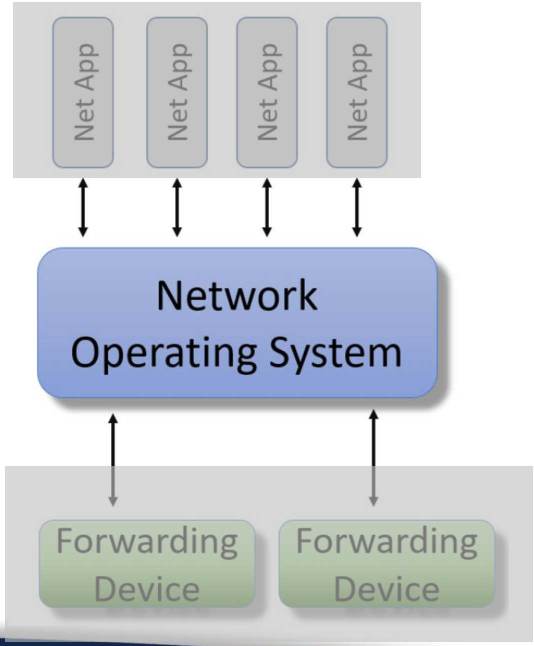
#1: Forwarding abstraction

- Express intent independent of implementation
  - Don’t want to deal with proprietary HW and SW
- Design details concern exact nature of:
  - Header matching
  - Allowed actions



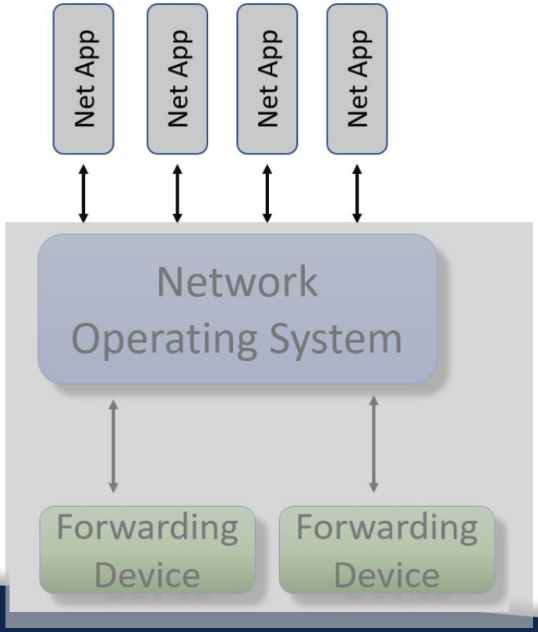
#2: Network state abstraction

- Abstraction: global network view
  - Annotated network graph provided through an API
- Creates a logically centralized view of the network (Network Operating System)
  - Runs on replicated servers in network (“controllers”)
- Information flows both ways
  - Information *from* routers/switches to form “view”
  - Configurations *to* routers/switches to control forwarding



#3: Specification abstraction

- Control mechanism expresses desired behavior
  - Whether it be isolation, access control, or QoS
- It should not be responsible for implementing that behavior on physical network infrastructure
  - Requires configuring the forwarding tables in each switch
- Abstract view of network
  - Models only enough detail to specify goals
  - Will depend on task semantics



Each goal is an app via specification abstraction

- What if an operator wants X?
- What if a customer wants to do weighted traffic splitting?
- …

- There is an app for it!
  - Write your own routing protocol, load balancing algorithm, access control policies

Reason about each app via network state abstraction

- Now that the network is not distributed anymore and is a simple graph, we can verify whatever the correctness of whatever we specified

Logically centralized control plane

- A distinct (typically remote) controller interacts with local control agents (CAs)
- Each router contains a flow table
- Each entry of the flow table defines a match-action rule
- Entries of the flow table is computed and distributed by the (logically) centralized controller

SDN: Many challenges remain

- Hardening the control plane: dependable, reliable, performance-scalable, secure distributed system
  - Robustness to failures: leverage strong theory of reliable distributed system for control plane
  - Dependability, security: “baked in” from day one?
- Networks, protocols meeting mission-specific requirements
  - E.g., real-time, ultra-reliable, ultra-secure
- Internet-scaling

Some progress in the wide-area network (WAN)

- Google and Microsoft use SDN to manage traffic between datacenters
- One centralized controller to rule the entire world (well, their world)

5-minute break!

