Link Layer, SDN, Course Summary

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https://qiaoxiang.me/courses/cnns-xmuf21/index.shtml

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This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

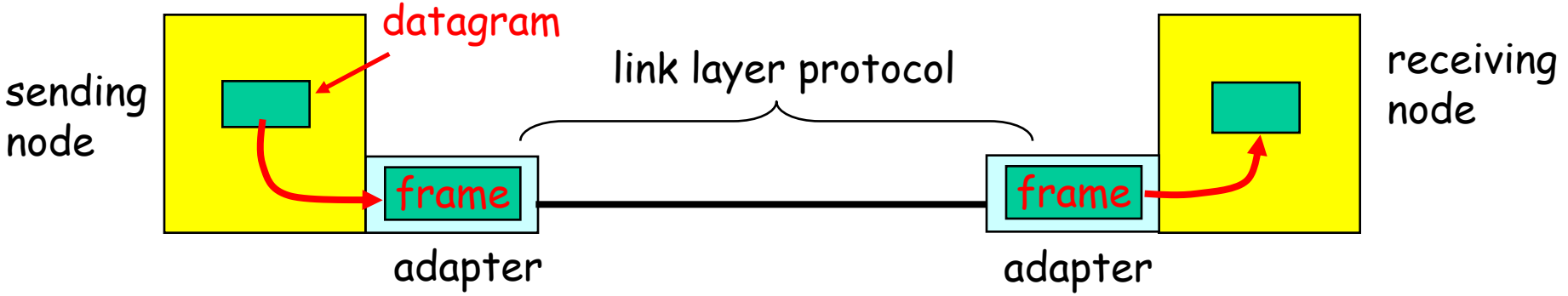
Outline

- Admin and recap
- Link layer
- Software defined networking
- Course Summary

Recap: Link Layer Services

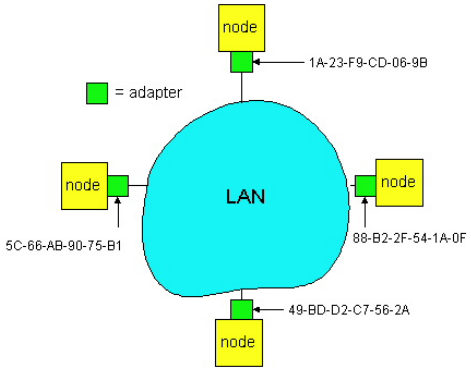
- Framing
  - encapsulate datagram into frame, adding header, trailer and error detection/correction
- Multiplexing/demultiplexing
  - frame headers to identify src, dest
- Reliable delivery between adjacent nodes
  - we learned how to do this already !
  - seldom used on low bit error link (fiber, some twisted pair)
  - common for wireless links: high error rates
- Media access control
- Forwarding/switching with a link-layer (Layer 2) domain

Recap: Adaptors Communicating



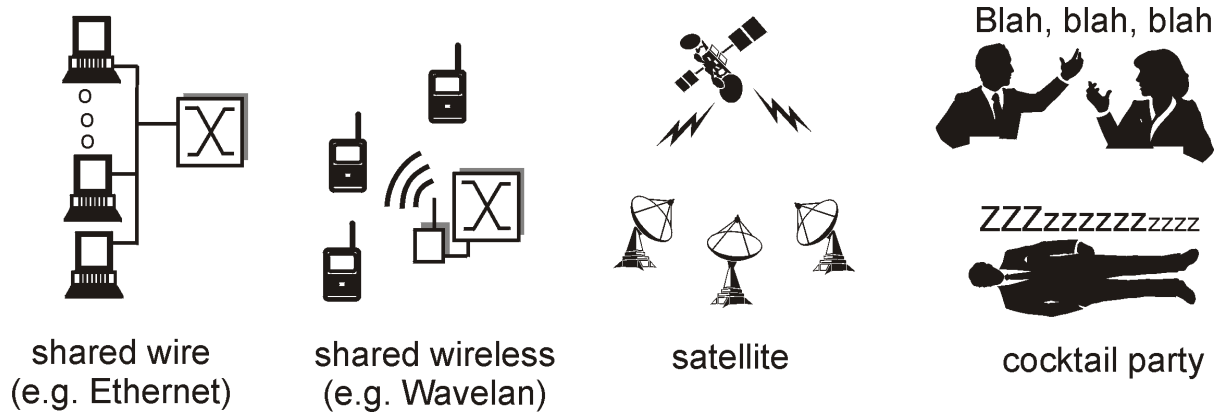
- link layer typically implemented in "adaptor" (aka NIC)
  - Ethernet card, modem, 802.11 card, cloud virtual switch
- adapter is semi-autonomous, implementing link & physical layers

- in most link-layer, each adapter has a unique link layer address (also called MAC address)



Recap: Multiple Access Links and Protocols

- Many link layers use broadcast (shared wire or medium)
  - traditional Ethernet; Cable networks
  - 802.11 wireless LAN; cellular networks
  - satellite



- Problem: if two or more simultaneous transmissions, due to interference, only one node can send successfully at a time (see CDMA later for an exception)

Recap: Ideal Mulitple Access Protocol

Broadcast channel of rate R bps

- Efficiency: when only one node wants to transmit, it can send at full rate R
- Rate allocation:
  - simple fairness: when N nodes want to transmit, each can send at average rate R/N
  - we may need more complex rate control
- Decentralized:
  - no special node to coordinate transmissions
  - no synchronization of clocks
- Simple

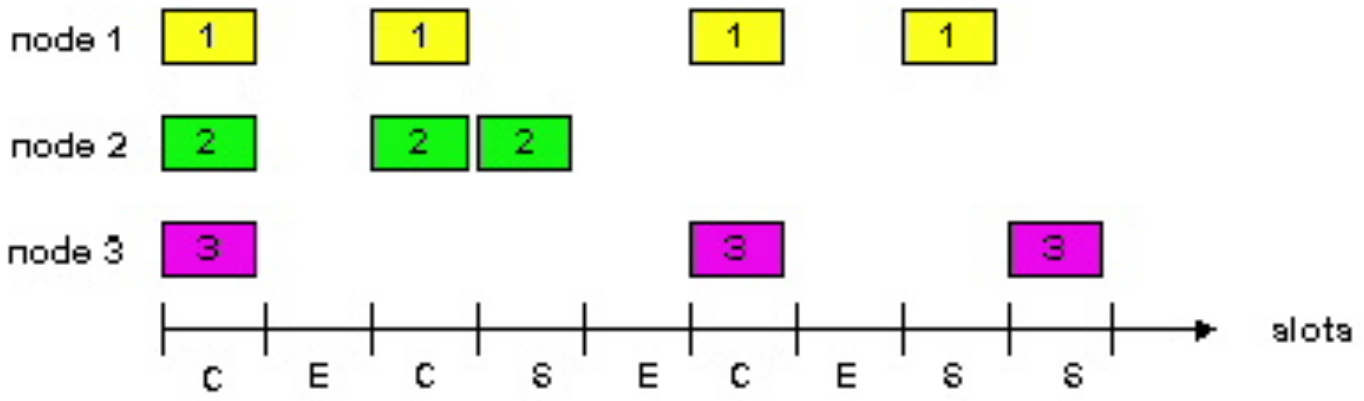
Recap: Random Access Protocols

- Examples of random access MAC protocols:
  - slotted ALOHA and pure ALOHA
  - CSMA and CSMA/CD, CSMA/CA
  - Ethernet, WiFi 802.11

- Key design points:
  - when to access channel?
  - how to detect collisions?
  - how to recover from collisions?

Slotted Aloha [Norm Abramson]

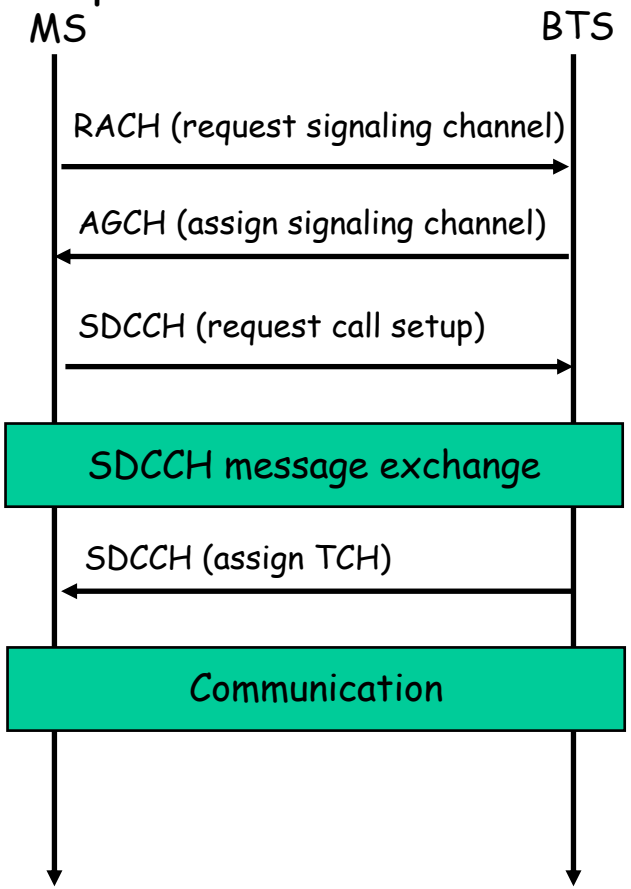
- Time is divided into equal size slots (= pkt trans. time)
- Node with new arriving pkt: transmit at beginning of next slot
- If collision: retransmit pkt in future slots with probability p, until successful.



Success (S), Collision (C), Empty (E) slots

Slotted Aloha in Real Life

- call setup in GSM



- Notations:
  - Broadcast control channel (BCCH): from base station, announces cell identifier, synchronization
  - Random access channel (RACH): MSs for initial access, **slotted Aloha**
  - access grant channel (AGCH): BTS informs an MS its allocation
  - standalone dedicated control channel (SDCCH): signaling and short message between MS and an MS
  - Traffic channels (TCH)

Slotted Aloha Efficiency

Q: What is the fraction of successful slots?

suppose n stations have packets to send

suppose each transmits in a slot with probability *p*

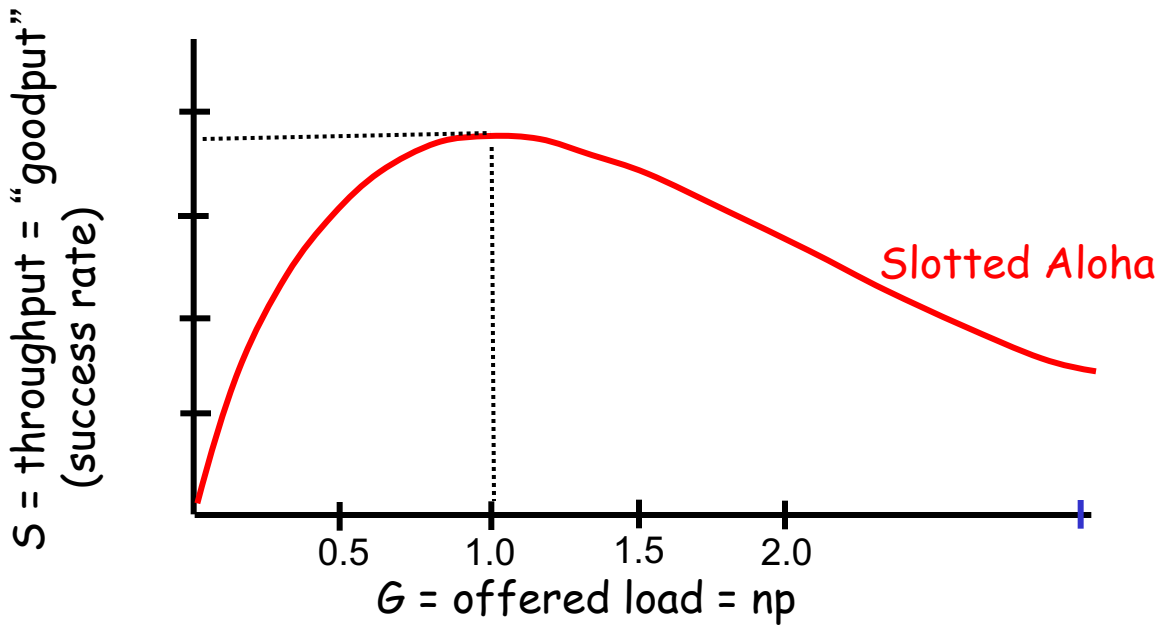
- prob. of succ. by a specific node: $p\,(1-p)^{(n-1)}$

- prob. of succ. by any one of the N nodes

  S(p) = n * Prob (only one transmits)

  = $n\,p\,(1-p)^{(n-1)}$

Goodput vs. Offered Load for Slotted Aloha



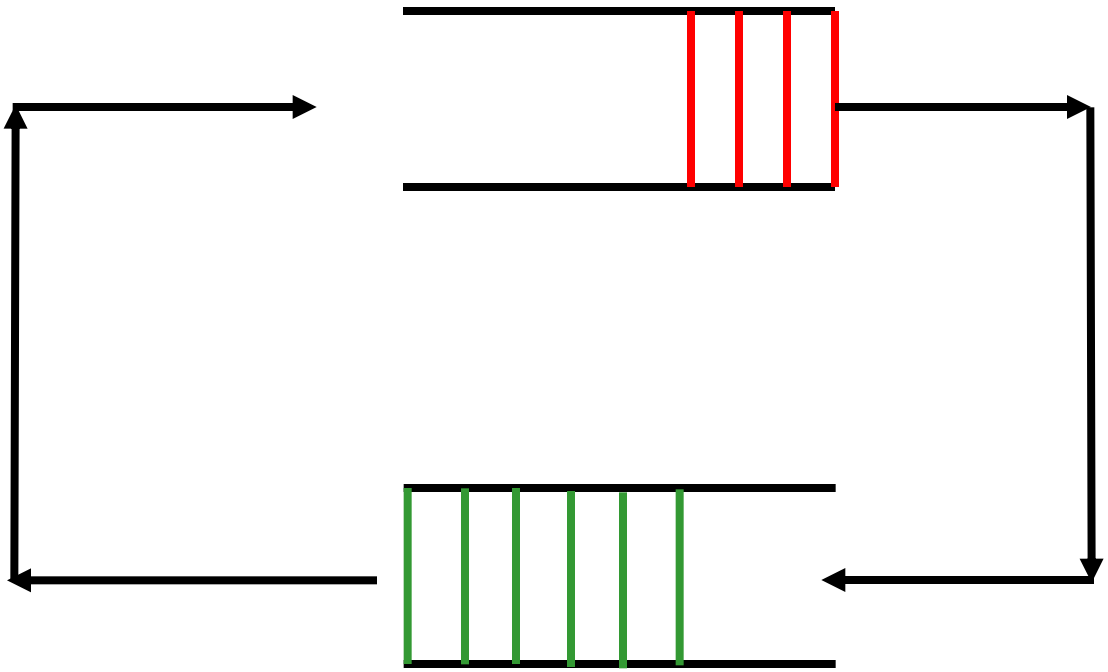
- when p n < 1, as p (or n) increases
  - probability of empty slots reduces
  - probability of collision is still low, thus goodput increases
- when p n > 1, as p (or n) increases,
  - probability of empty slots does not reduce much, but
  - probability of collision increases, thus goodput decreases
- goodput is optimal when p n = 1

Dynamics of (Slotted) Aloha

- Slotted Aloha has maximum throughput when np = 1
  - Implies we need to adjust p as the number of backlog stations varies.
- Early design question: what is the effect if we do not change p--use a fixed p
  - Assume we have a total of m stations (the machines on a LAN):
    - n of them are currently backlogged, each tries with a (fixed) probability p
    - the remaining m-n stations are not backlogged. They may start to generate packets with a probability p_a, where p_a is much smaller than p

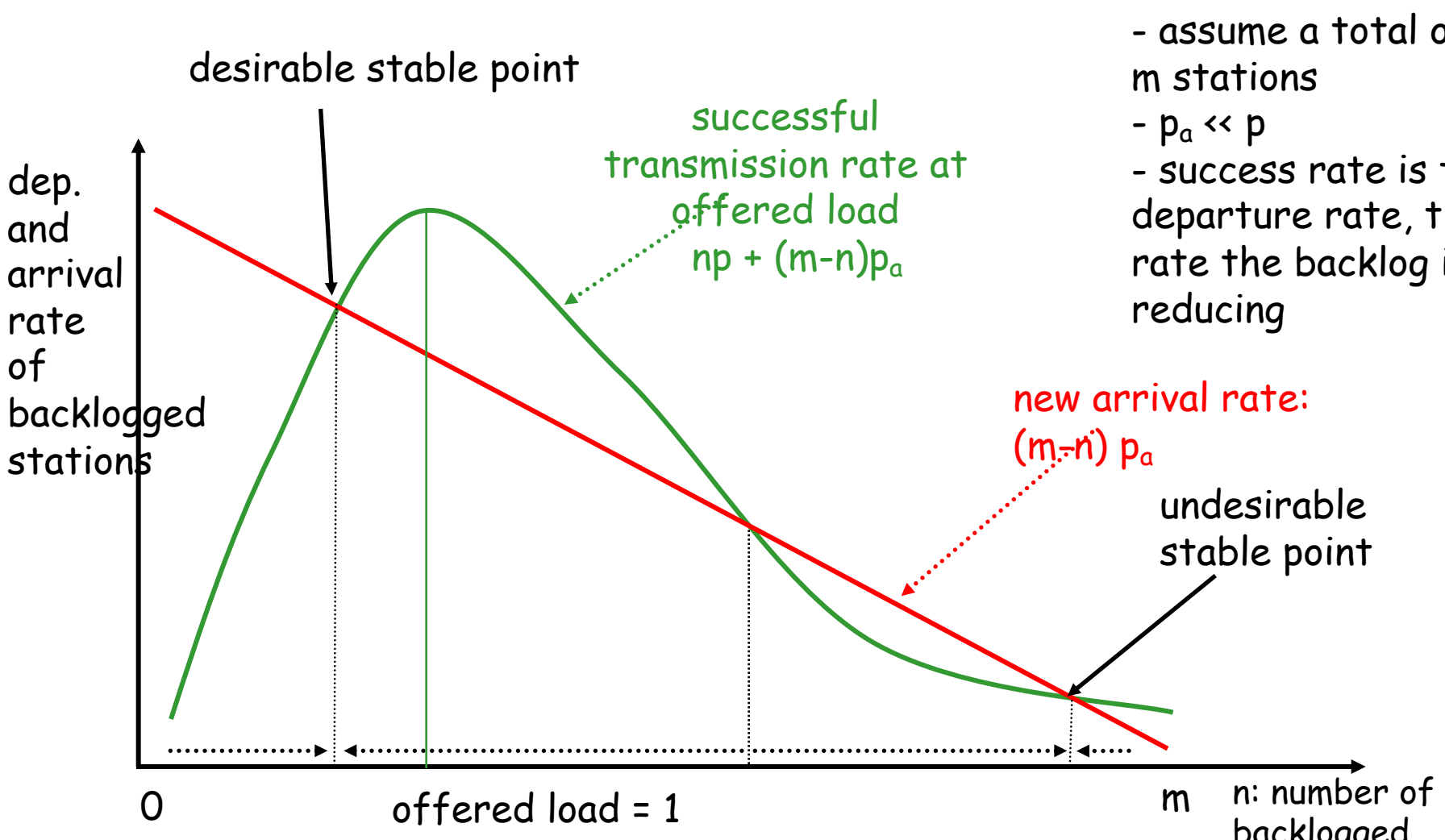
Model

n backlogged
each transmits with prob. p



m-n: unbacklogged
each transmits with prob. p_a

Dynamics of Aloha: Effects of Fixed Probability



- assume a total of m stations
- $p_a \ll p$
- success rate is the departure rate, the rate the backlog is reducing

