EECS 489
Computer Networks

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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

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

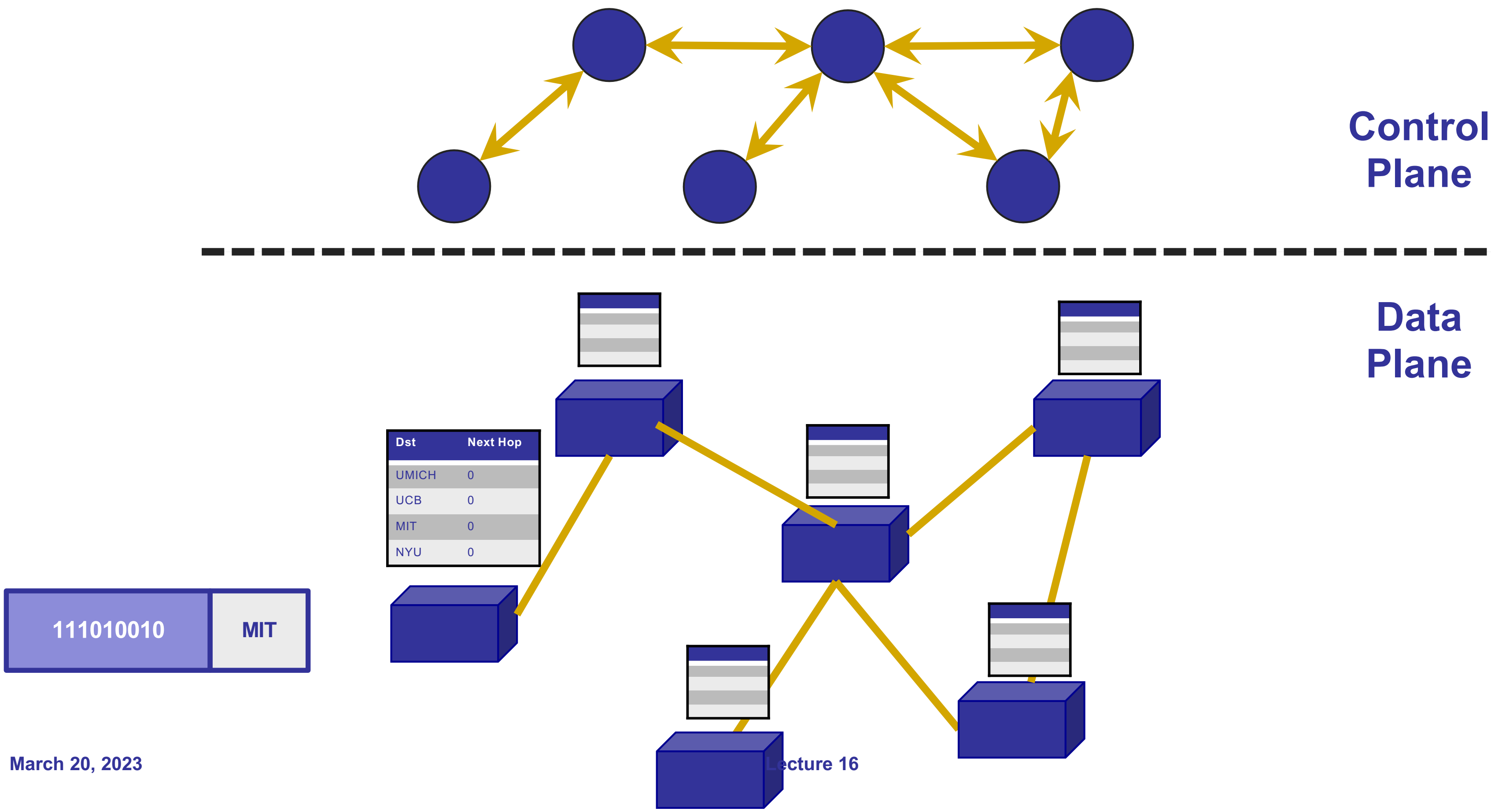
- Abstraction: global network view
  - Annotated network graph provided through an API
- Creates a logically centralized view of the network (Network Operating System)
  - Runs on replicated servers in network (“controllers”)
- Information flows both ways
  - Information *from* routers/switches to form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