A tale of two planes

- **Data plane**: forwarding packets
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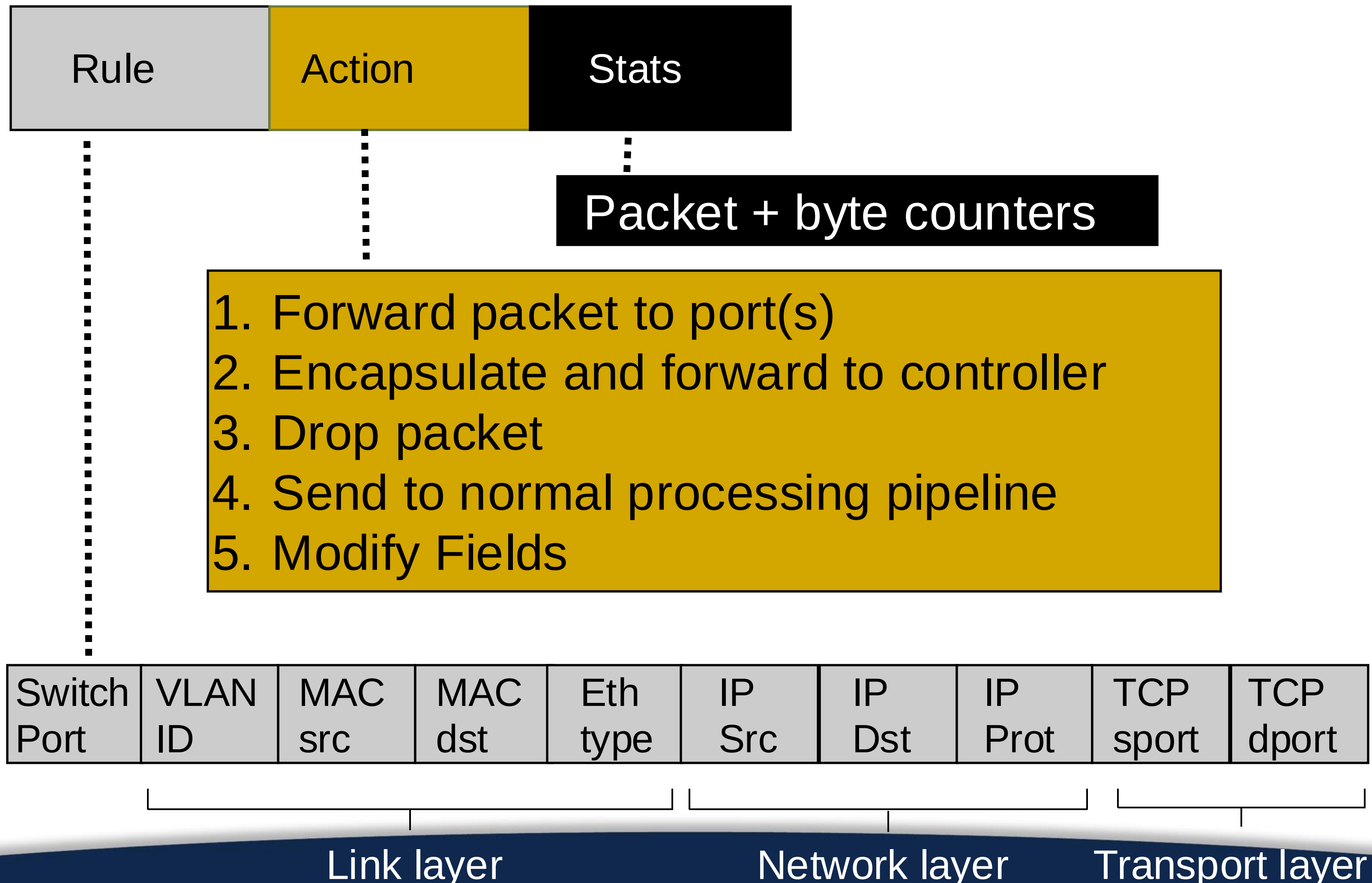
OpenFlow data plane abstraction