Lesson: if we fix p, but n varies, we may have an undesirable stable point

Summary of Problems of Aloha Protocols

- Problems
  - slotted Aloha has better efficiency than pure Aloha but clock synchronization is hard to achieve
  - Aloha protocols have low efficiency due to collision or empty slots
    - when offered load is optimal (p = 1/N), the goodput is only about 37%
    - when the offered load is not optimal, the goodput is even lower
  - undesirable steady state at a fixed transmission rate, when the number of backlogged stations varies

- Ethernet design: address the problems:
  - optimal transmission rate

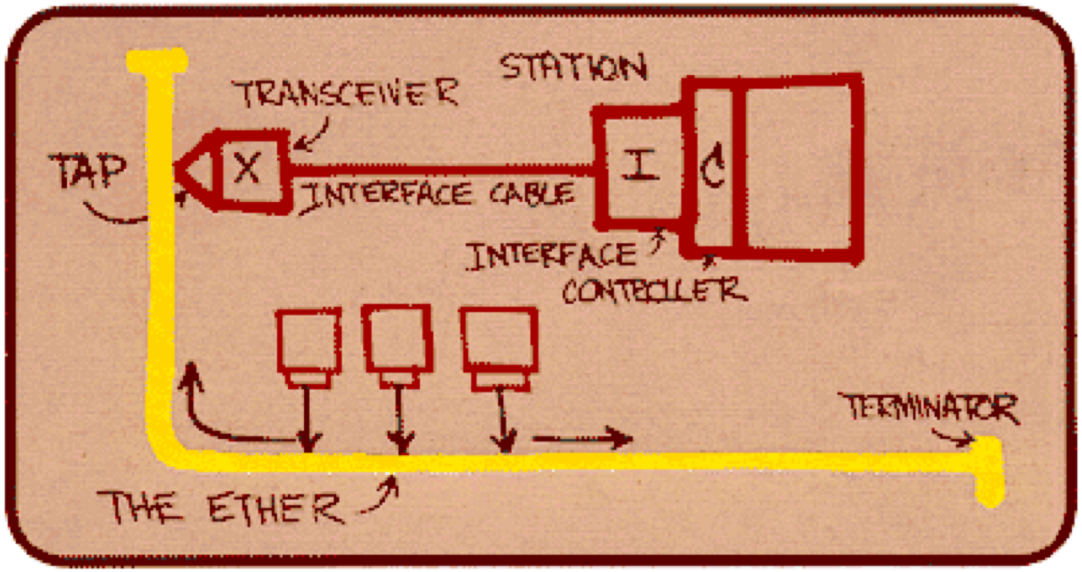
The Basic MAC Mechanisms of Ethernet

```
get a packet from upper layer;
K := 0; n := 0; // K: control wait time; n: no. of collisions
repeat:
   wait for K * 512 bit-time;
   while (network busy) wait;
   wait for 96 bit-time after detecting no signal;
   transmit and detect collision;
   if detect collision
      stop and transmit a 48-bit jam signal;
      n ++;
      m:= min(n, 10), where n is the number of collisions
      choose K randomly from {0, 1, 2, …, 2^m-1}.
      if n < 16 goto repeat
      else give up
```

Ethernet

"Dominant" LAN technology:

- First widely used LAN technology
- Kept up with speed race: 10 Mbps, 100 Mbps, 1 Gbps, 10 Gbps



Metcalfe's Ethernet sketch

Outline

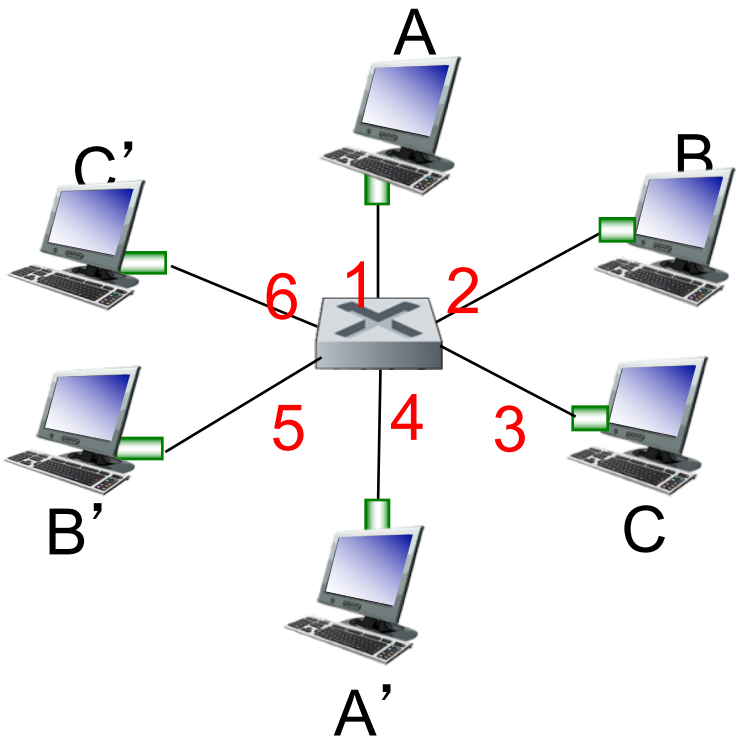
- Admin and recap
- Link layer
  - Ethernet switch

Ethernet Switch

- link-layer device: takes an *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, selectively forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- *transparent*
  - hosts are unaware of presence of switches
- *plug-and-play, self-learning*
  - switches do not need to be configured

Switch: *Multiple* Simultaneous Transmissions

- hosts have dedicated, direct connection to switch
- switches buffer packets
- Ethernet protocol used on *each* incoming link, but no collisions; full duplex
  - each link is its own collision domain
- *switching:* A-to-A' and B-to-B' can transmit simultaneously, without collisions



switch with six interfaces (1,2,3,4,5,6)

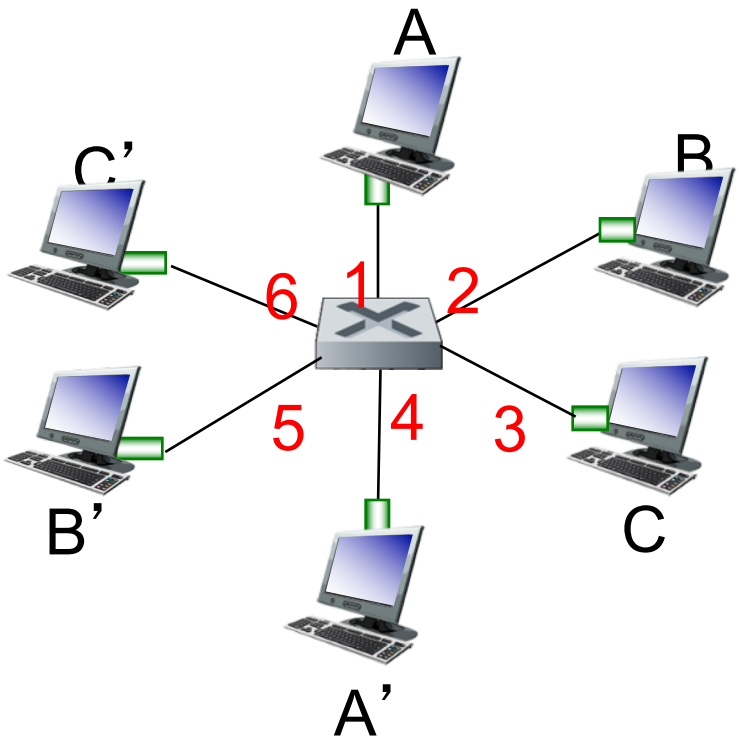
Switch Forwarding Table

Q: how does switch know A' reachable via interface 4, B' reachable via interface 5?

- *A:* each switch has a switch table, each entry:
  - (MAC address of host, interface to reach host, time stamp)
  - looks like a routing table!

Q: how are entries created, maintained in switch table?

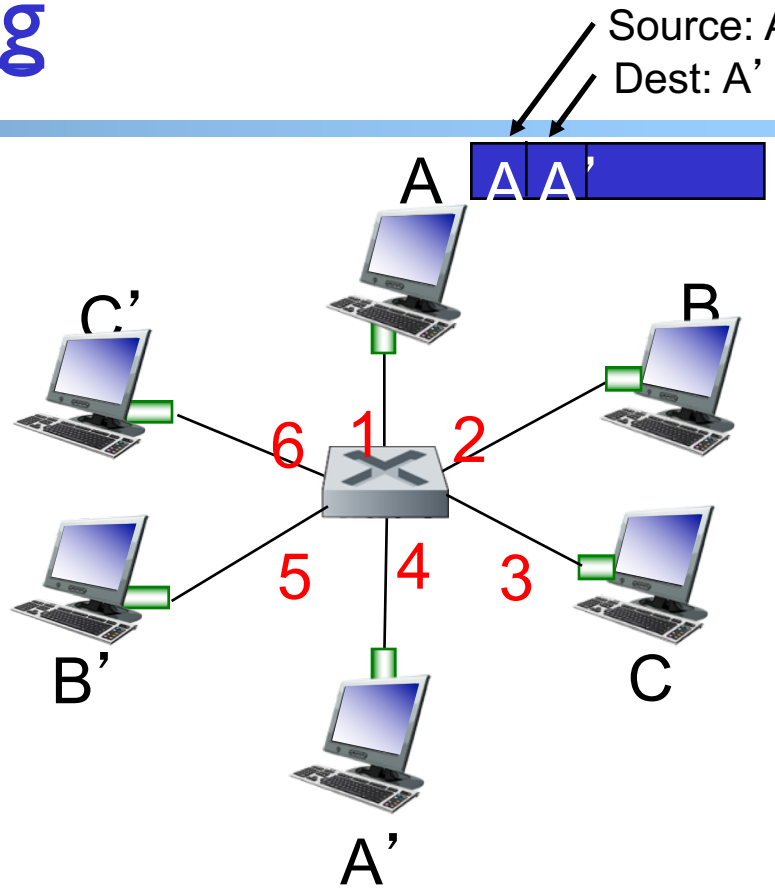
- something like a routing protocol?



switch with six interfaces (1,2,3,4,5,6)

Switch: Self-Learning

- switch *learns* which hosts can be reached through which interfaces
  - when frame received, switch "learns" location of sender: incoming LAN segment
  - records sender/location pair in switch table



MAC addr	interface	TTL
A	*1*	*60*

Switch table (initially empty)

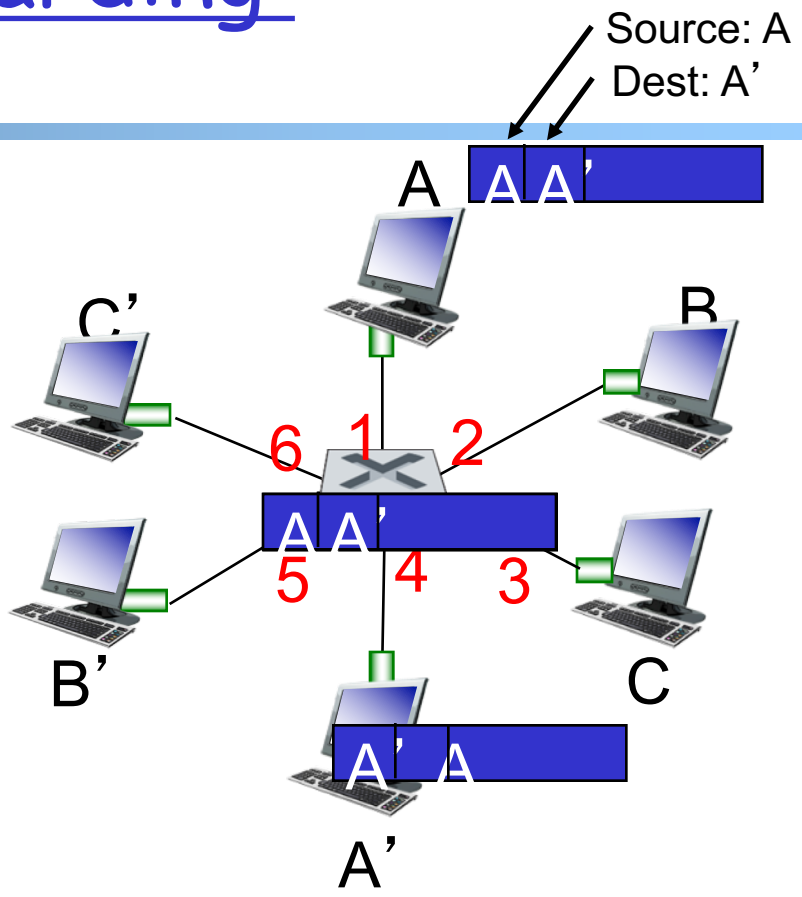
Switch: Frame Filtering /Forwarding

when frame received at switch:

1. record incoming link, MAC address of sending host
2. index switch table using MAC destination address
3. if entry found for destination
   then {
    if destination on segment from which frame arrived
      then drop frame
      else forward frame on interface indicated by entry
    }
   else flood /* forward on all interfaces except arriving
                 interface */

Self-Learning, Forwarding: Example

- frame destination, A', location unknown: *flood*
- destination A location known: selectively send on just one link

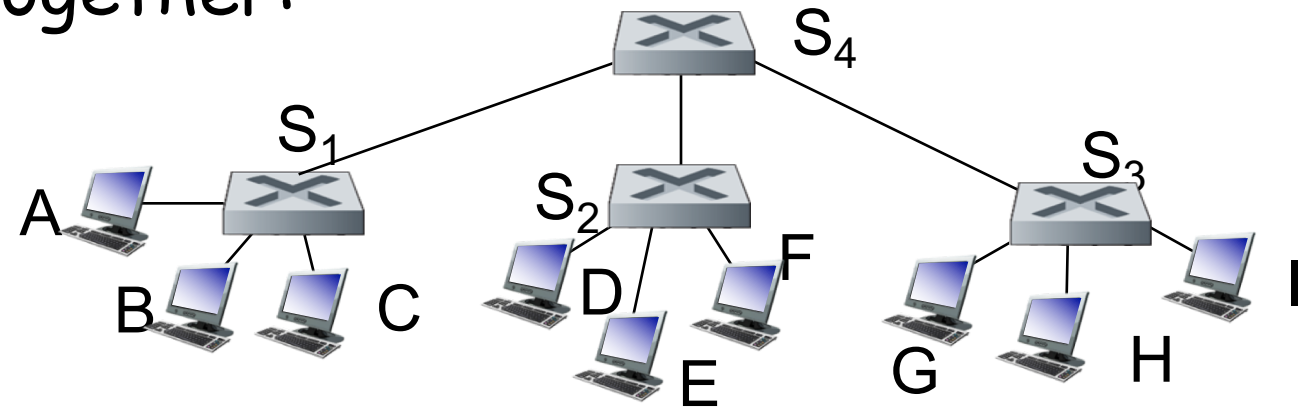


MAC addr	interface	TTL
A	*1*	*60*
A'	*4*	*60*

switch table (initially empty)

Interconnecting Switches

self-learning switches can be connected together:

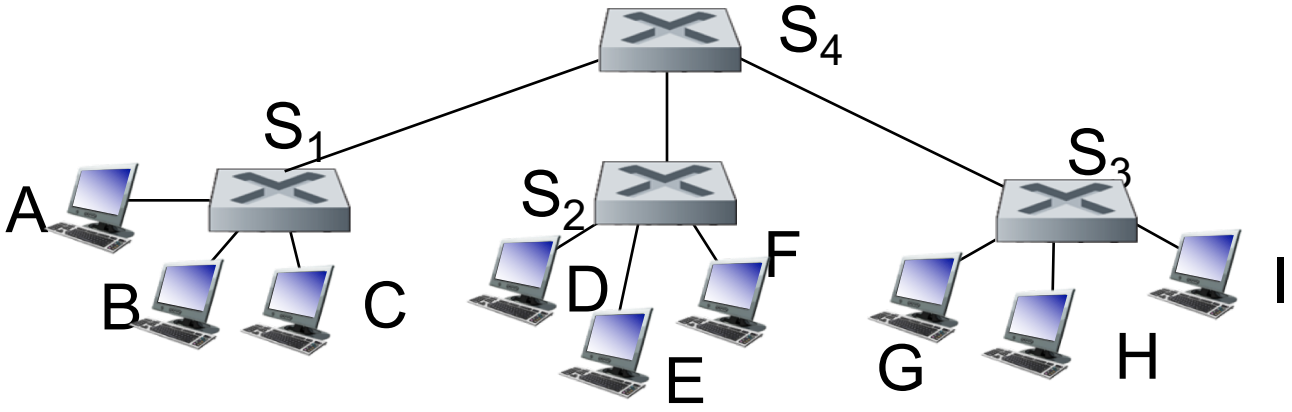


Q: sending from A to G - how does S_1 know to forward frame destined to G via S_4 and S_3?

- *A:* self learning! (works exactly the same as in single-switch case!)