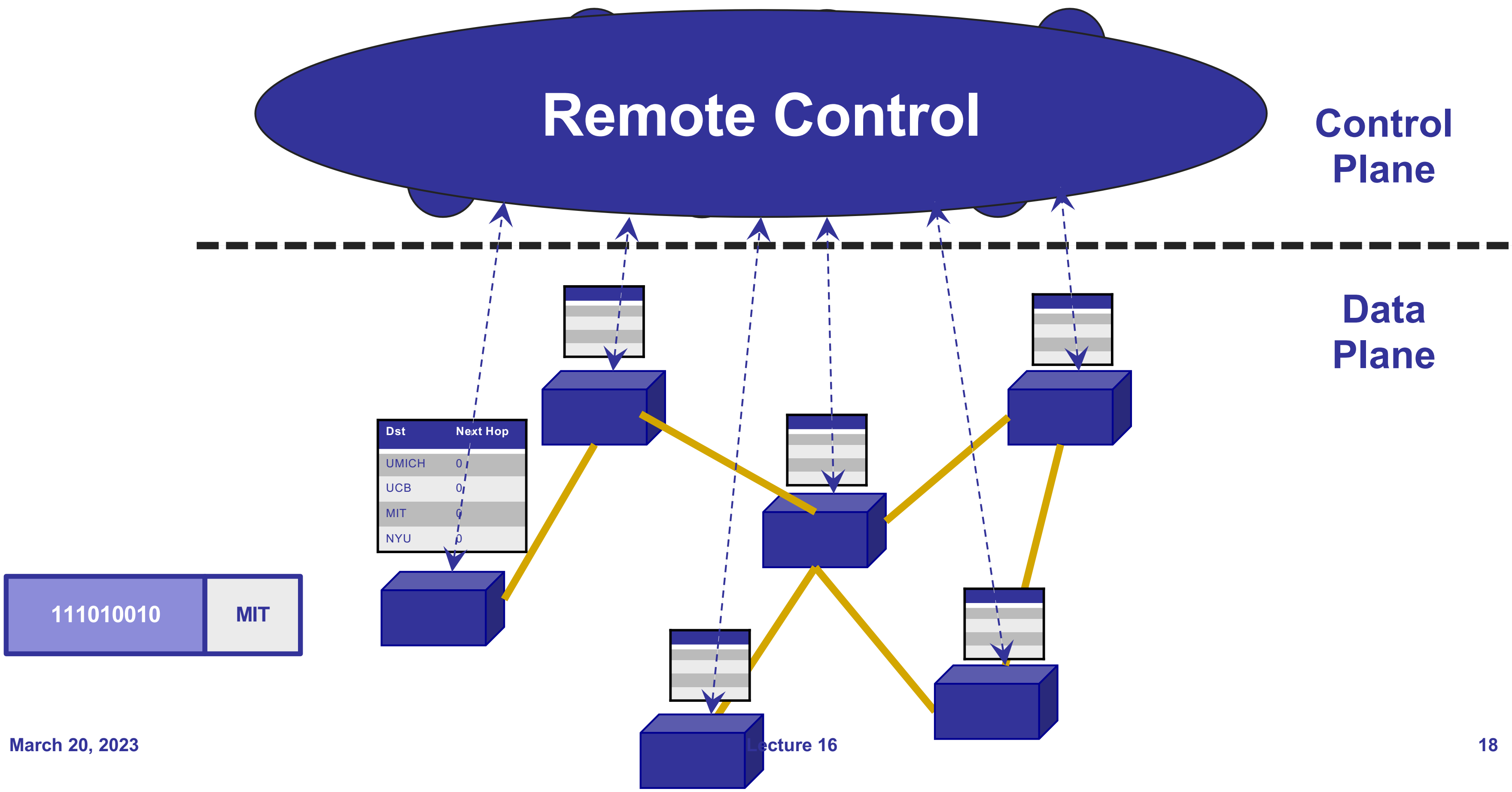
Traditional fully decentralized control plane

- Individual routing algorithm components in every router interact in the control plane



Logically centralized control plane

- A distinct (typically remote) controller interacts with local control agents (CAs)



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)

Figure 1: B4 global topology. Each marker indicates a site or multiple sites located in close geographical proximity. B4 consists of 33 sites as of January, 2018.