- Flow is defined by header fields
- Generalized forwarding: simple packet-handling rules
  - Pattern: match values in packet header fields
  - Actions: for matched packet: drop, forward, modify, matched packet or send matched packet to controller
  - Priority: disambiguate overlapping patterns
  - Counters: #bytes and #packets

1. src=1.2.*.*, dest=3.4.5.* → drop
2. src = *.*.*.*, dest=3.4.*.* → forward(2)
3. src=10.1.2.3, dest=*.*.*.* → send to controller

OpenFlow: Flow table entries



Forwarding abstraction

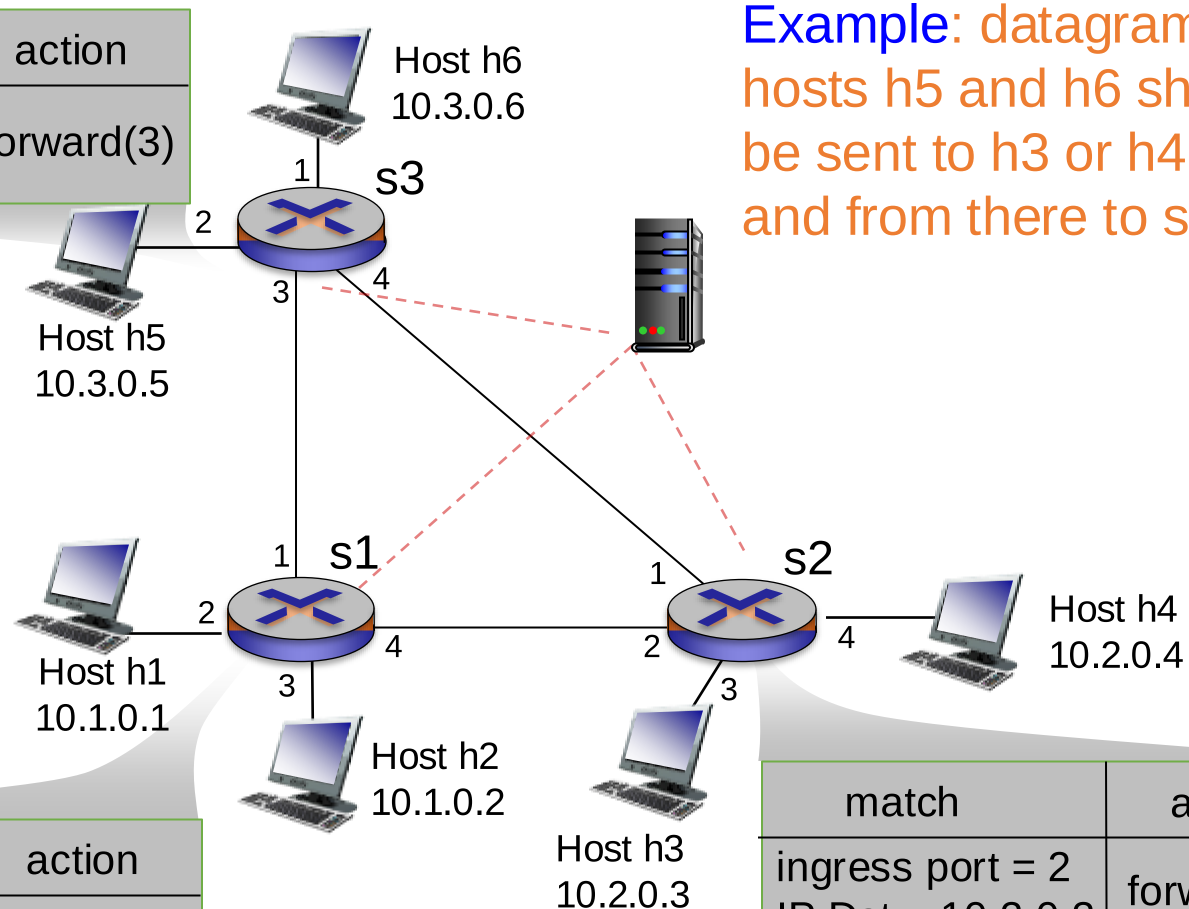
Match + Action: unifies different kinds of devices