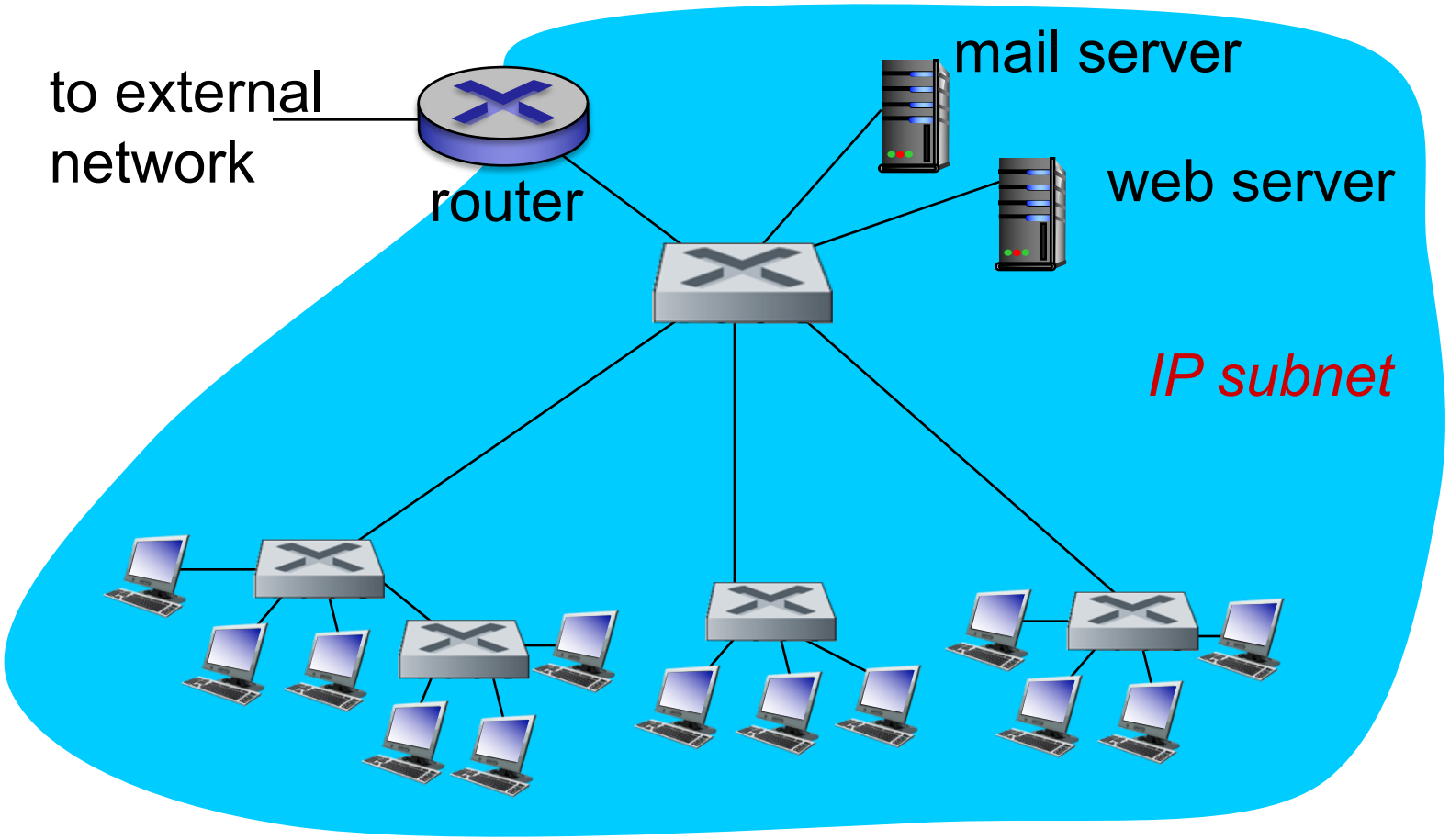
Self-Learning Multi-switch Example

Suppose C sends frame to I, I responds to C



- Offline Exercise: show switch tables and packet forwarding in S_1, S_2, S_3, S_4

Institutional Network



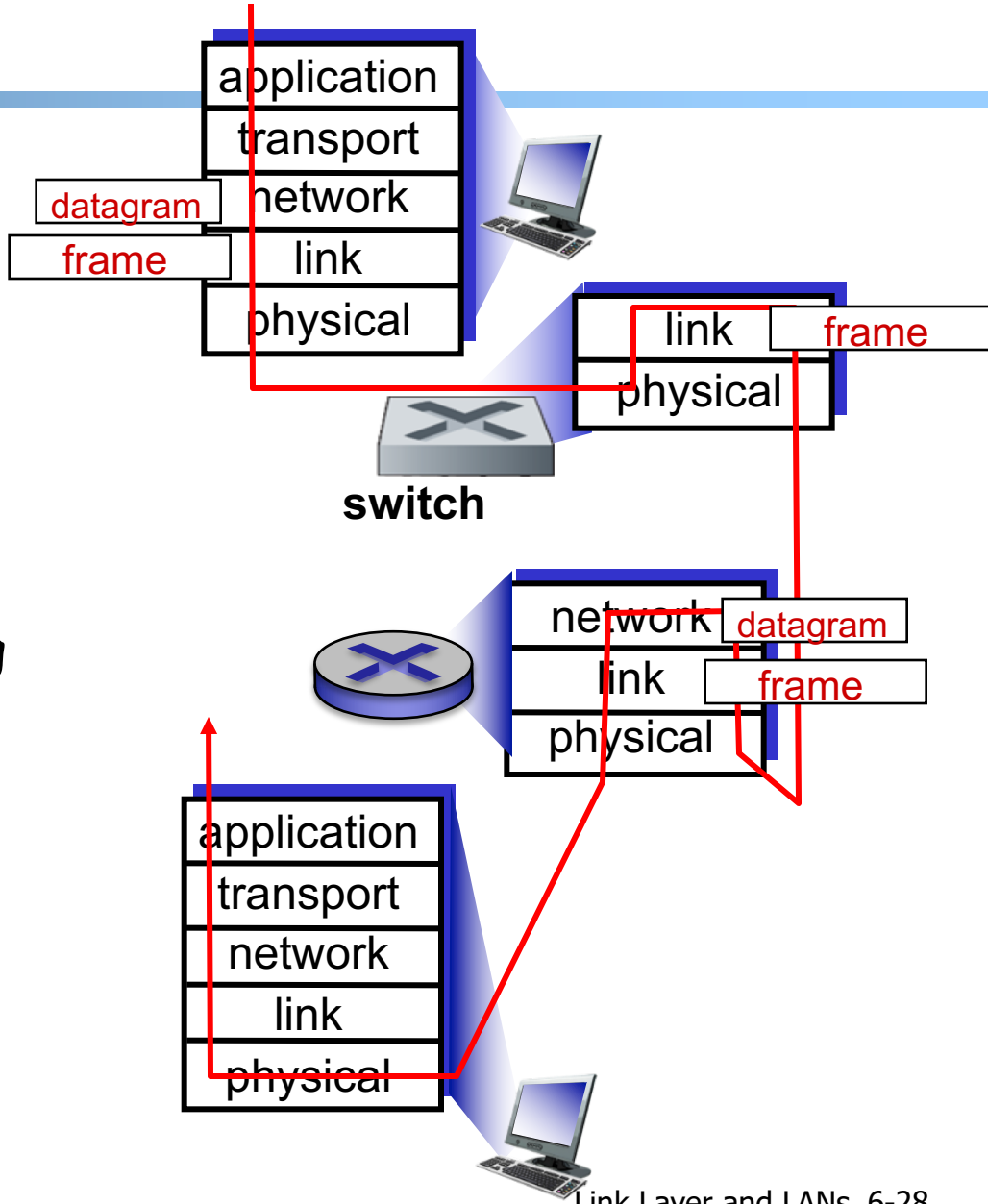
Switches vs. Routers

both are store-and-forward:

- *routers:* network-layer devices (examine network-layer headers)
- *switches:* link-layer devices (examine link-layer headers)

both have forwarding tables:

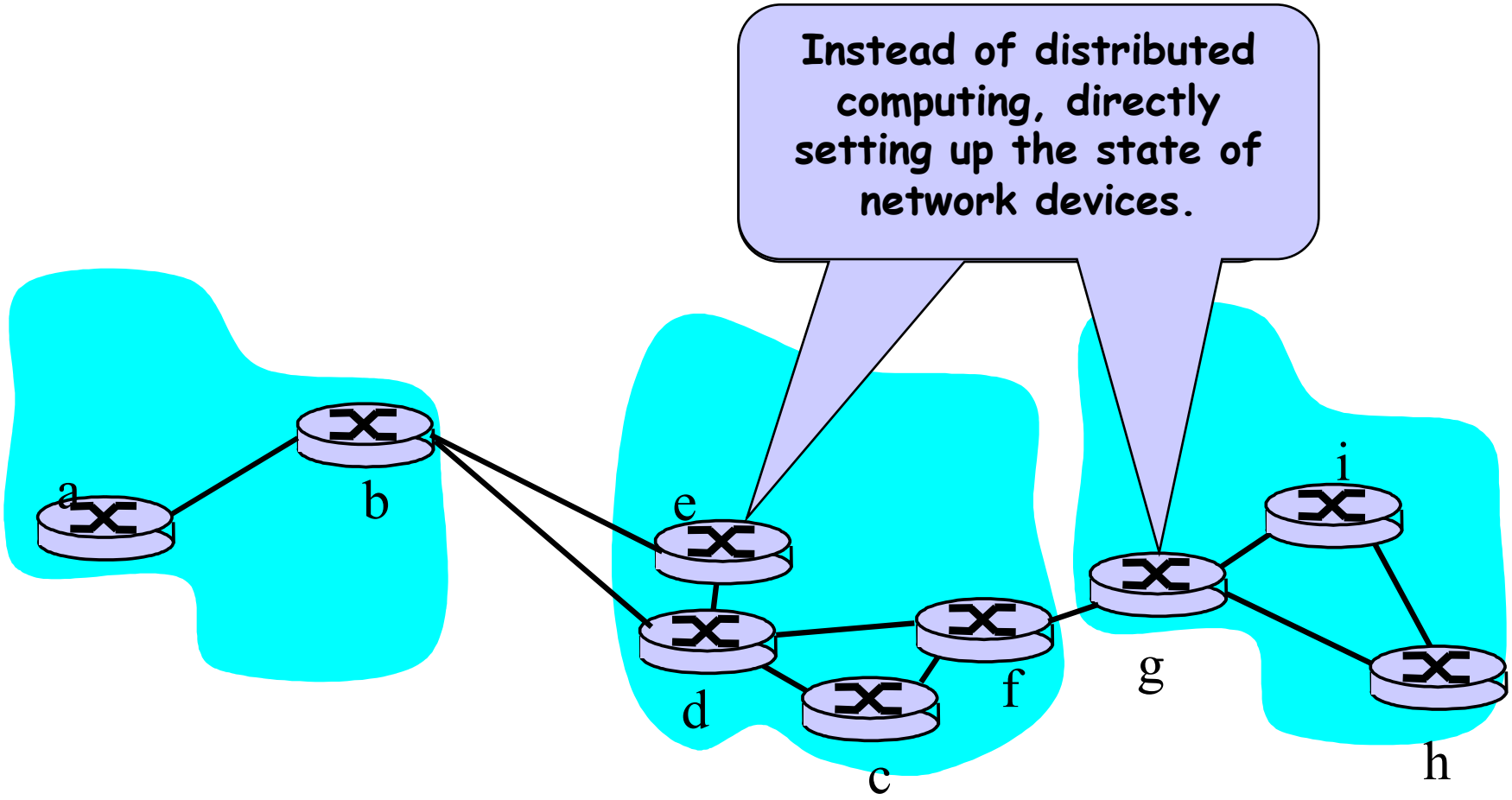
- *routers:* compute tables using routing algorithms, IP addresses
- *switches:* learn forwarding table using flooding, learning, MAC addresses



Outline

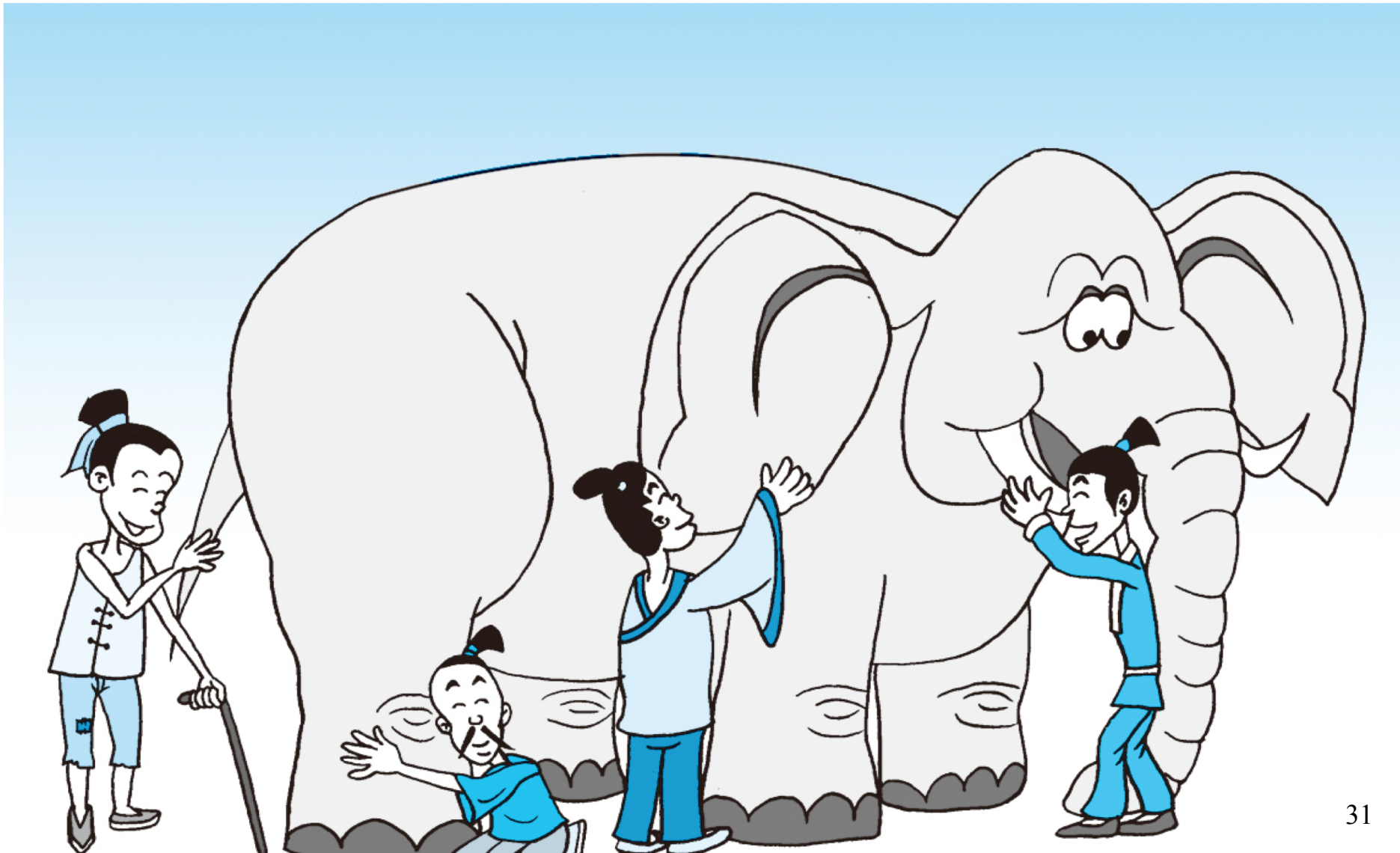
- Admin and recap
- Link layer
- Software defined networking
  - Motivation: from simple forwarding to network functions
  - Design overview

Alternative Design: Software Defined Networking



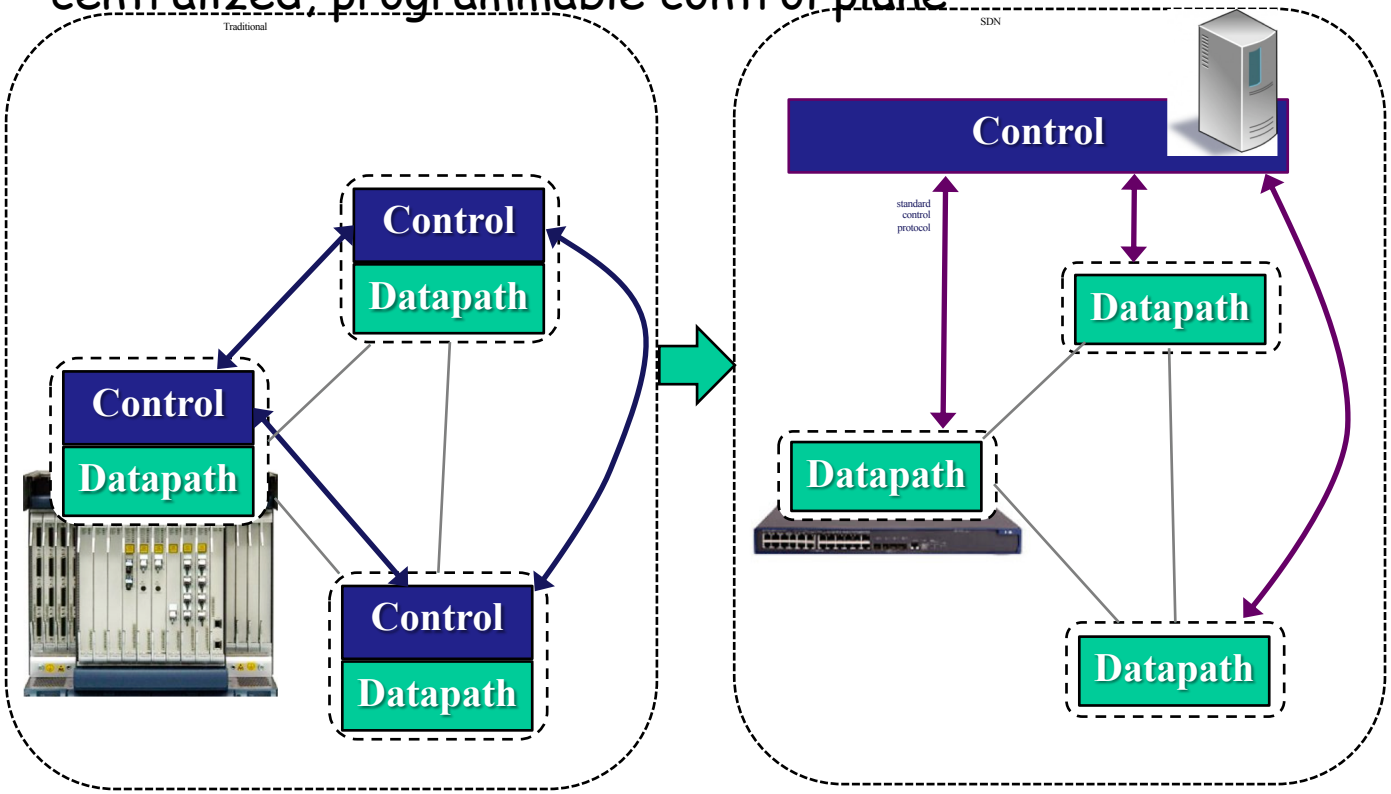
Discussion: key components of the architecture?

What is Software Defined Networking (SDN)?