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

Rule	Action	Stats

Packet + byte counters

1. Forward packet to port(s)
2. Encapsulate and forward to controller
3. Drop packet
4. Send to normal processing pipeline
5. Modify Fields

Switch Port	VLAN ID	MAC src	MAC dst	Eth type	IP Src	IP Dst	IP Prot	TCP sport	TCP dport

Link layer

Network layer

Transport layer

Forwarding abstraction

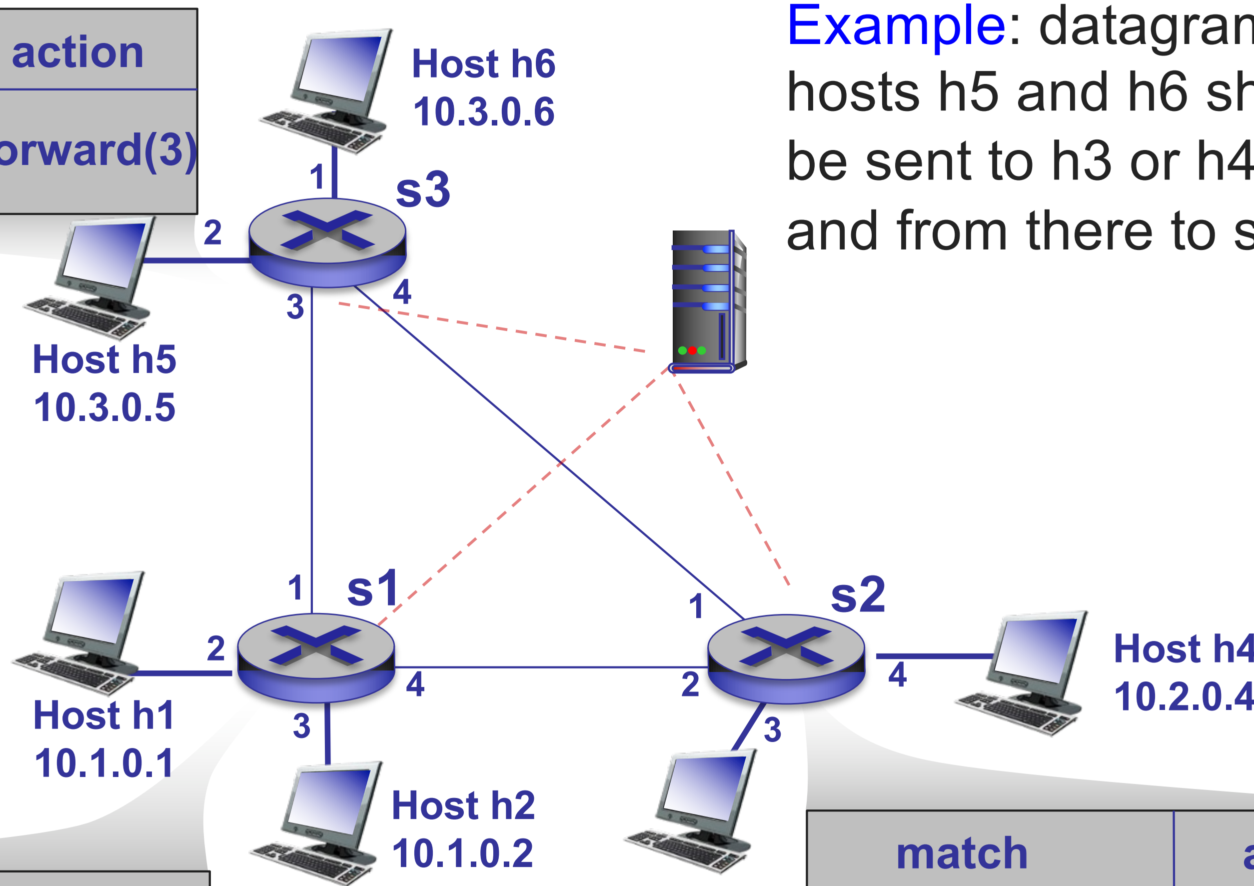
Match + Action: unifies different kinds of devices