- Router
  - Match: longest destination IP prefix
  - Action: forward out a link
- Switch
  - Match: destination MAC address
  - Action: forward or flood
- Firewall
  - Match: IP addresses and TCP/UDP port numbers
  - Action: permit or deny
- NAT
  - Match: IP address and port
  - Action: rewrite address and port

OpenFlow example

Example: datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2

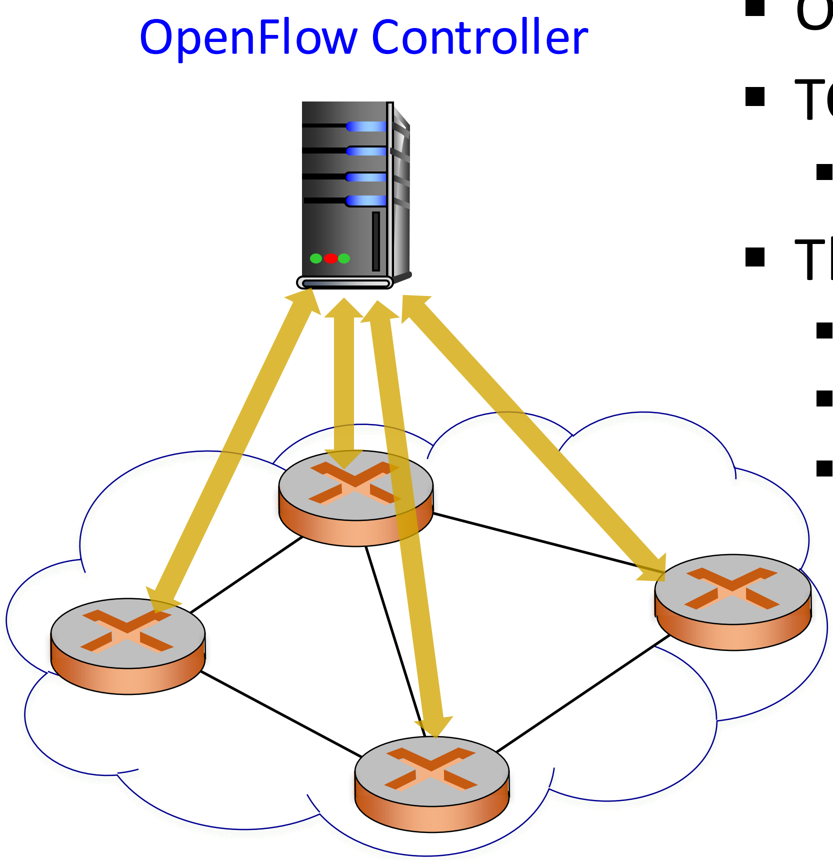
match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



match	action
ingress port = 1 IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(4)

match	action
ingress port = 2 IP Dst = 10.2.0.3	forward(3)
ingress port = 2 IP Dst = 10.2.0.4	forward(4)