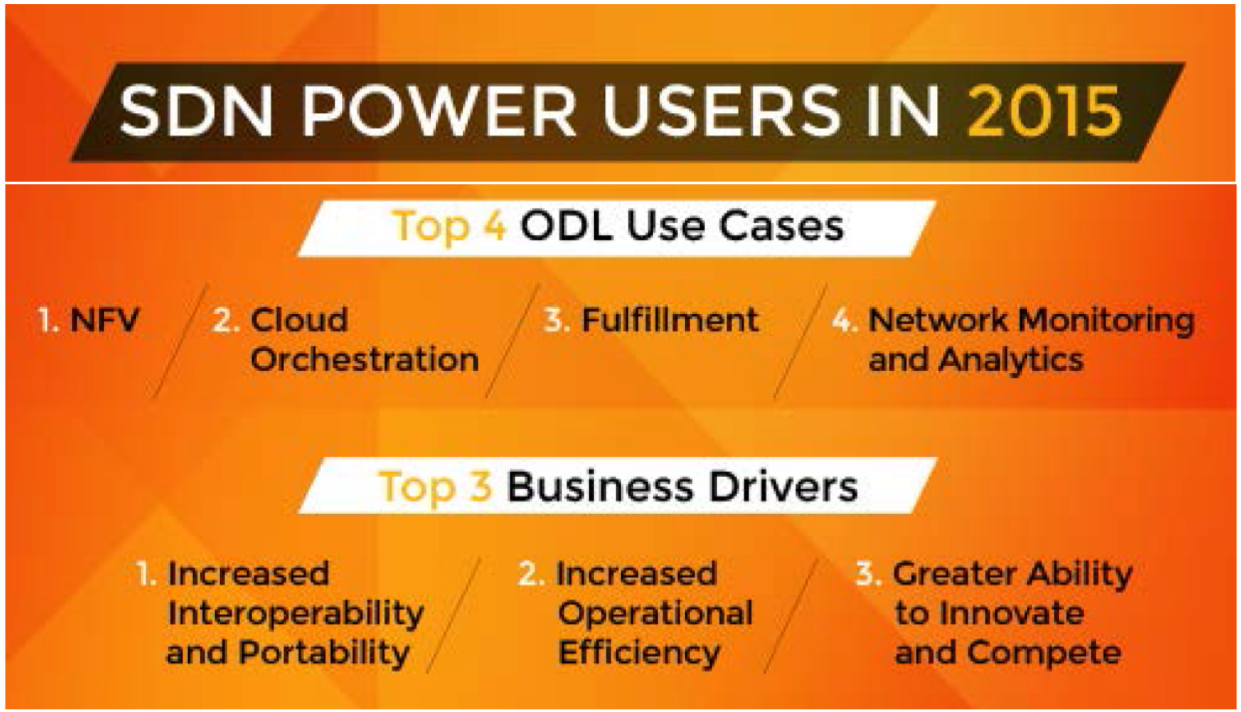


What is SDN: a "Main-Stream" View

- Separation of data and control paths, with a logically centralized, programmable control plane



Some Use Cases of SDN



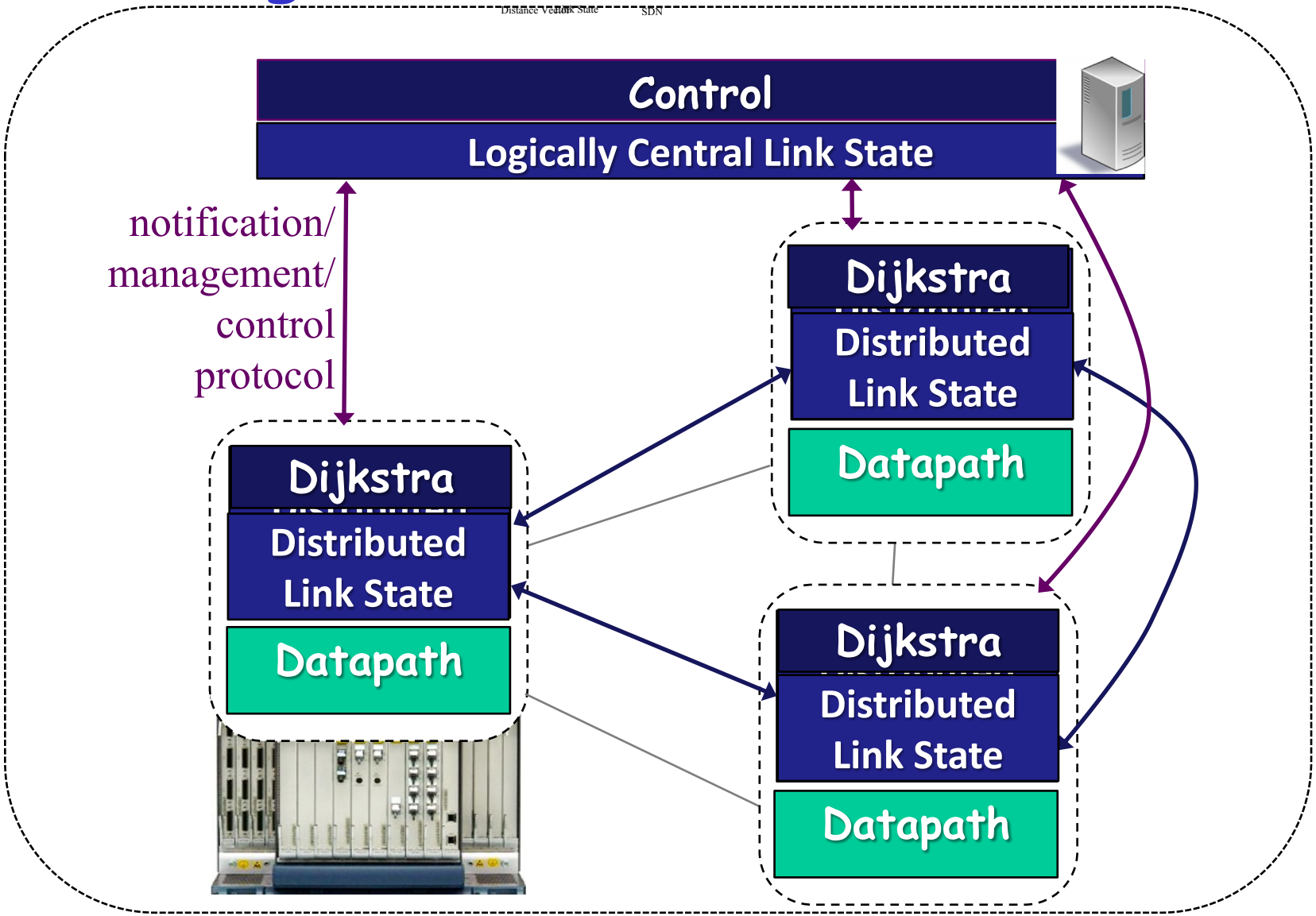
Source: Neela Jacques, July 2015.

- 128 Companies responded
  - 31% Telcos/Service Providers
  - 24% Research/Academia
  - 20% Enterprises
  - 10% Services/Consulting
  - 9% Software/Hardware
  - 6% Other

Why SDN (A "Wiseman" View)?

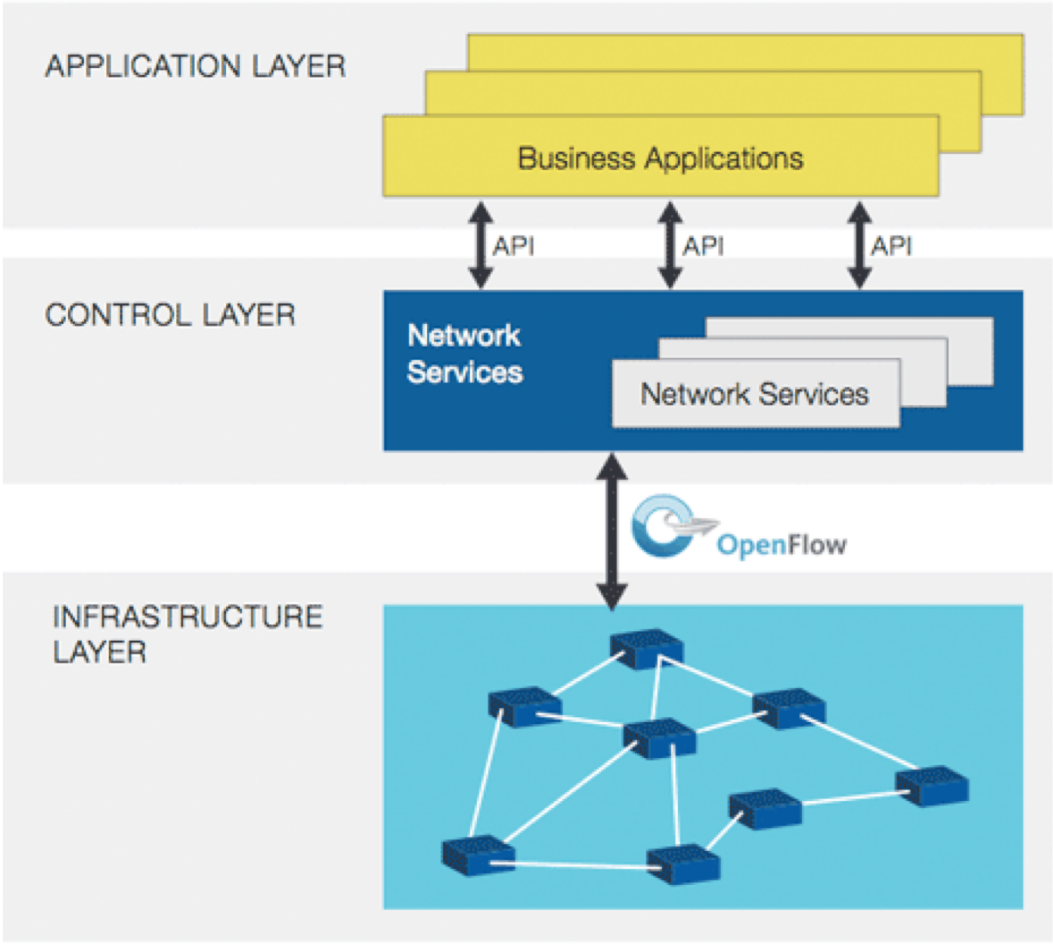
- Distributed computing is hard, e.g.,
  - FLP Impossibility Theorem
  - Arrow's Impossibility Theorem
- Achieved good design for few distributed-computing tasks (e.g., state distribution, leader election).

An Evolution View of Intradomain Routing Toward SDN



Software-Defined Networking (SDN)

- Directly programmable
- Agile
- Centrally managed
- Programmatically configured
- Open standards-based and vendor-neutral



https://www.opennetworking.org/sdn-resources/sdn-definition

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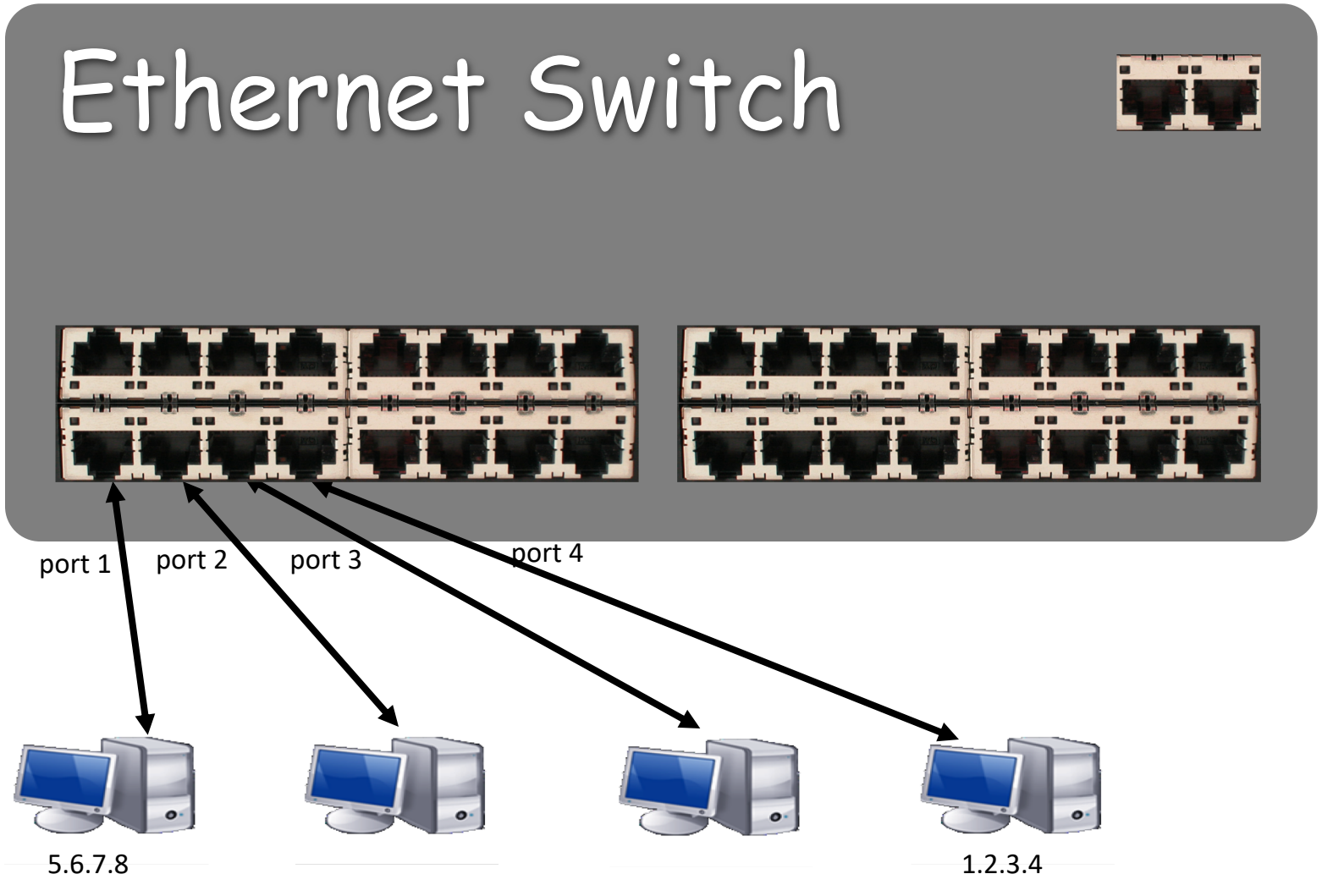
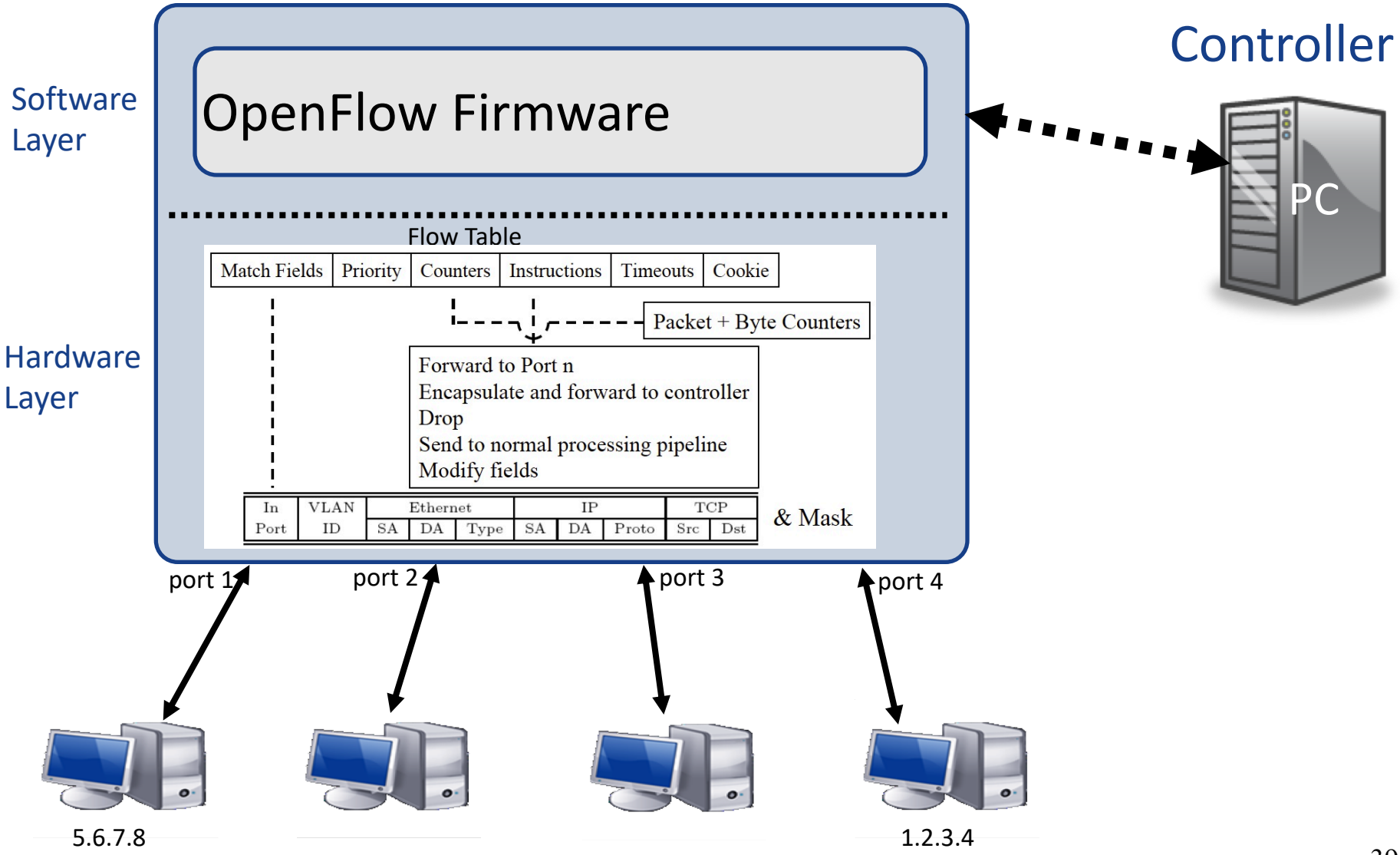
  - Design overview
  - Data path (OpenFlow)