- 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

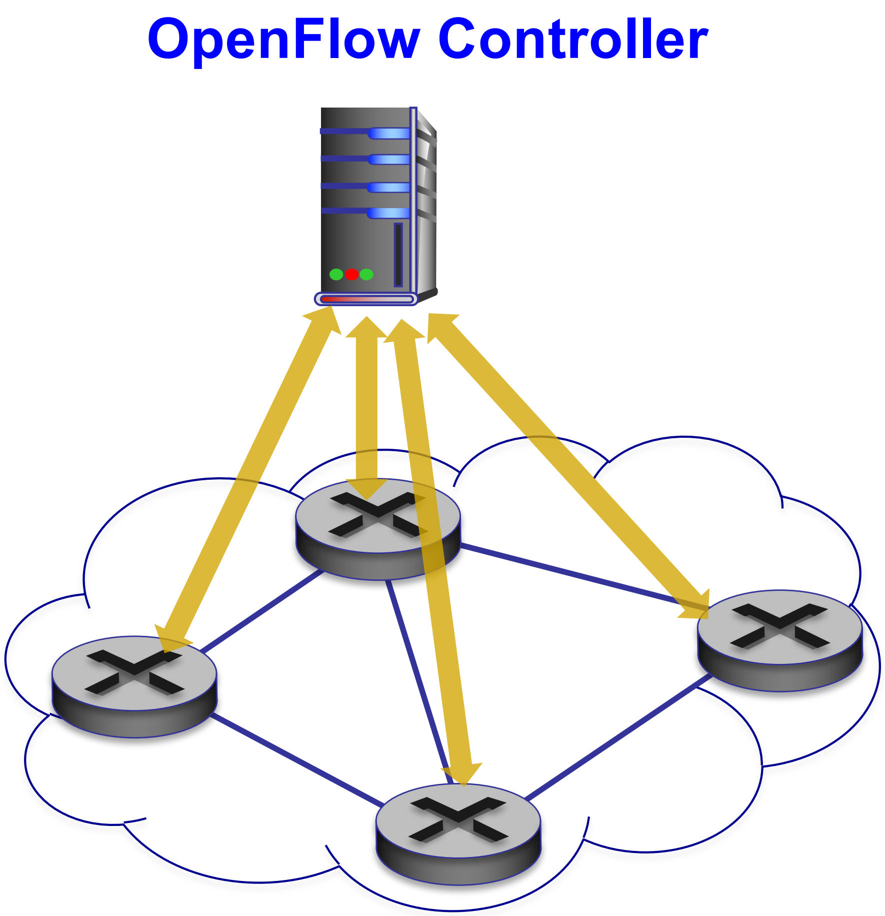
match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