OpenFlow protocol



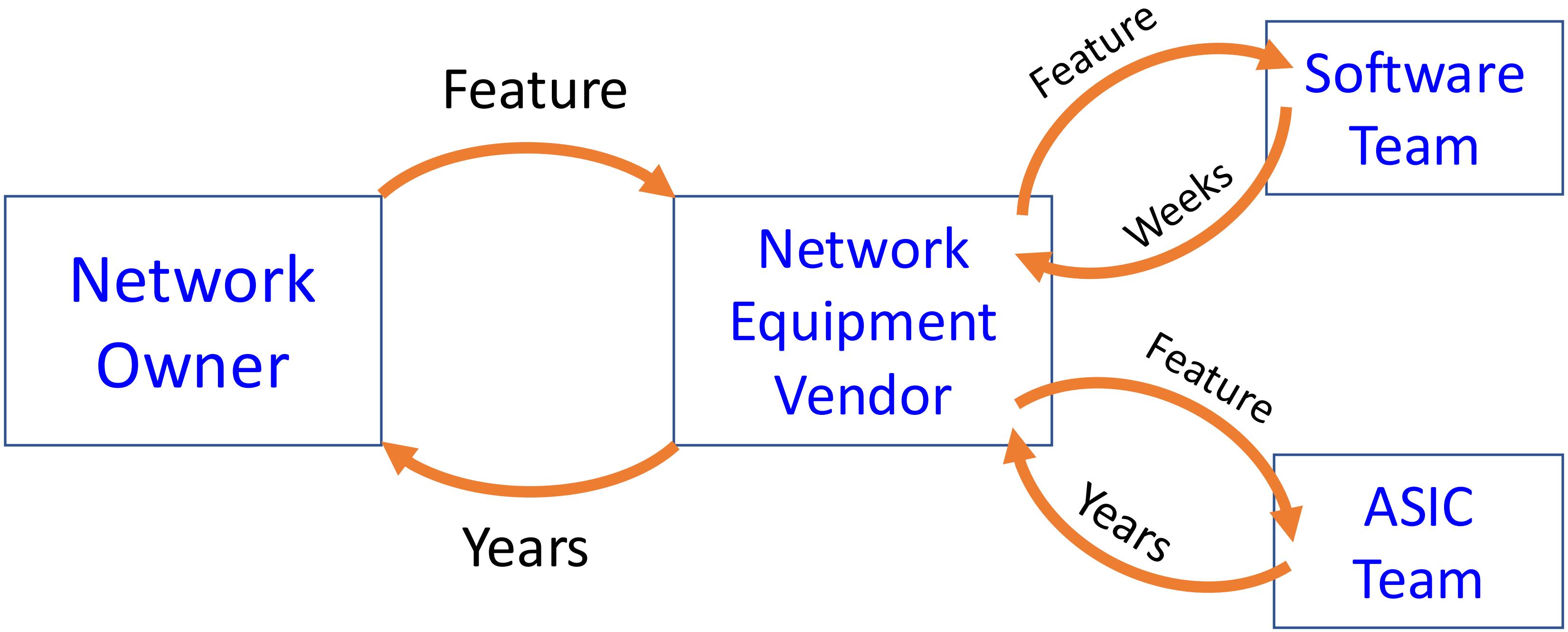
- Operates between controller, switch
- TCP used to exchange messages
  - Optional encryption
- Three classes of OpenFlow messages:
  - Controller-to-switch
  - Asynchronous (switch to controller)
  - Symmetric (misc.)

Fixed-function data plane

- Traditional switches are fixed-function
  - They can do whatever they can do at birth, but they cannot change!
  - Bottom-up design

- Even OpenFlow was designed to be a fixed protocol
  - With a fixed table format
  - Capable of doing limited things

Takes forever to get a feature



Programmable data plane

- What if we could tell switches exactly what we want?
  - What table to keep?
  - What rules to use?
  - What data to keep track of?
  - …

Top-down approach

- Precisely specify what you want to do and how you want a packet to be processed

```
table int_table {
  reads {
    ip.protocol
  }
  actions {
    export_queue_latency
  }
}
```