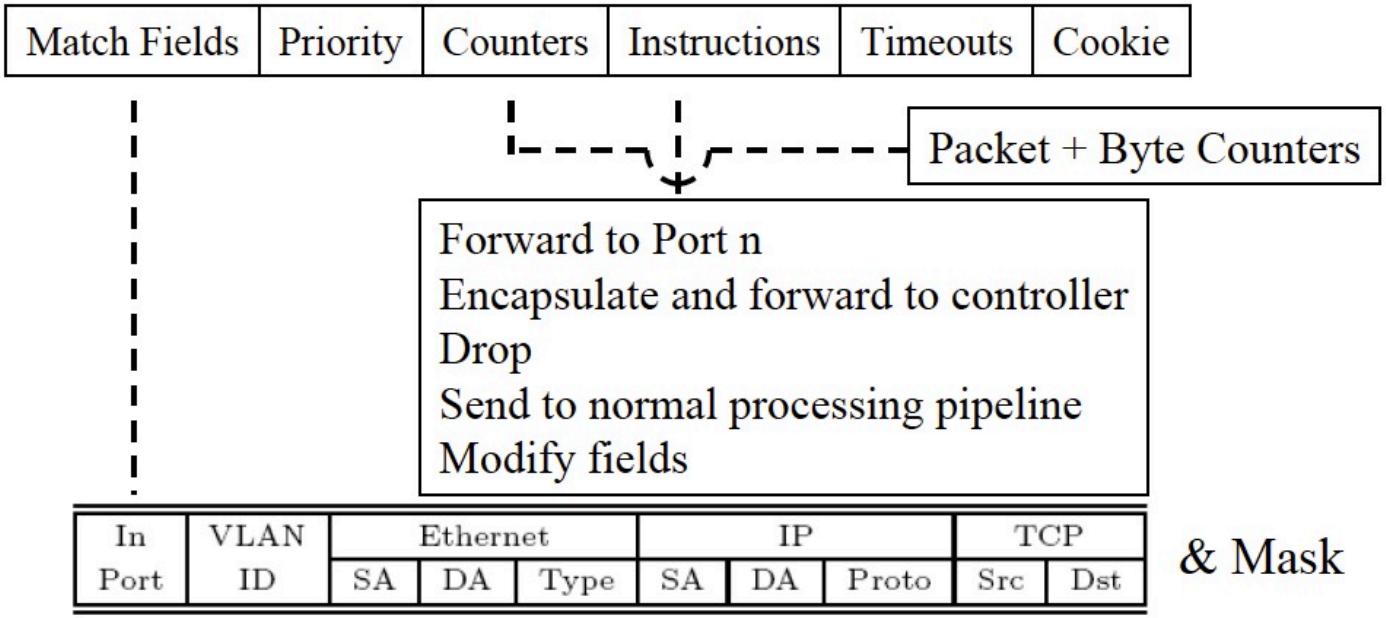
OpenFlow Datapath



OpenFlow Datapath

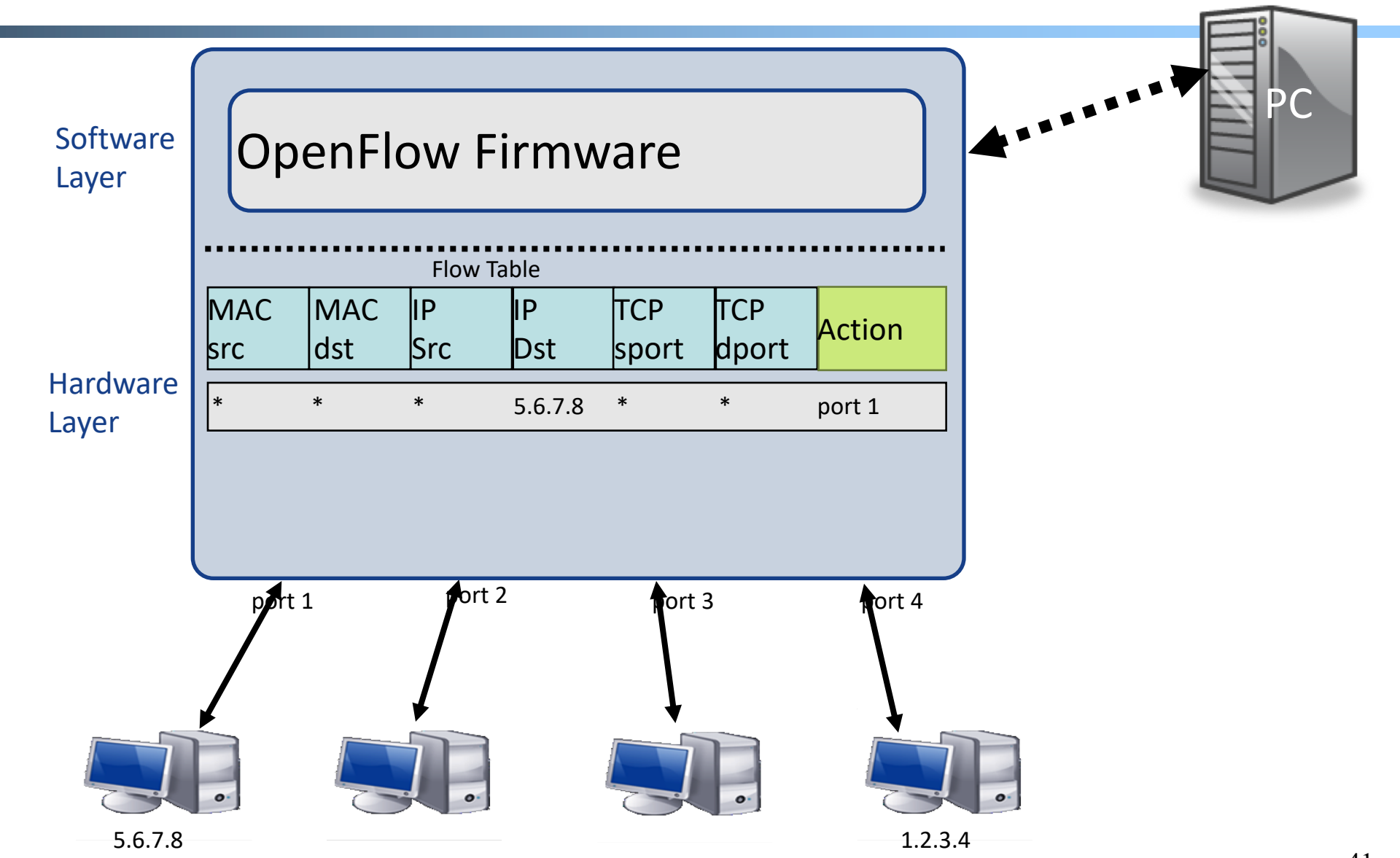


Datapath Model: OpenFlow



Priority	Match	Action
1000	tcp_dst:22	drop
20	ip_dst: 101.22.0.0/16	port 2
1	in_port:1, mac_dst: 0xffffffffffff	ports 2,3,4

OpenFlow Datapath: Example



OpenFlow Datapath: Examples

Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f:..	*	*	*	*	*	*	*	port6

Flow Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
port3	00:20..	00:1f..	0800	vlan1	1.2.3.4	5.6.7.8	4	17264	80	port6

Firewall

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

OpenFlow Datapath: Examples

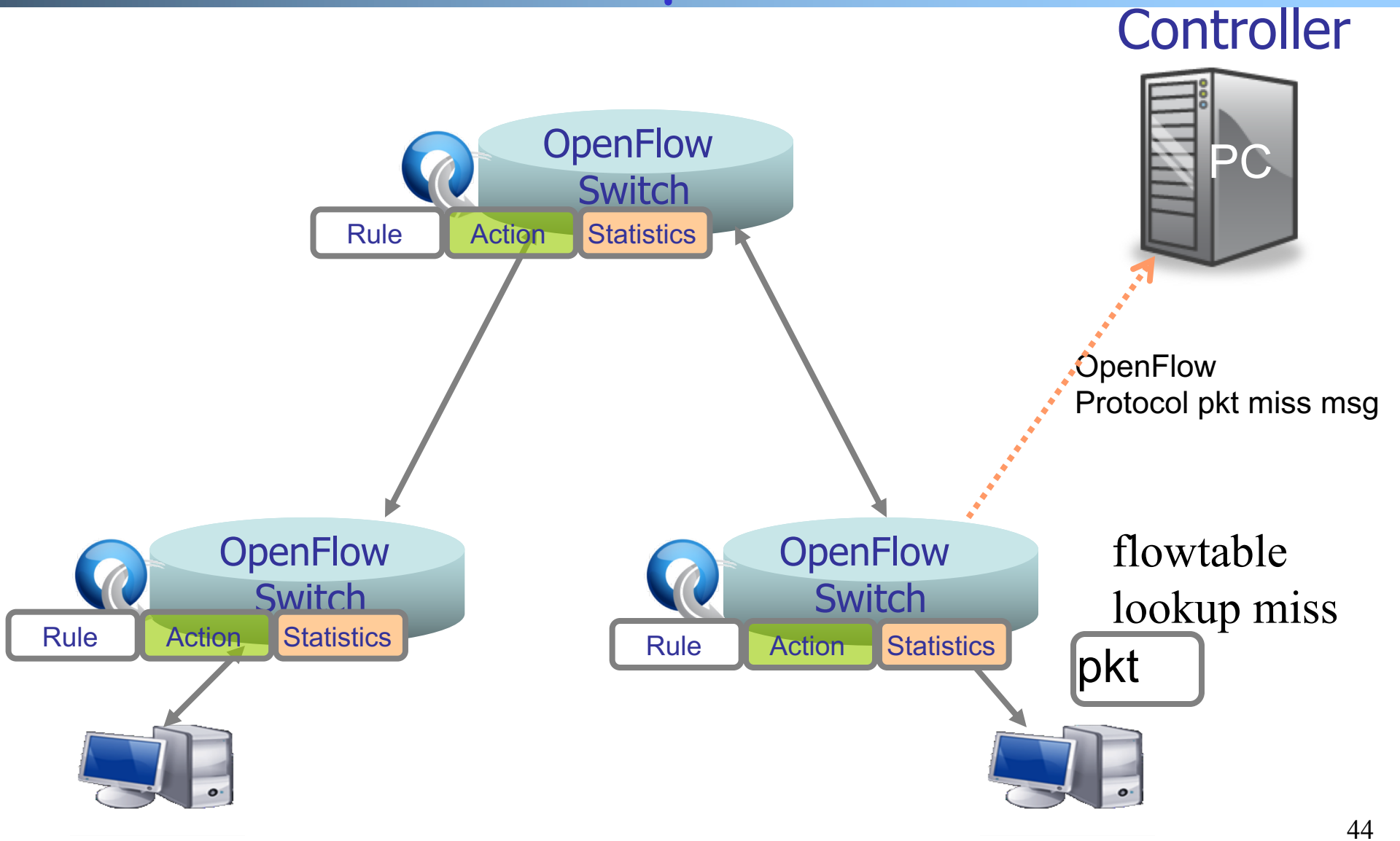
Routing

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	5.6.7.8	*	*	*	port6

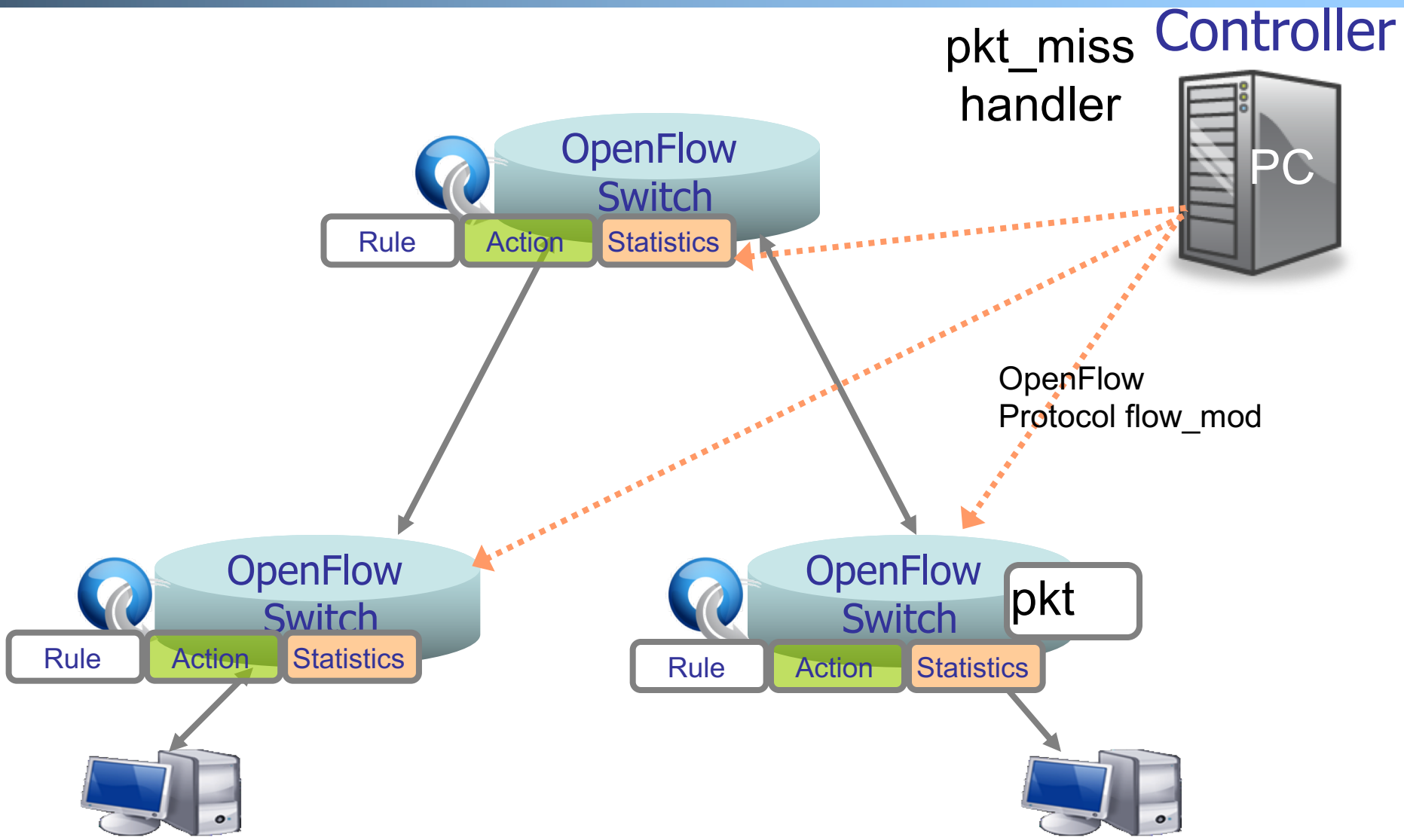
VLAN Switching

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	00:1f..	*	vlan1	*	*	*	*	*	port6, port7, port9

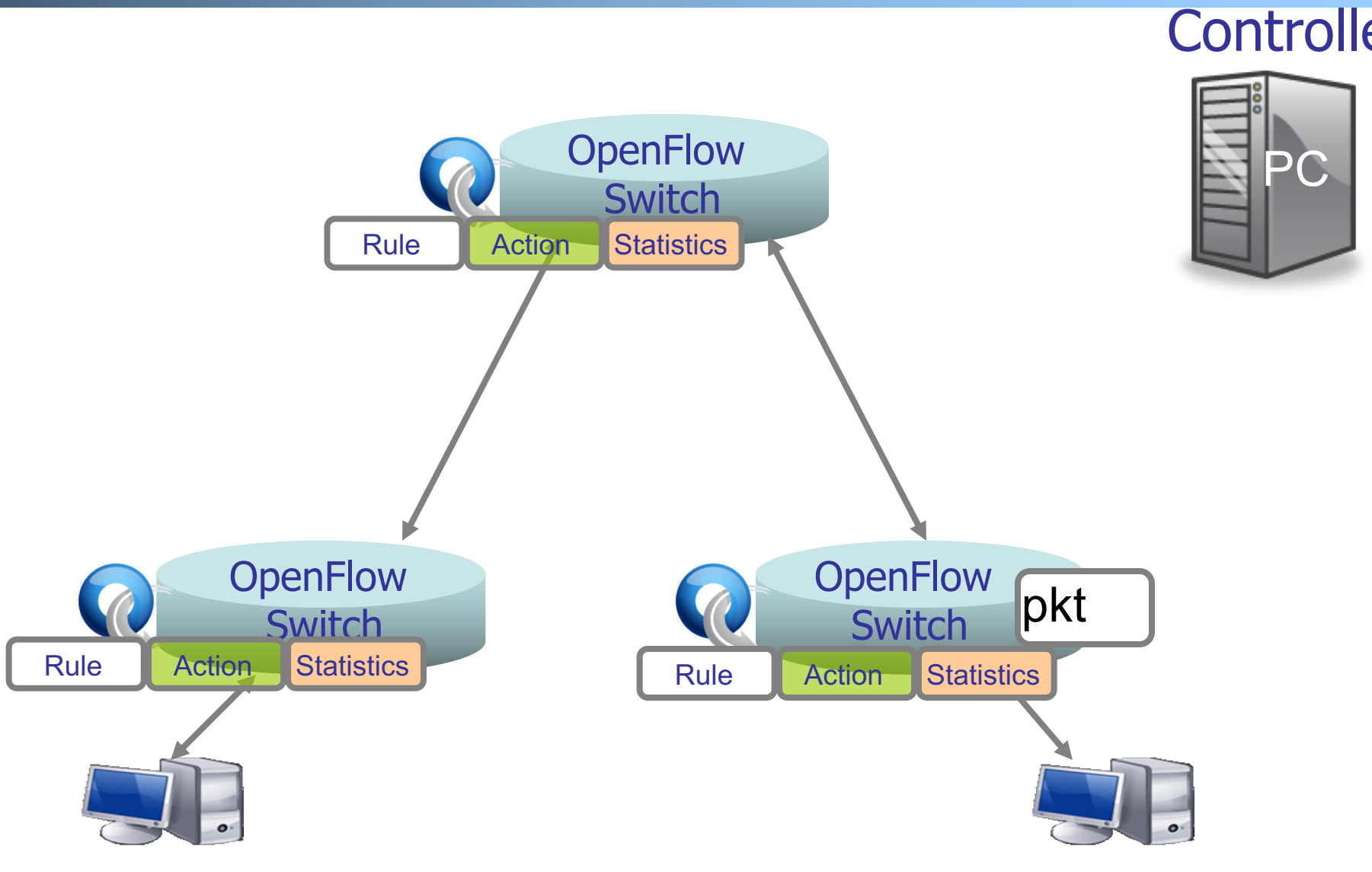
OpenFlow Message Flows: Reactive Mode (pkt miss)



OpenFlow Message Flows: Reactive Mode (flow mod)



OpenFlow Message Flows: Reactive Mode (forward)



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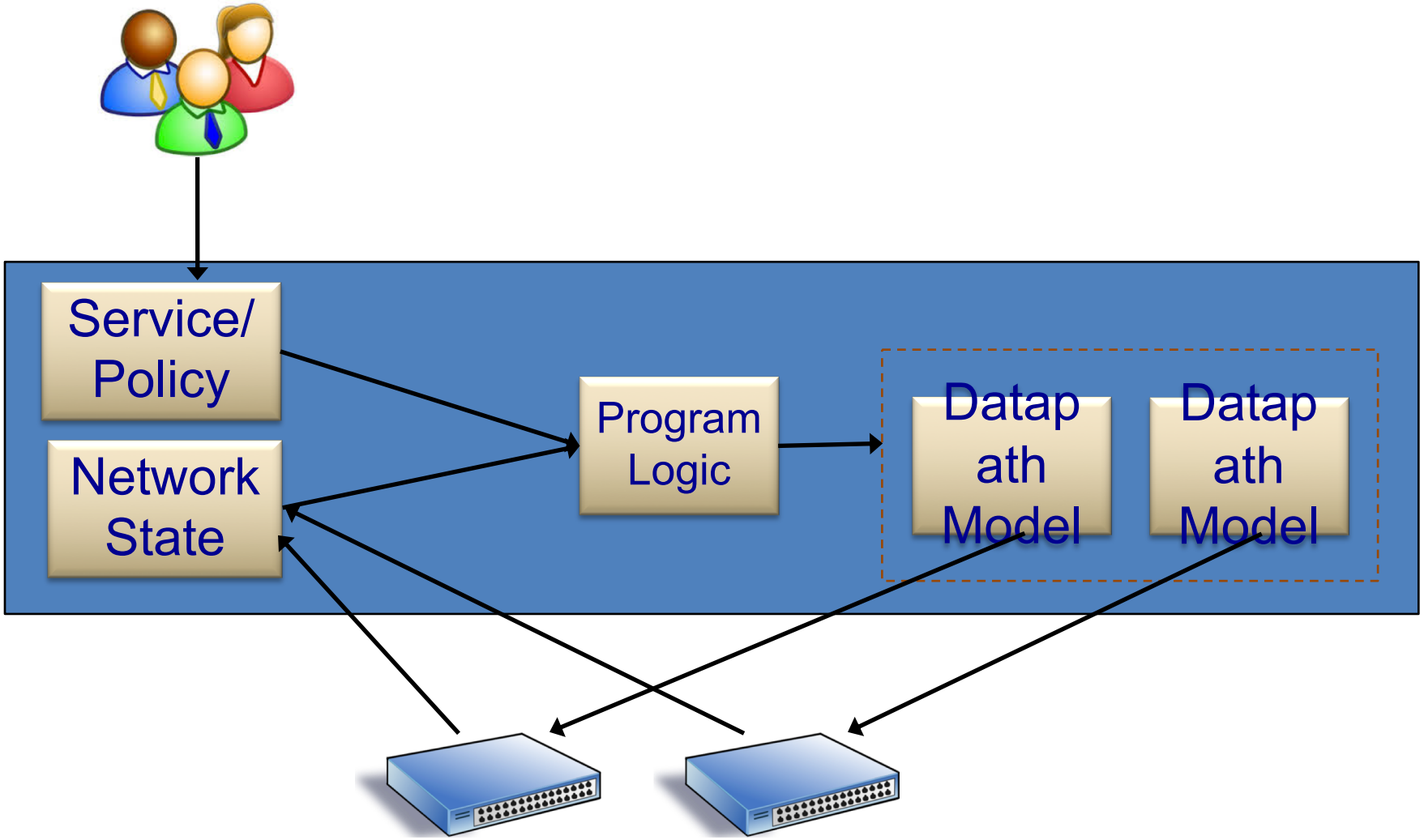
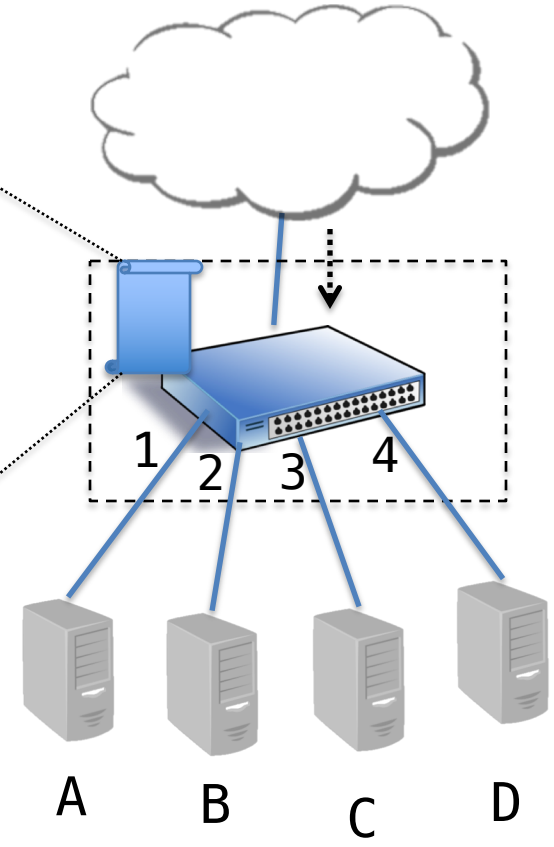
  - Motivation: from simple forwarding to network functions
  - Design overview
  - Data path (OpenFlow)
  - Control path (programming model) [Optional]

SDN Programming Model



An Example: A Simple SDN Controller

```
badPort = 22          // policy
hostTbl = {A:1,B:2,
           C:3,D:4} // net view

def onPacketIn(p):
  if badPort == p.tcp_dst:
    drop
  else:
    forward([hostTbl(p.eth_dst)])
```



Assume only packets to A,B,C,D can appear.