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

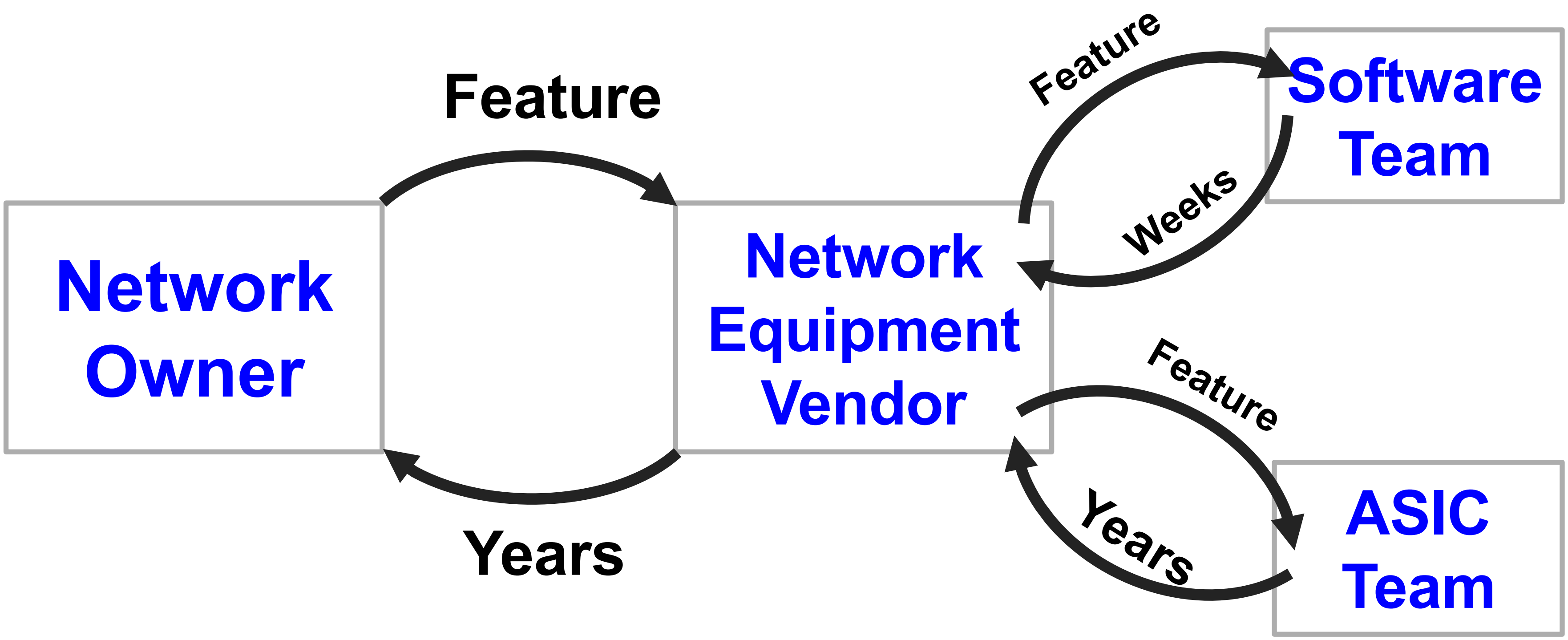


- Operates between controller, switch
- TCP used to exchange messages
  - Optional encryption
- Three classes of OpenFlow messages:
  - Controller-to-switch
  - Asynchronous (switch to controller)
  - Symmetric (misc.)

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
  }
}
```

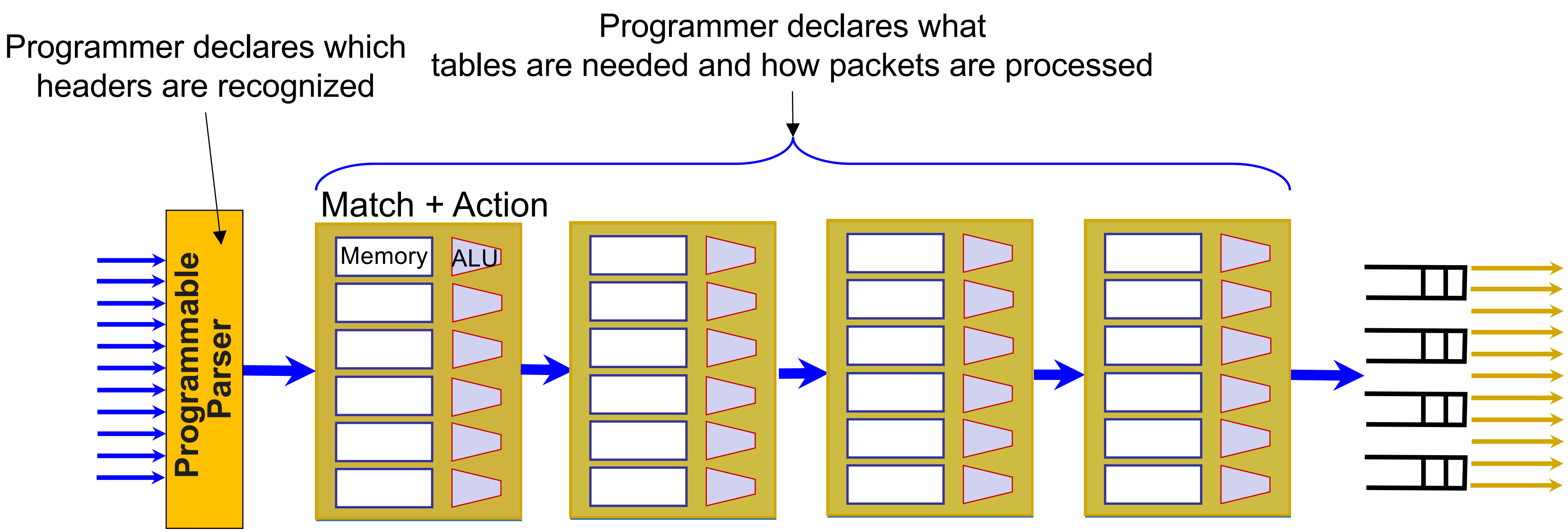
```
action export_queue_latency (sw_id) {
  add_header(int_header);
  modify_field(int_header.kind, TCP_OPTION_INT);
  modify_field(int_header.len, TCP_OPTION_INT_LEN);
  modify_field(int_header.sw_id, sw_id);
  modify_field(int_header.q_latency,
                    intrinsic_metadata.deq_timedelta);
  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