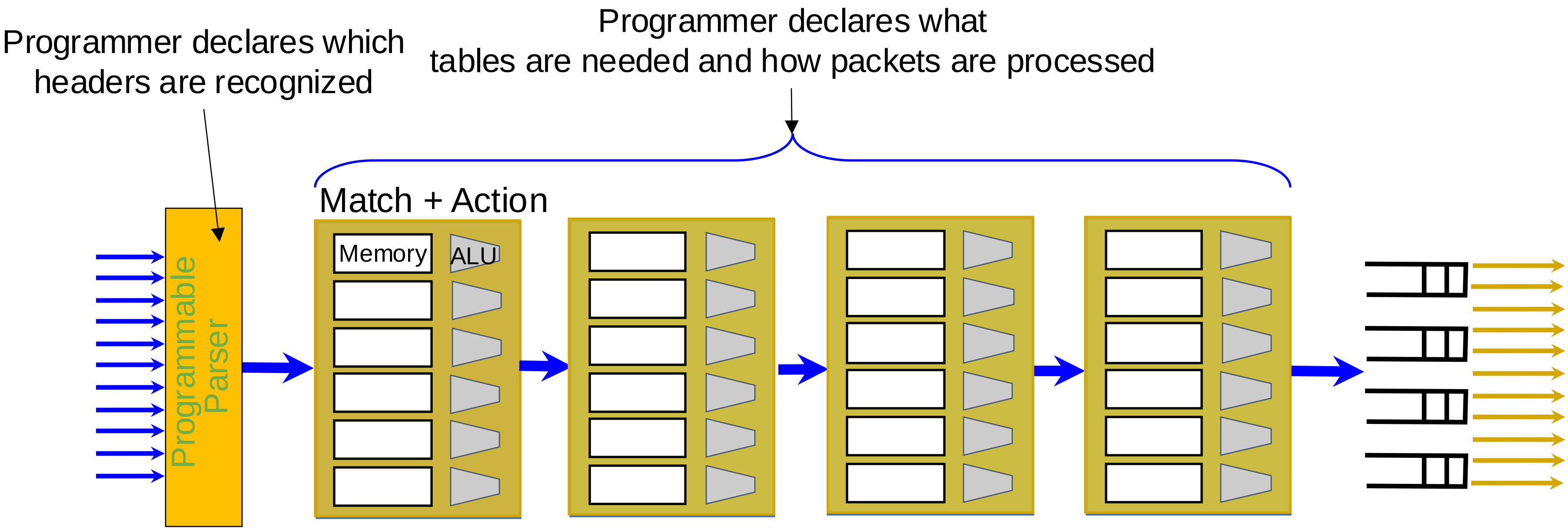
```
action export_queue_latency (sw_id) {
  add_header(int_header);
  modify_field(int_header.kind, TCP_OPTION_INT);
  modify_field(int_header.len, TCP_OPTION_INT_LEN);
  modify_field(int_header.sw_id, sw_id);
  modify_field(int_header.q_latency,
                    intrinsic_metadata.deq_timedelta);
  add_to_field(tcp.dataOffset, 2);
  add_to_field(ipv4.totalLen, 8);
  subtract_from_field(ingress_metadata.tcpLength, 12);
}
```

What's left?

- Compile it down to be something runnable on a programmable switch
  - Similar to other high-level languages we use to run code on hardware like CPU, GPU, FPGA etc.
  - P4 for programmable switches

- But which switch?

PISA: Protocol Independent Switch Architecture



All stages are identical – makes PISA a good "compiler target"

How’s programmability used today?

- Remove features to reduce complexity
- Add proprietary features
- Silicon independence or avoid vendor lock-in
- Telemetry and measurements

Example: In-band network telemetry (INT)

- “Which path did my packet take?”
- “Which rules did my packet follow?”
- “How long did it queue at each switch?”
- “Who did it share the queues with?”

Why now?

- One of the earlier incarnation of programmable networks was in mid 90s
  - Active networks

- What's changed after two+ decades?
  - **Hardware:** We can now make programmable switches as fast as fixed ones
  - **Software:** We have found a (so far) reasonable balance between programmability, performance, and security