Controller Program with Flow Table Management

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({‘match':{'tcp_dst':22},
         ‘action’:[]})

  else:
   forward([hostTbl(p.eth_dst)])

 installRule({‘match’: {‘eth_dst’:p.eth_dst,
              ’tcp_dst’!=22},
        ‘action’:[hostTbl(p.eth_dst)]})
```

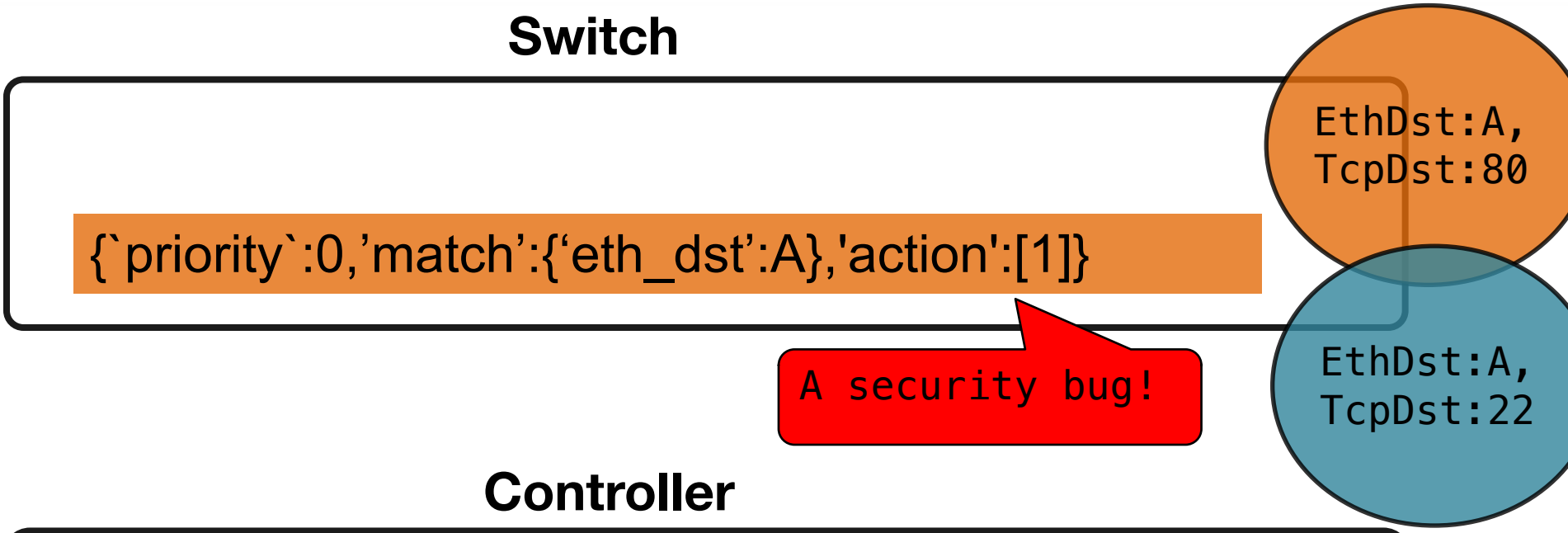
match does not support logic negation

Controller Program with Flow Table Management

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({'priority':1,
        'match':{'tcp_dst':22},
        'action':[]})

  else:
    forward([hostTbl(p.eth_dst)])

  installRule({'priority':0,
        'match': {'eth_dst':p.eth_dst},
        'action':[hostTbl(p.eth_dst)]})
```

Does the Program Work?

Switch



Controller

```
def onPacketIn(p):
  if 22 == p.tcp_dst:
   drop
   installRule({`priority`:1,'match':{'tcp_dst':22},'action':[]})
  else:
   installRule({`priority`:0,'match':{'eth_dst':p.eth_dst},
                'action':[hostTbl(p.eth_dst)]})
   forward([hostTbl(p.eth_dst)])
```

OVS Approach: Using Exact Match

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({'priority':1,
        'match':exactMatch(p),
        'action':[]})

  else:
    forward([hostTbl(p.eth_dst)])