Summary

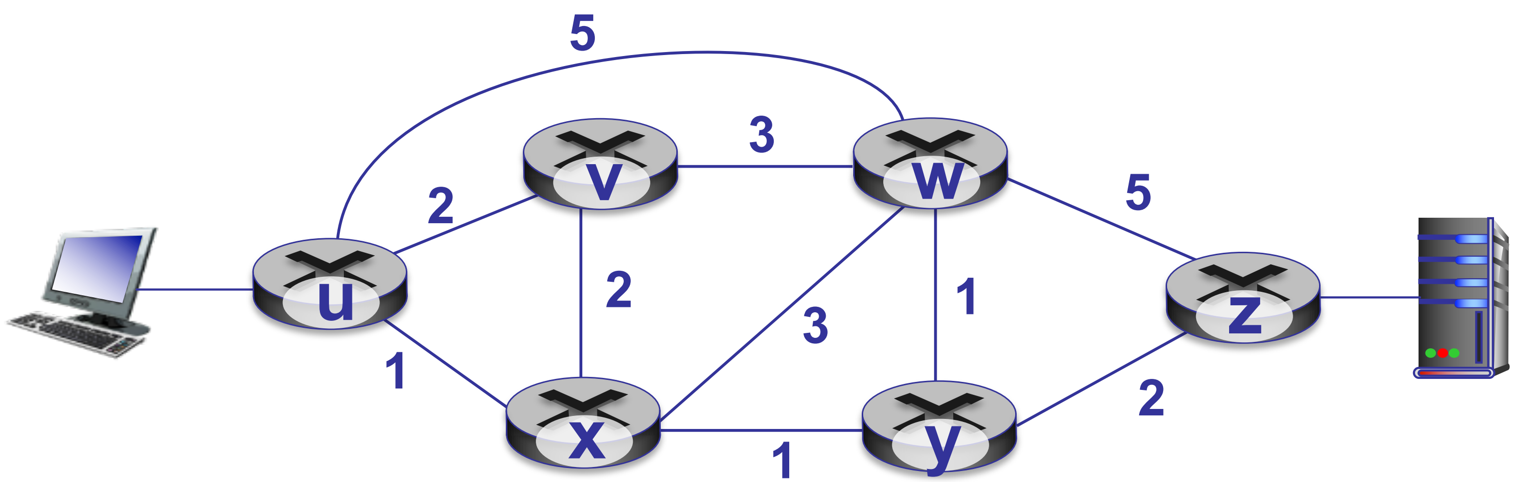
- Abstractions beget modularity
  - Modularity is (almost always) good
- Programmability is powerful
  - Finding the right balance is hard