Lecture Quiz : SDN

- https://forms.gle/JjwBSRWm1bYAV8oB8

Summary

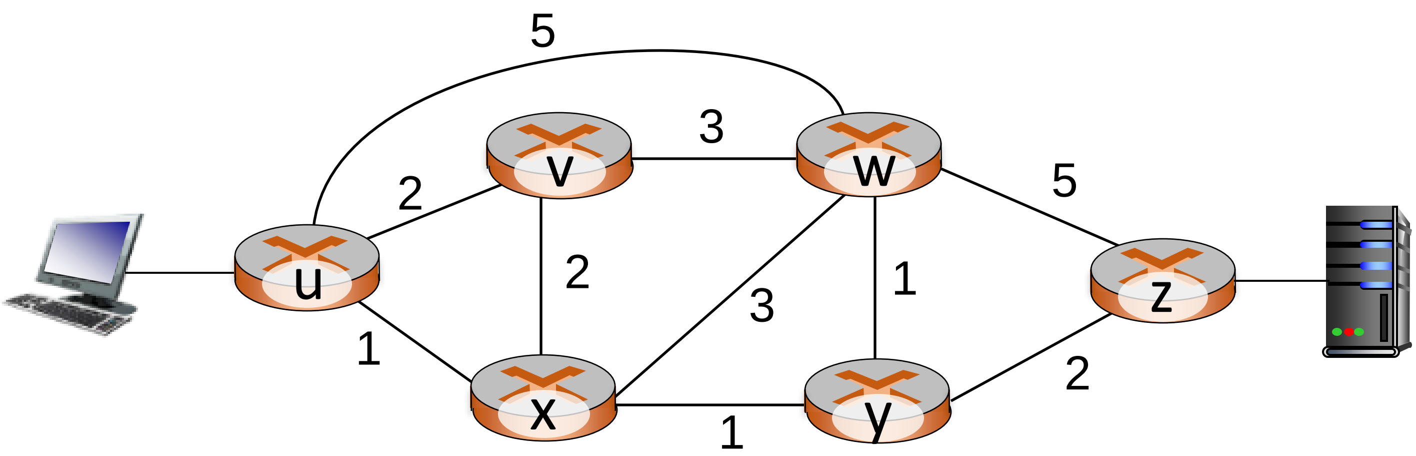
- Abstractions beget modularity
  - Modularity is (almost always) good
- Programmability is powerful
  - Finding the right balance is hard

- Next lecture: Wireless Networks

Traffic engineering

- Want to avoid persistent overloads on links
- Choose routes to spread traffic load across links

Traffic engineering: Difficult

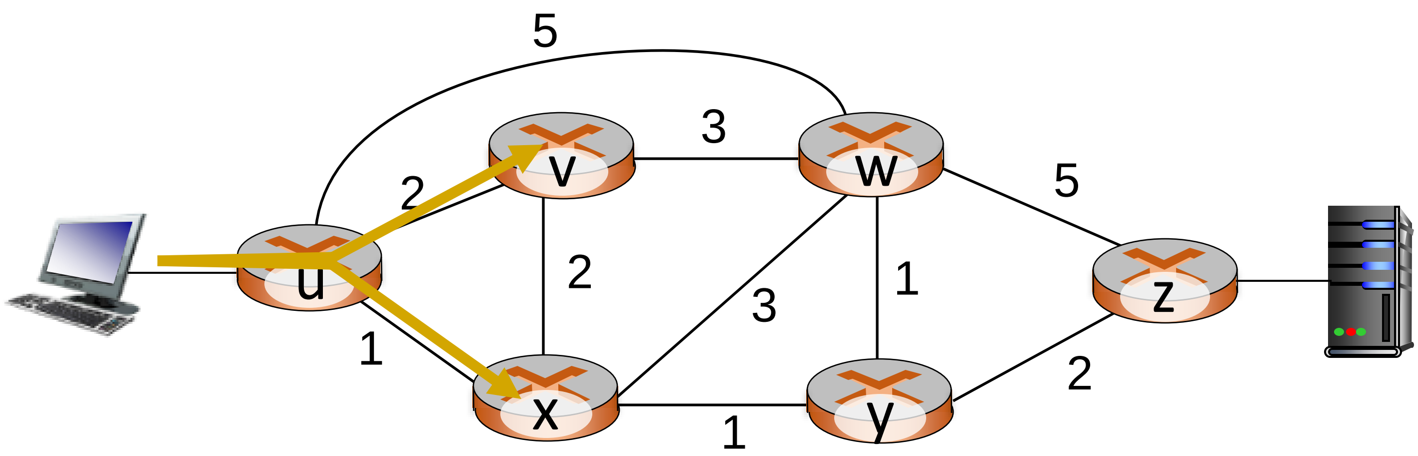


Q: What if network operator wants u-to-z traffic to flow along uvwz, x-to-z traffic to flow xwyz?