  installRule({'priority':0,
        'match':exactMatch(p),
        'action':[hostTbl(p.eth_dst)]})
```

Problems of OVS Approach

	Match									
Priority	inport	MAC src	MAC dst	MAC proto	IP src	IP dst	TCP src	TCP dst	...	Action
0	1	B	A	0x0806	12...	78...	...	22		drop
0	1	B	A	0x0806	12...	78...	9881	80		port 1
0	1	B	A	0x0806	12...	78...	...	7231		port 1
0	2	C	A	0x0806	32...	78...	...	7232		port 1
0	1	A	B	0x0806	78...	12...	80	9881		port 2

- Each new TCP flow delayed for flow setup (10-100 ms)
- Number of flow table rules may exceed capacity (typically a few thousands)

Outline

- Admin and recap
- Link layer
- Software defined networking
  - Motivation: from simple forwarding to network functions
  - Design overview
  - Data path (OpenFlow)
  - Control path (programming model)
    - Problems
    - What would you do?

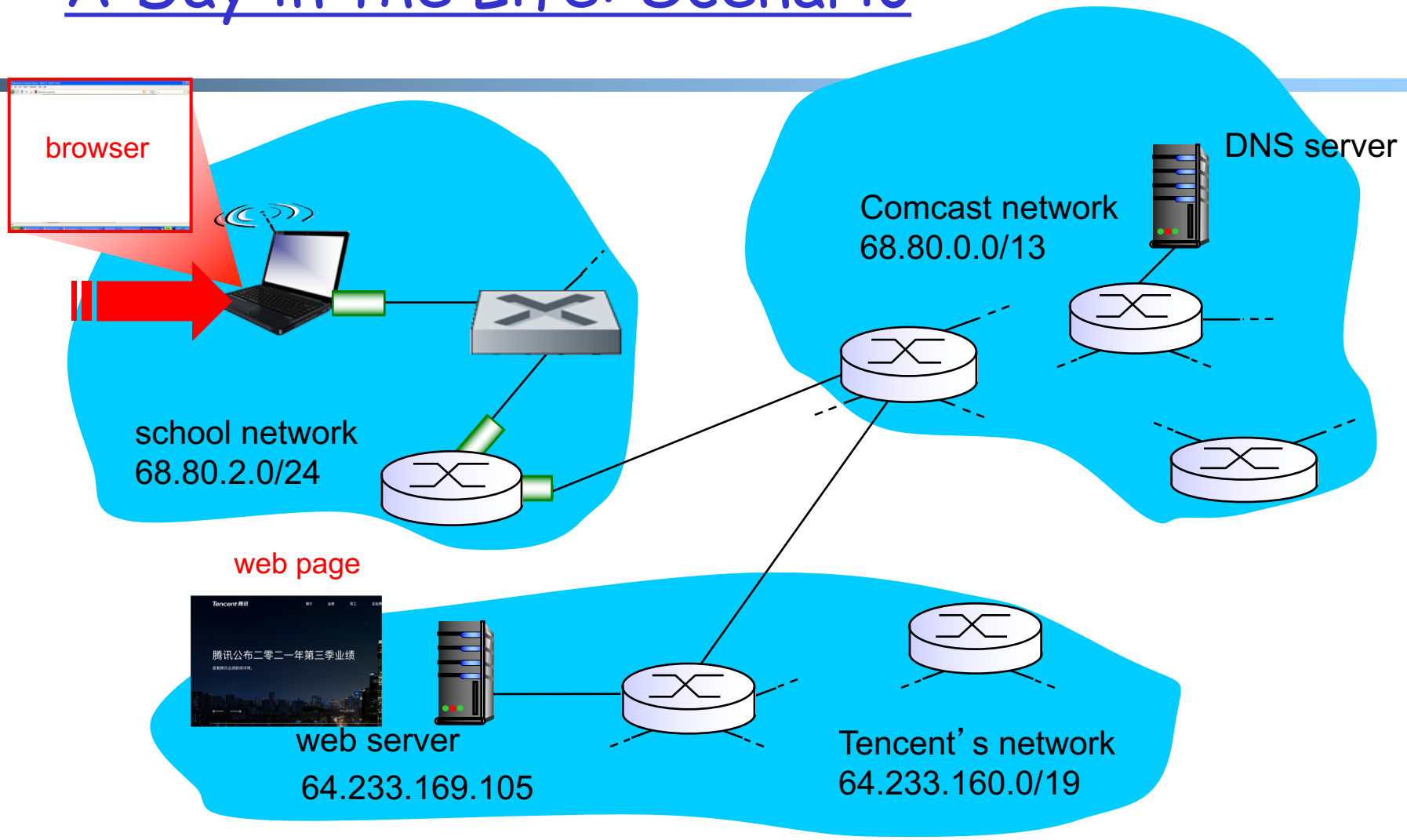
Outline

- Admin and recap
- Link layer
- Software defined networking
  - Motivation: from simple forwarding to network functions
  - Design overview
  - Data path (OpenFlow)
  - Control path (programming model) [Optional]
- Course Summary

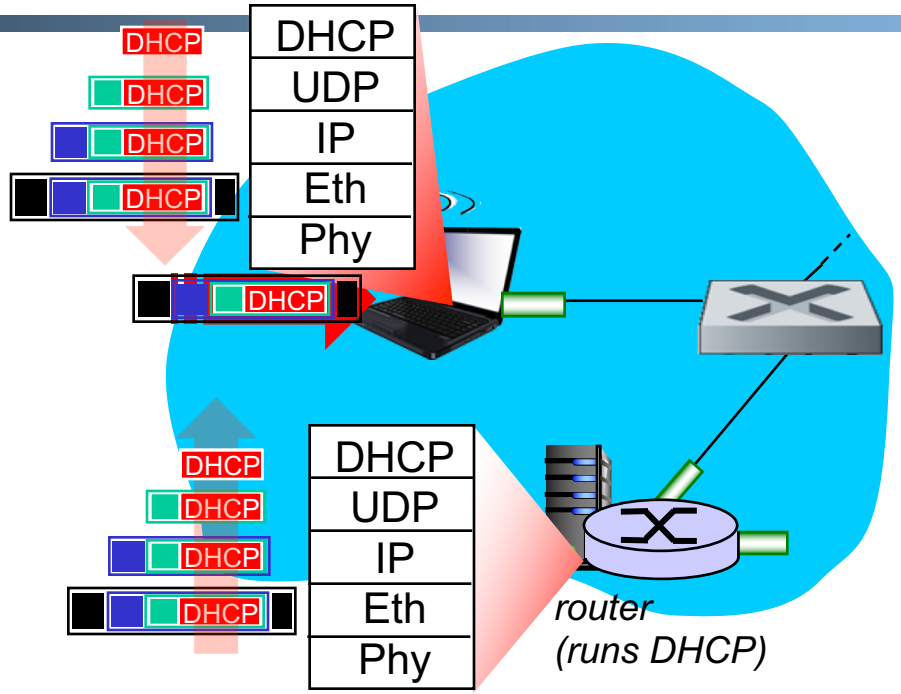
Synthesis: A Day in the Life of a Web Request

- journey down protocol stack complete!
  - application, transport, network, link
- putting-it-all-together: synthesis!
  - *goal:* identify, review, understand protocols (at all layers) involved in seemingly simple scenario: requesting www page
  - *scenario:* student attaches laptop to campus network, requests/receives www.tencent.com

A Day in the Life: Scenario

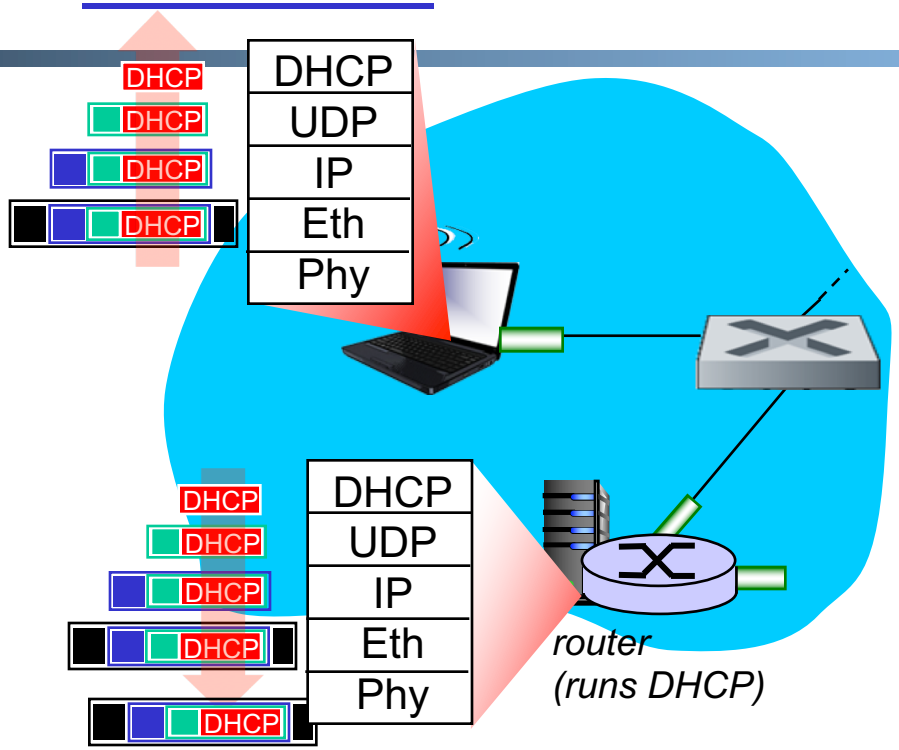


A Day in the Life… Connecting to the Internet



- connecting laptop needs to get its own IP address, addr of first-hop router, addr of DNS server: use *DHCP*
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.3 Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

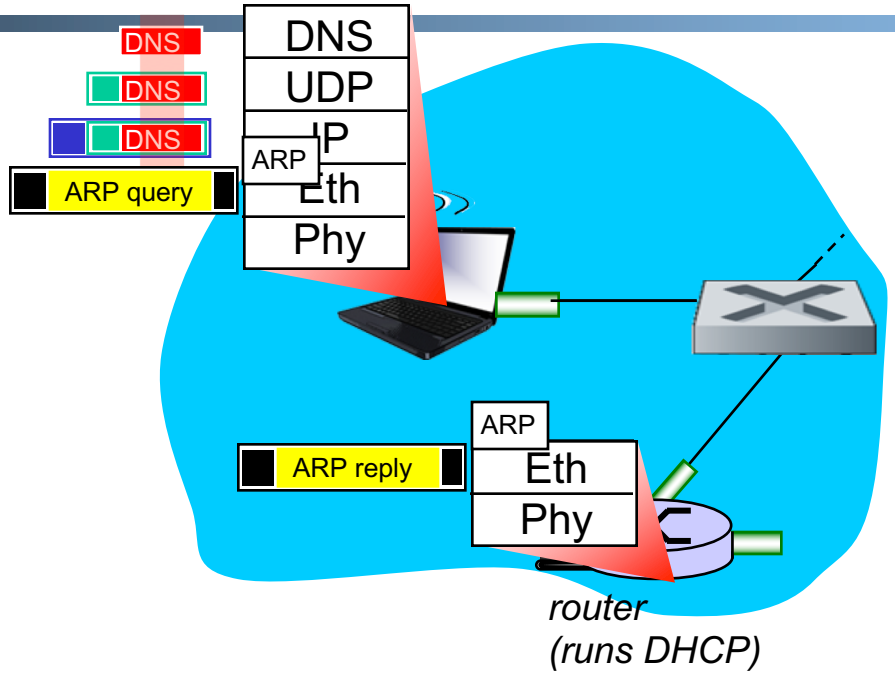
A Day in the Life… Connecting to the Internet



- DHCP server formulates *DHCP ACK* containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation at DHCP server, frame forwarded (switch learning) through LAN, demultiplexing at client
- DHCP client receives DHCP ACK reply

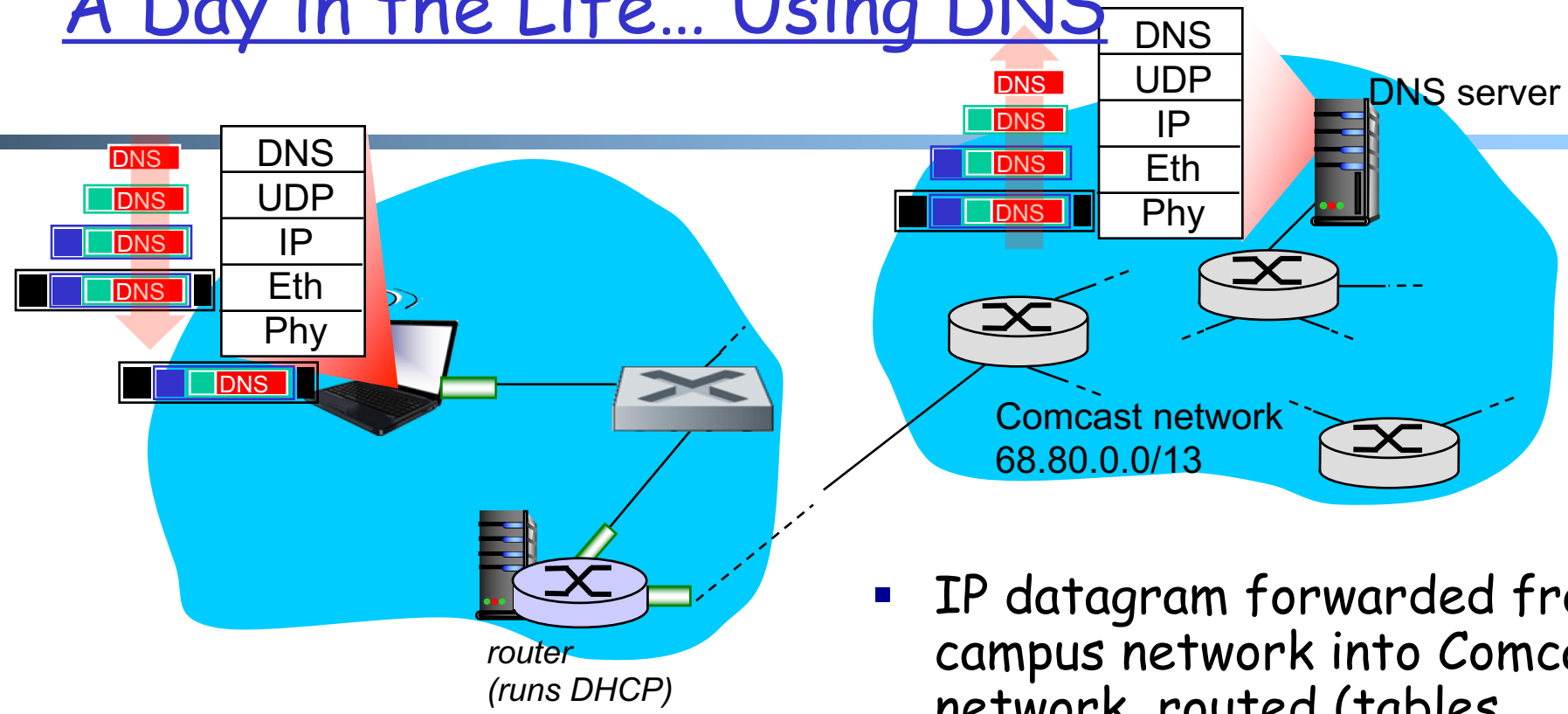
Client now has IP address, knows name & addr of DNS server, IP address of its first-hop router

A Day in the life… ARP (before DNS, before HTTP)



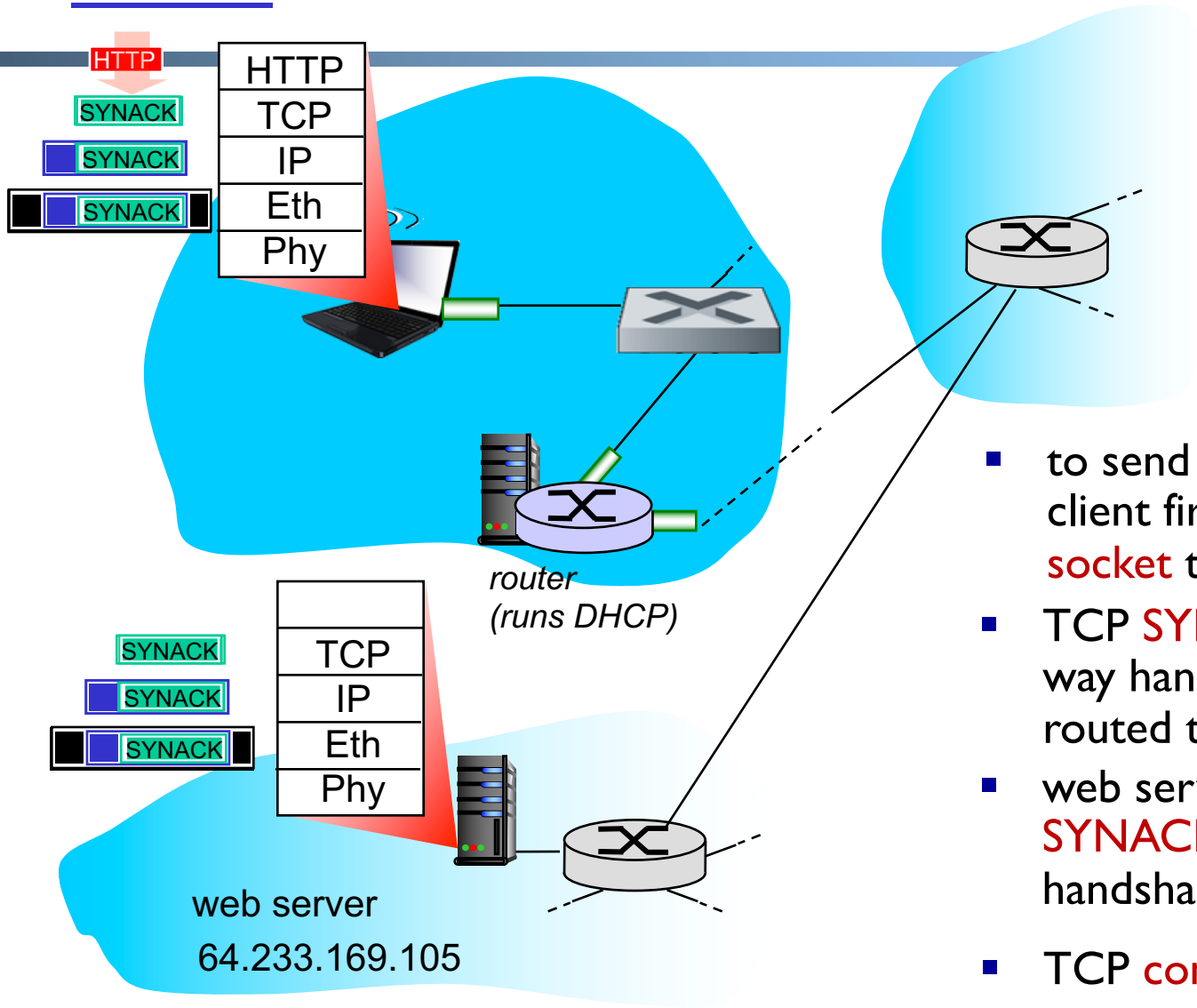
- before sending *HTTP* request, need IP address of www.tencent.com: *DNS*
- DNS query created, encapsulated in UDP, encapsulated in IP, encapsulated in Eth. To send frame to router, need MAC address of router interface: ARP
- ARP query broadcast, received by router, which replies with ARP reply giving MAC address of router interface
- client now knows MAC address of first hop router, so can now send frame containing DNS query

A Day in the Life… Using DNS



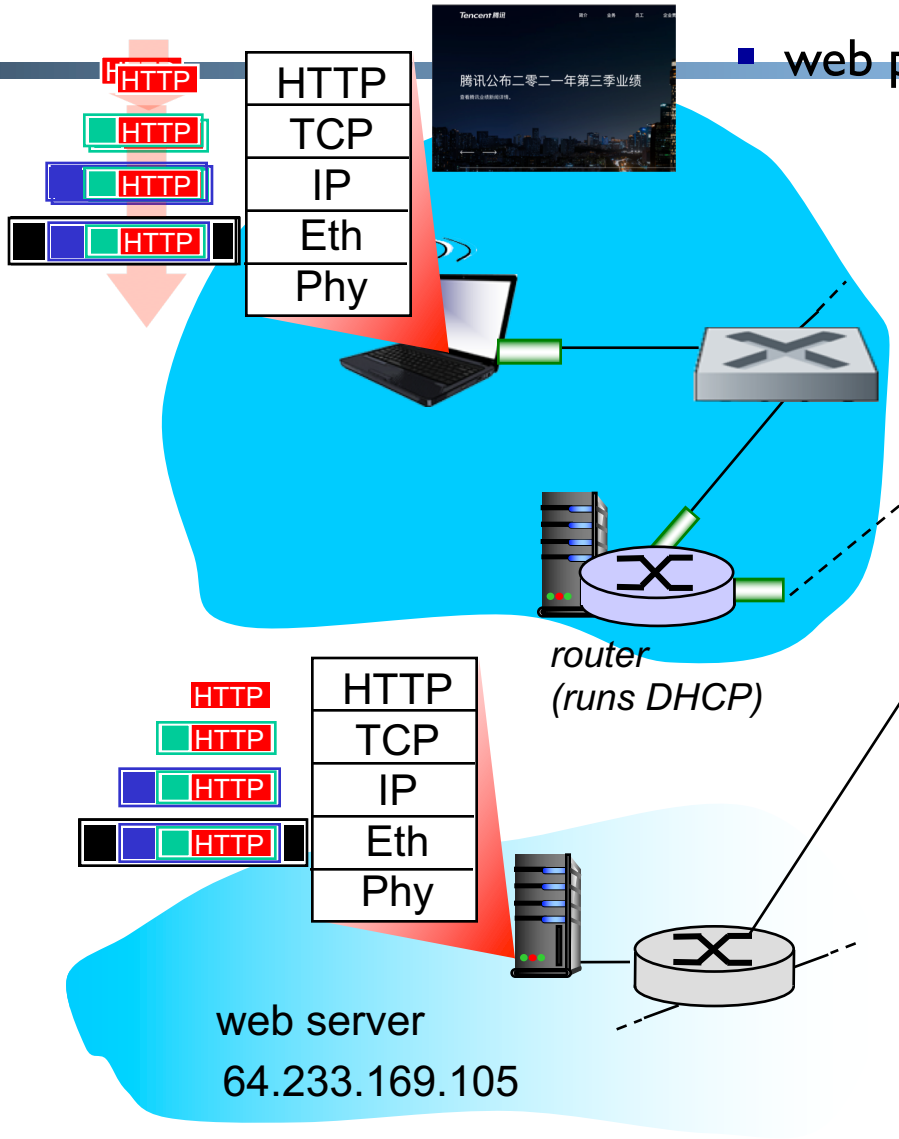
- IP datagram containing DNS query forwarded via LAN switch from client to 1st hop router
- IP datagram forwarded from campus network into Comcast network, routed (tables created by RIP, OSPF, IS-IS and/or BGP routing protocols) to DNS server
- demuxed to DNS server
- DNS server replies to client with IP address of www.tencent.com

A Day in the Life…TCP Connection Carrying HTTP



- to send HTTP request, client first opens TCP socket to web server
- TCP SYN segment (step 1 in 3-way handshake) inter-domain routed to web server
- web server responds with TCP SYNACK (step 2 in 3-way handshake)
- TCP connection established!

A Day in the Life... HTTP Request/Reply



- web page finally (!!!) displayed

- HTTP request sent into TCP socket
- IP datagram containing HTTP request routed to www.tencent.com
- web server responds with HTTP reply (containing web page)
- IP datagram containing HTTP reply routed back to client

Course Topics Summary

- The Internet is a general-purpose, large-scale, distributed computer network
- Major design features/principles
  - packet switching/statistical multiplexing
    - time-reversibility, queueing theory and performance analysis
  - layered architecture, hour-glass architecture
    - end-to-end principle
  - decentralized (social-technocal) architecture
    - e.g., DNS (hierarchy delegation), interdomain routing (peer-to-peer)
  - resource allocation framework
    - axiom-based design (NBS); optimization decomposition through duality
  - adaptive control
    - e.g., sliding window self clocking, AIMD adaptation, Ethernet exp backoff
  - tradeoff between theoretical impossibility and practice

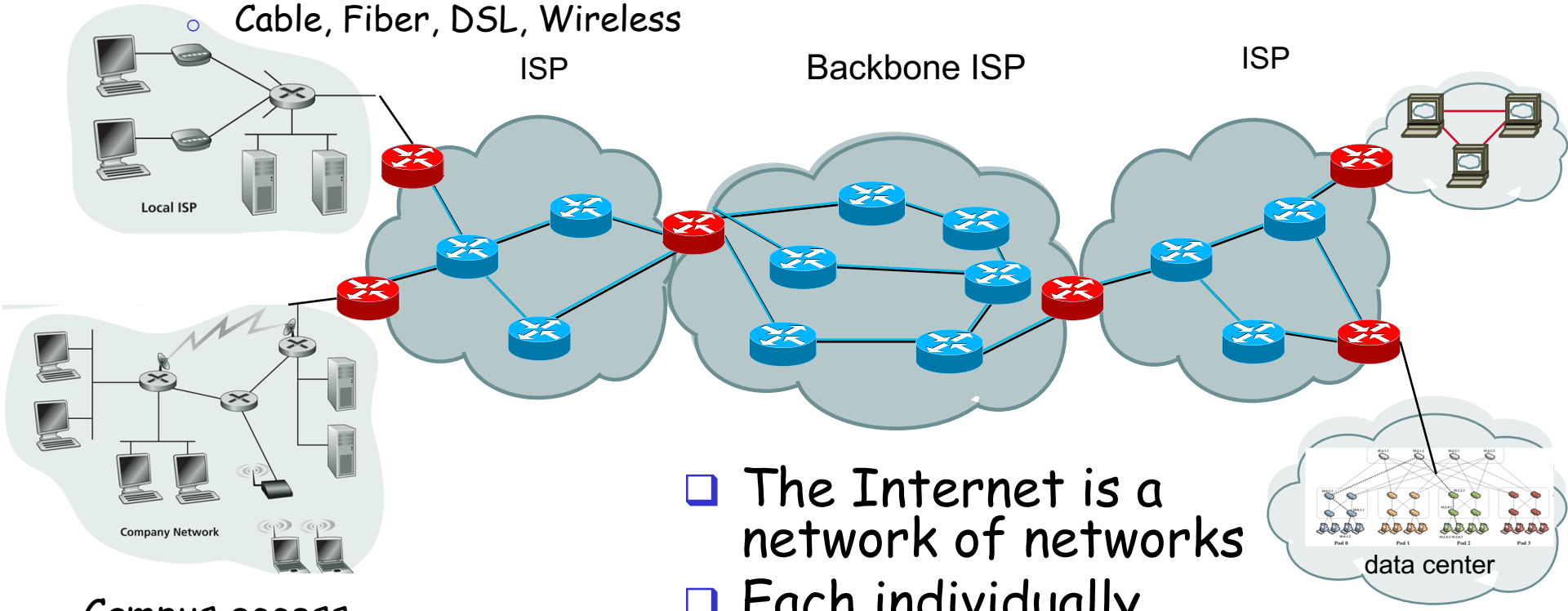
First-Day Class: What is a Network Protocol?

- A **network protocol** defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission and/or receipt of a message or other events.

Protocols that we have touched on?

First-Day Class: Internet Physical Infrastructure

Residential access
- Cable, Fiber, DSL, Wireless



Campus access, e.g.,
- Ethernet
- Wireless

- The Internet is a network of networks
- Each individually administrated network is called an Autonomous System (AS)