- Next lecture: Layer 2

Traffic engineering

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

Traffic engineering: Difficult

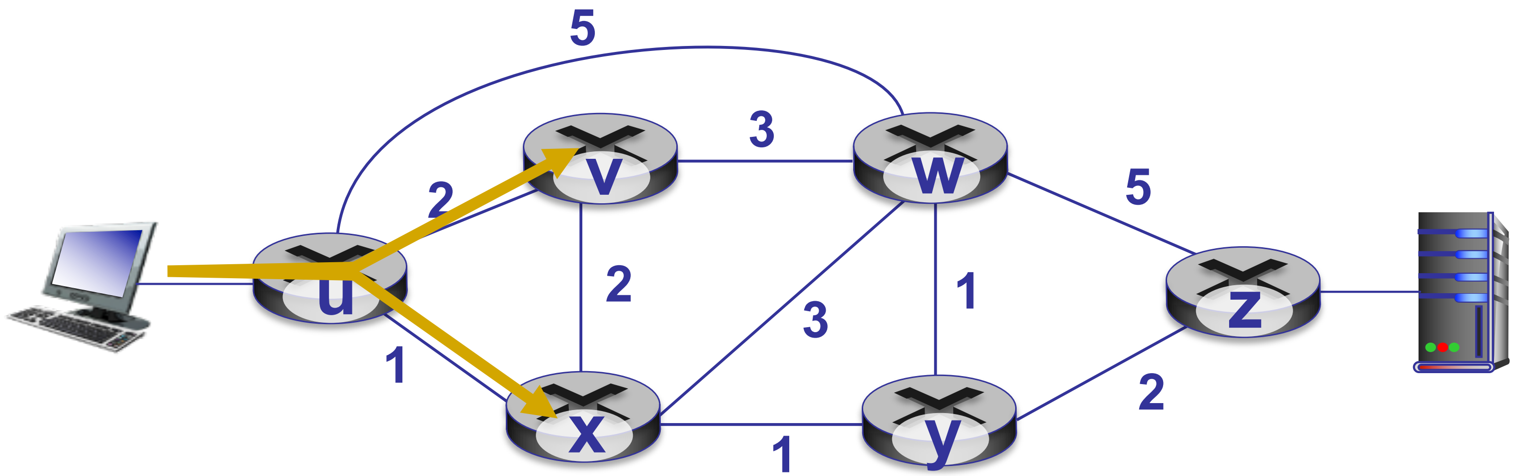


Q: What if network operator wants u-to-z traffic to flow along uvwz, x-to-z traffic to flow xwyz?

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"

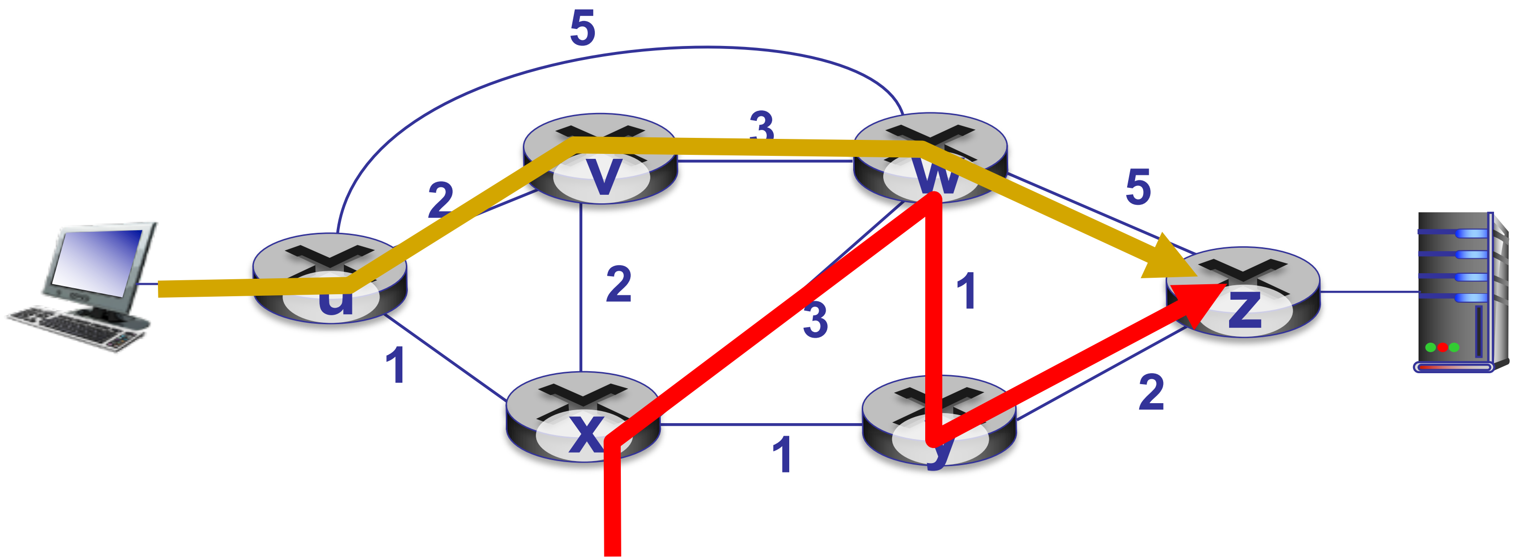
Traffic engineering: Difficult



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