A: Need to define link weights so traffic routing algorithm computes routes accordingly (or need a new routing algorithm)!

Link weights are only control "knobs"

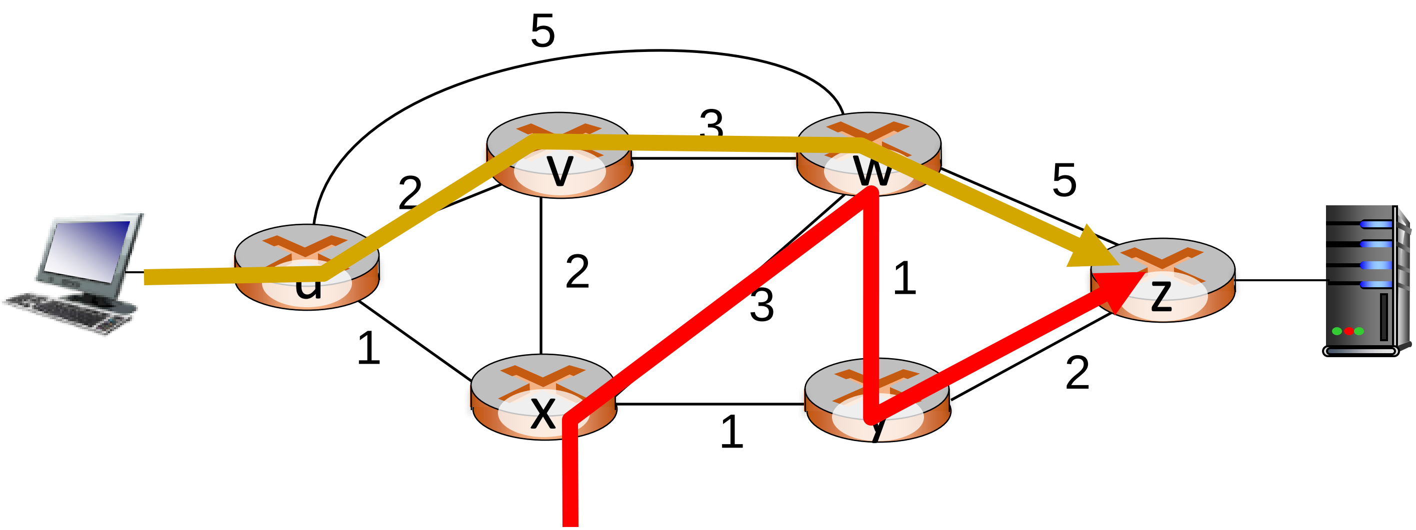
Traffic engineering: Difficult



Q: What if network operator wants to split u-to-z traffic along uvwz and uxyz (load balancing)?

A: Can’t do it (or need a new routing algorithm)

Traffic engineering: Difficult



Q: What if w wants to route the two flows differently?

A: Can't do it (with LS or DV)

OpenFlow: Controller-to-switch messages

- Key controller-to-switch messages
  - Features: controller queries switch features, switch replies
  - Configure: controller queries/sets switch configuration parameters
  - Modify-state: add, delete, modify flow entries in the OpenFlow tables
  - Packet-out: controller can send this packet out of specific switch port

OpenFlow: Switch-to-controller messages

- Key switch-to-controller messages
  - Packet-in: transfer packet (and its control) to controller. See packet-out message from controller
  - Flow-removed: flow table entry deleted at switch
  - Port status: inform controller of a change on a port
- Network operators do not “program” switches by creating/sending OpenFlow messages directly.
  - Instead, they use higher-level abstraction at controller