https://www.google.com/loon/how/

First-Day Class: General Complexity

- Complexity in highly organized systems arises primarily from design strategies intended to create robustness to uncertainty in their environments and component parts.
  - Scalability is robustness to changes to the size and complexity of a system as a whole.
  - Evolvability is robustness of lineages to large changes on various (usually long) time scales.
  - Reliability is robustness to component failures.
  - Efficiency is robustness to resource scarcity.
  - Modularity is robustness to component rearrangements.

First-Day Class: Evolution

- Driven by Technology, Infrastructure, Policy, Applications (usage), and Understanding:
  - technology
    - e.g., wireless/optical communication technologies and device miniaturization (sensors)
  - infrastructure
    - e.g., cloud computing vs local computing
  - applications (usage)
    - e.g., mobile computing, content distribution, game, tele presence, sensing
  - understanding
    - e.g., resource sharing principle, routing principles, mechanism design, optimal stochastic control (randomized access)
- Complexity comes from evolution.
- Don't be afraid to challenge the foundation and redesign!

Have a great winter break!

Optional Read:
Channel Partitioning MAC

Example Channel Partitioning: CDMA

CDMA (Code Division Multiple Access)

- Used mostly in wireless broadcast channels (cellular, satellite, etc)
- A spread-spectrum technique

Hedy Lamarr and George Antheil. Photo of Hedy Lamarr courtesy of the Academy of Motion Picture Arts & Sciences. Photo of George Antheil courtesy of the Estate of George Antheil.

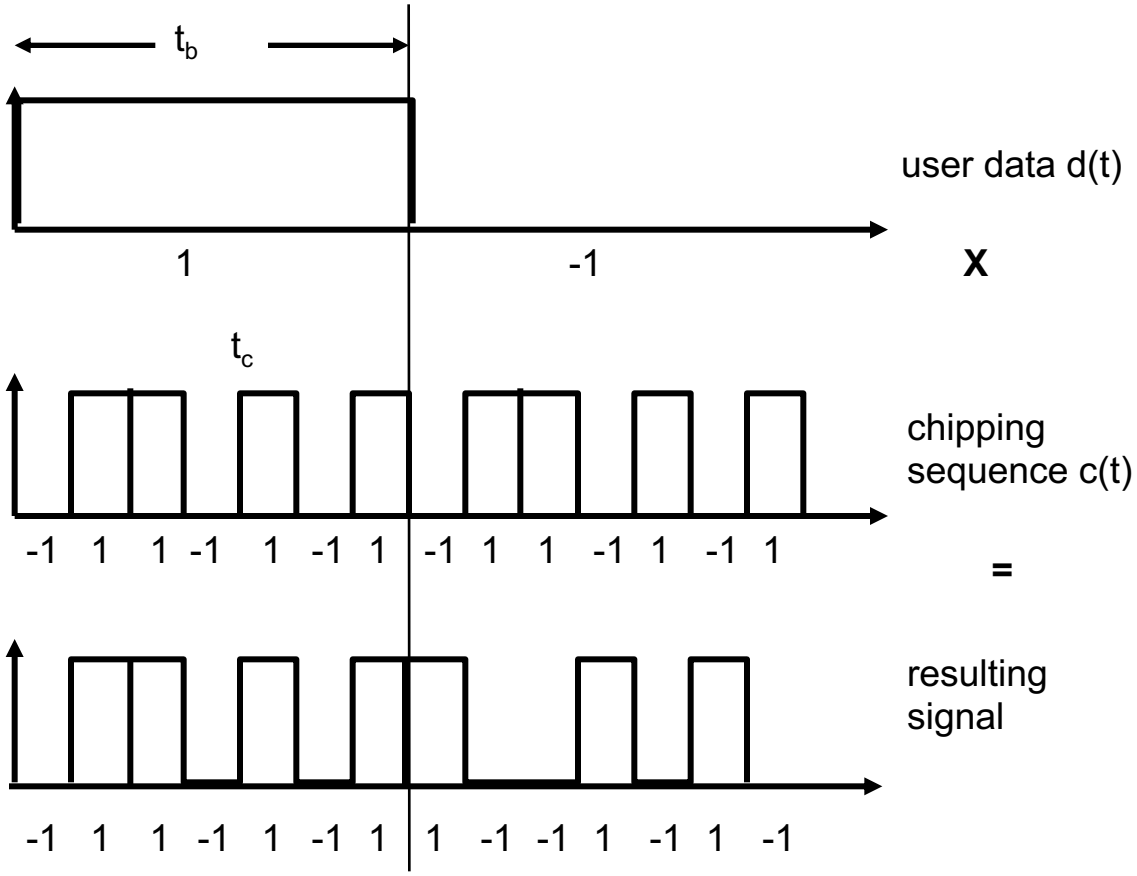
History: http://people.seas.harvard.edu/~jones/cscie129/nu_lectures/lecture7/hedy/lemarr.htm

Examples: Sprint and Verizon, WCDMA

CDMA: Encoding

- All users share same frequency, but each user m has its own unique "chipping" sequence (i.e., code) c_m to encode data, i.e., code set partitioning
  - e.g. c_m = 1 1 1 -1 1 -1 -1 -1
- Assume original data are represented by 1 and -1
- *Encoded signal* = (original data) modulated by (chipping sequence)
  - assume c_m = 1 1 1 -1 1 -1 -1 -1
  - if data is d, send d c_m,
    - if data d is 1, send c_m
    - if data d is -1 send $-c_m$

CDMA: Encoding



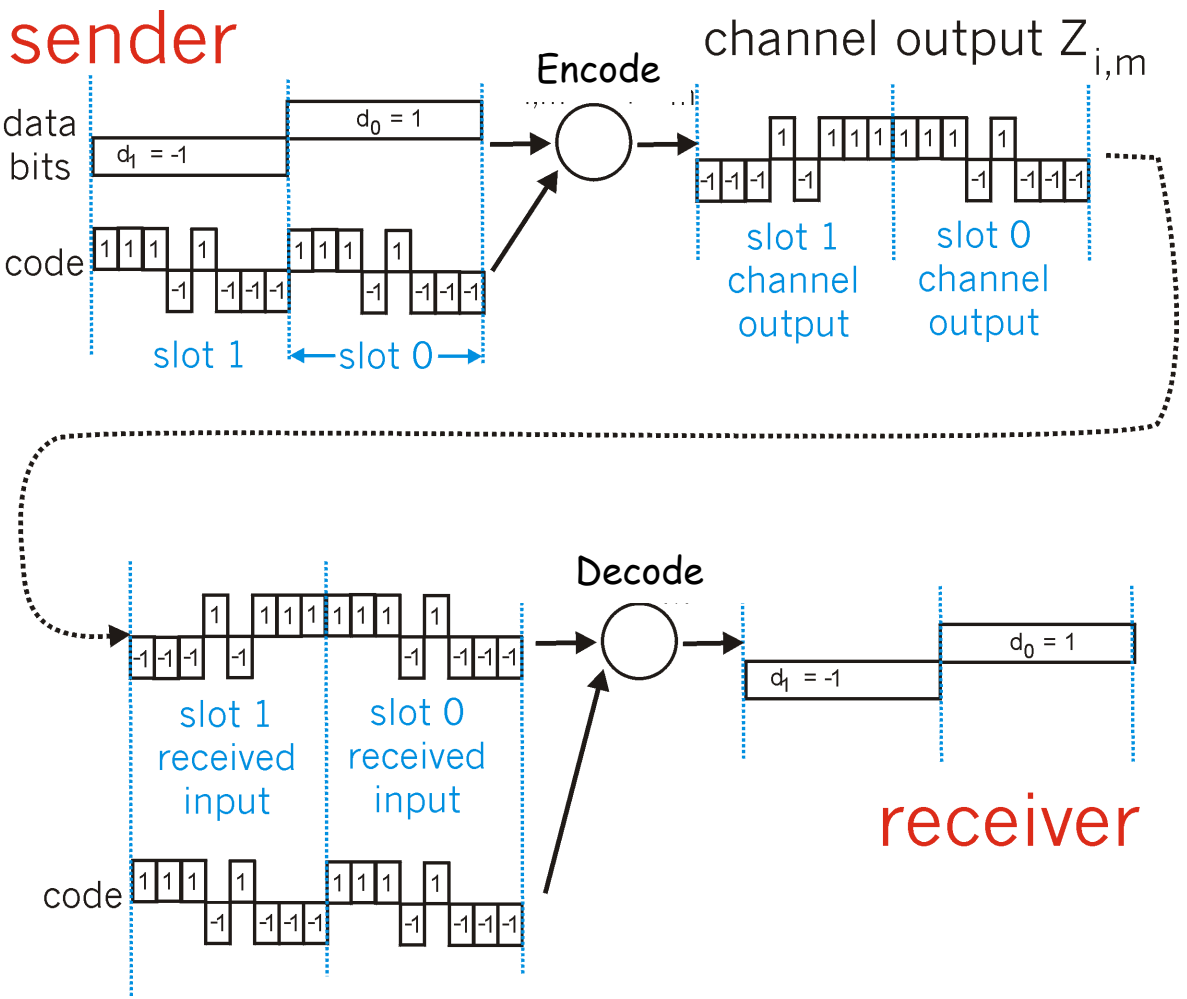
t_b: bit period
t_c: chip period

CDMA: Decoding

- Inner-product (summation of bit-by-bit product) of encoded signal and chipping sequence
  - if inner-product > 0, the data is 1; else -1

CDMA Encode/Decode

Code of user m c_m:
1 1 1 -1 1 -1 -1 -1



- The number of bits of each chipping sequence is M

CDMA: Deal with Multiple-User Interference

- Two codes c_i and c_j are orthogonal, if
  - $c_j \bullet c_i = 0$, where we use "•" to denote inner product, e.g.

C_1:	1	1	1	-1	1	-1	-1	-1
C_2:	1	-1	1	1	1	-1	1	1
$C_1 \bullet C_2$ =	1 +(-1) + 1 + (-1)			+1 +	1+ (-1)+(-1)=0			

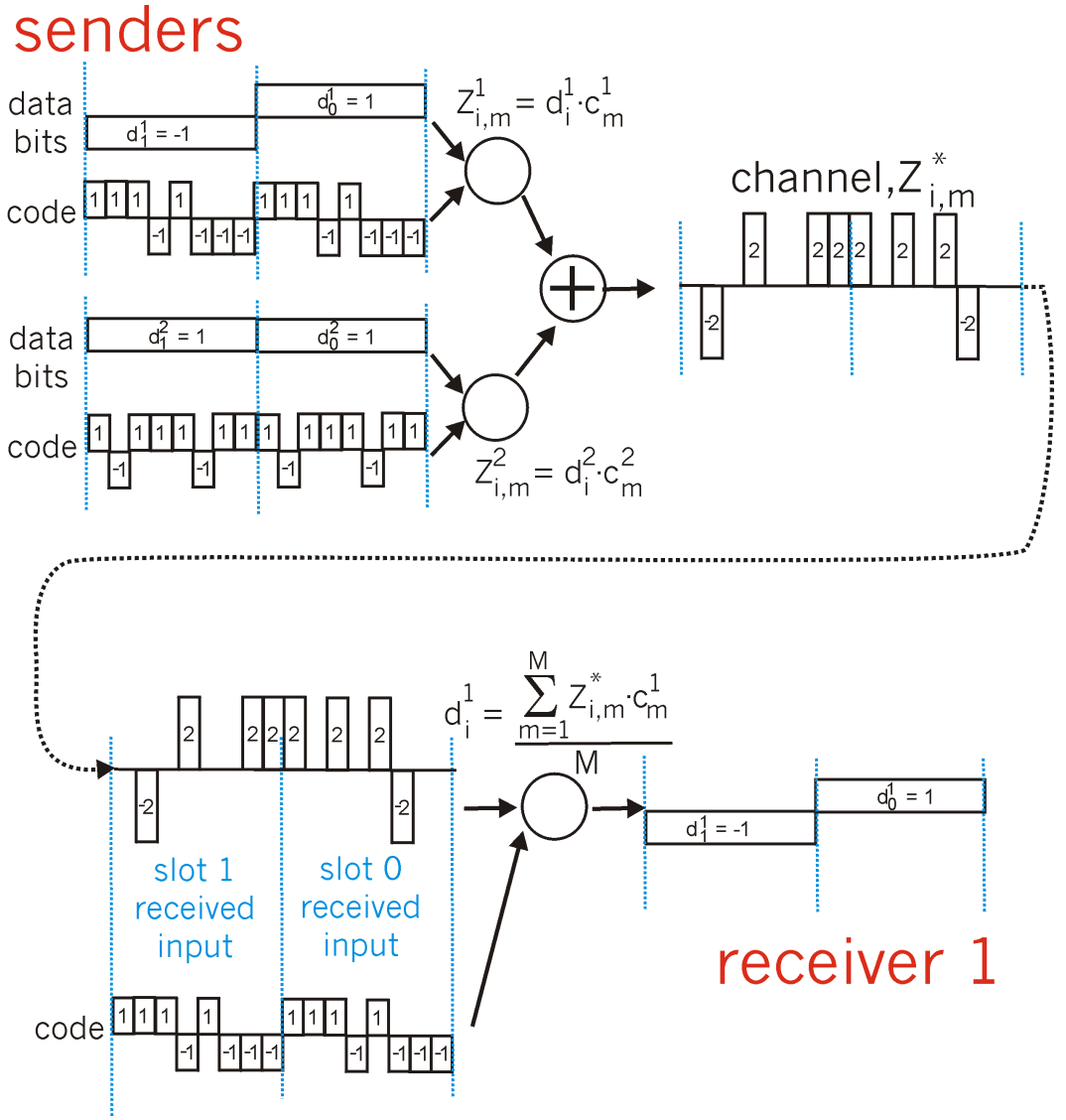
- If codes are orthogonal, multiple users can "coexist" and transmit simultaneously with minimal interference:

$$(\sum_j d_j c_j) \bullet c_i = d_i \|c_i\|$$

Analogy: Speak in different languages!

CDMA: Two-Sender Interference

Code 1: 1 1 1 -1 1 -1 -1 -1
Code 2: 1 -1 1 1 1 -1 1 1



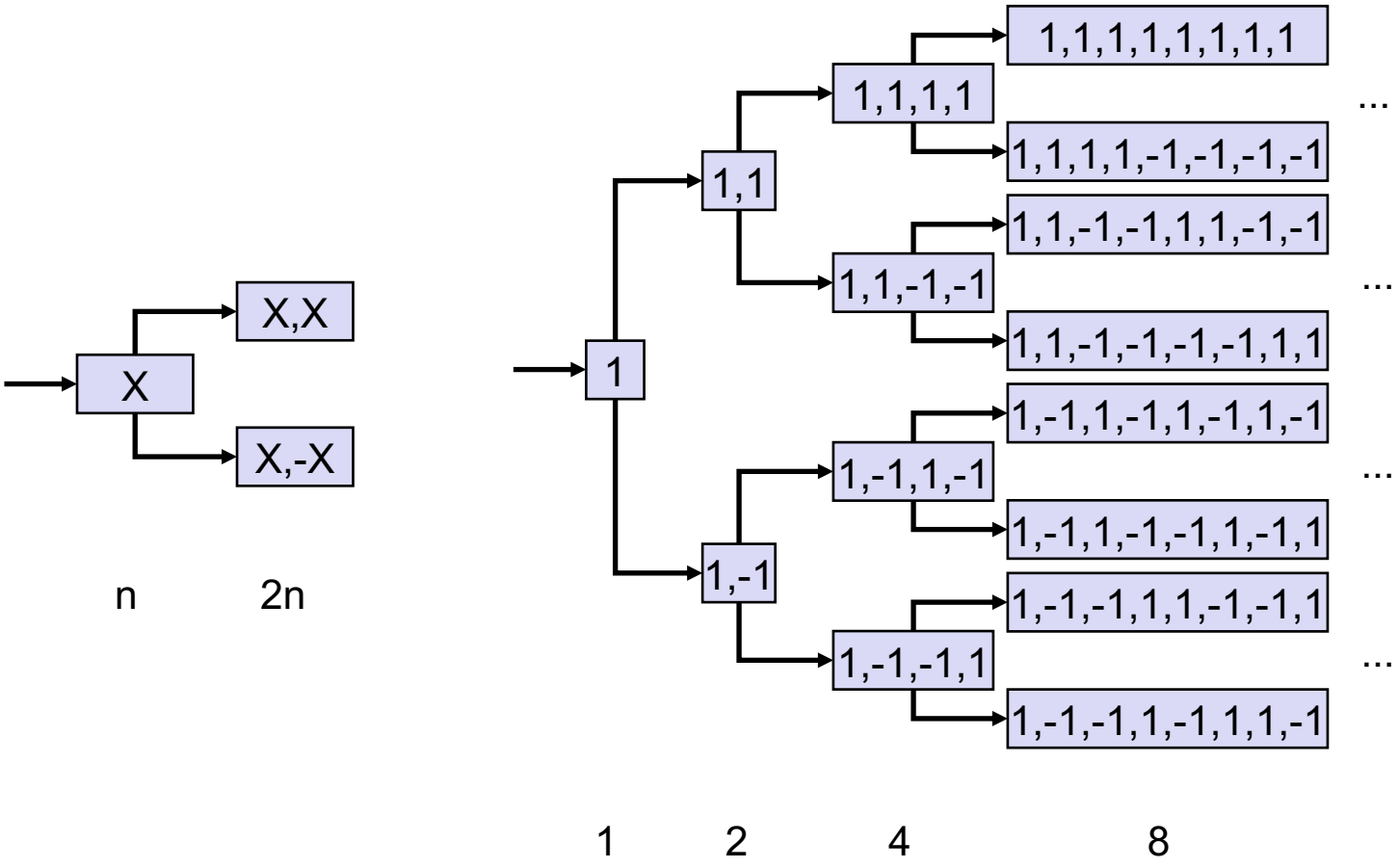
Generating Orthogonal Codes

- The most commonly used orthogonal codes in current CDMA implementation are the Walsh Codes

$$W_0 = (1)$$

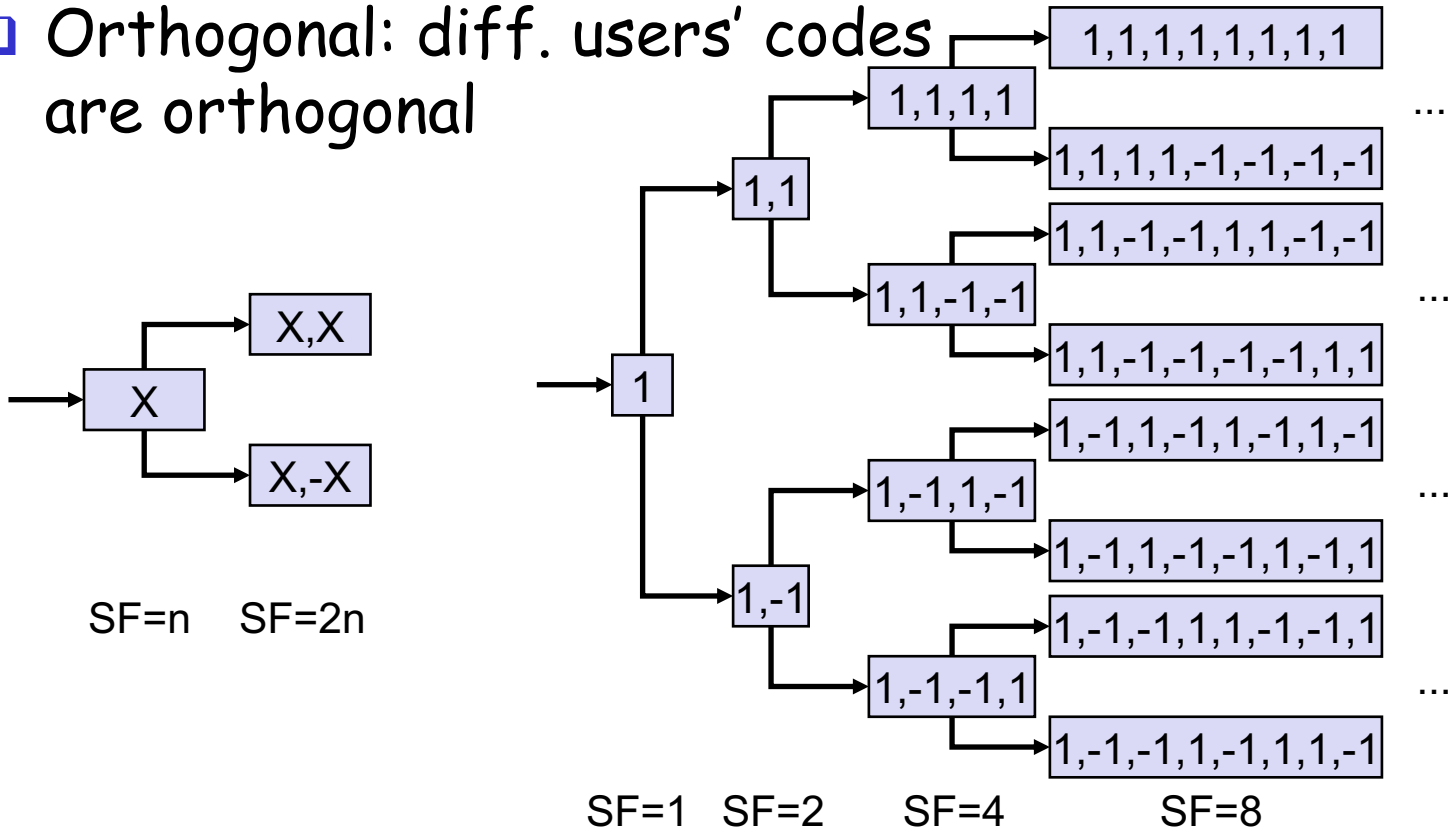
$$W_{2n} = \begin{pmatrix} W_n & W_n \\ W_n & \overline{W}_n \end{pmatrix}$$

Walsh Codes


X
X,X
X,-X
n
2n
1
1,1
1,-1
1,1,1,1
1,1,-1,-1
1,-1,1,-1
1,-1,-1,1
1,1,1,1,1,1,1,1
1,1,1,1,-1,-1,-1,-1
1,1,-1,-1,1,1,-1,-1
1,1,-1,-1,-1,-1,1,1
1,-1,1,-1,1,-1,1,-1
1,-1,1,-1,-1,1,-1,1
1,-1,-1,1,1,-1,-1,1
1,-1,-1,1,-1,1,1,-1
...
...
...
1
2
4
8

Orthogonal Variable Spreading Factor (OSVF)

- Variable codes: Different users use different lengths spreading codes
- Orthogonal: diff. users' codes are orthogonal



If user 1 is given code [1,1], what orthogonal codes can we give to other users?

WCDMA Orthognal Variable Spreading Factor (OSVF)

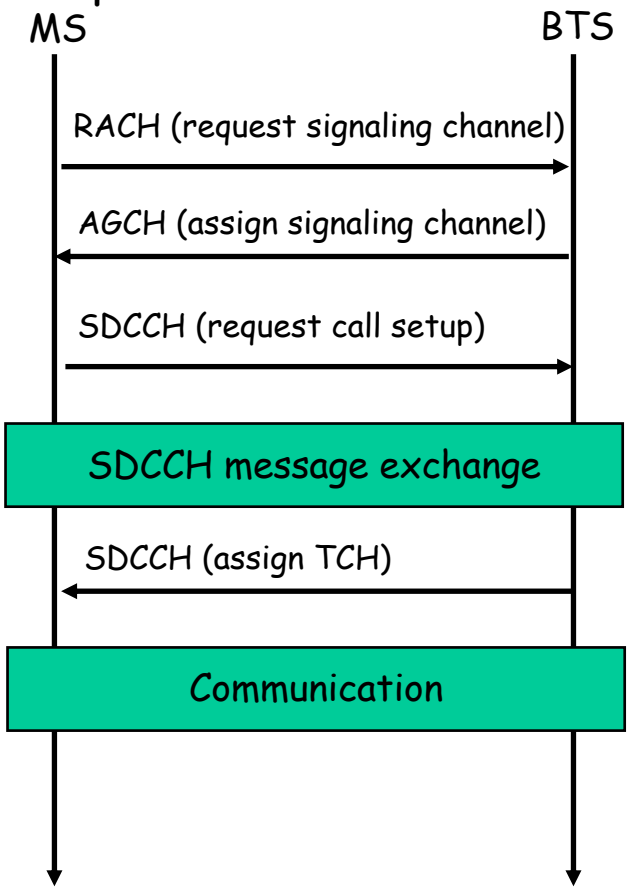
- Flexible code (spreading factor) allocation
  - up link SF: 4 – 256
  - down link SF: 4 - 512

WCDMA downlink

Spreading factor	Channel symbol rate (kbps)	Channel bit rate (kbps)	DPDCH channel bit rate range (kbps)	Max. user data rate with ½ rate coding (approx.)
512	7.5	15	3-6	1-3 kbps
256	15	30	12-24	6-12 kbps
128	30	60	42-51	20-24 kbps
64	60	120	90	45 kbps
32	120	240	210	105 kbps
16	240	480	432	215 kbps
8	480	960	912	456 kbps
4	960	1920	1872	936 kbps
4, with 3 parallel codes	2880	5760	5616	2.3 Mbps

Combined Random Access + Channel Partition: GSM Logical Channels and Request

- call setup from an MS



- Control channels
  - Broadcast control channel (BCCH)
    - from base station, announces cell identifier, synchronization
  - Common control channels (CCCH)
    - paging channel (PCH): base transceiver station (BTS) pages a mobile host (MS)
    - random access channel (RACH): MSs for initial access, **slotted Aloha**
    - access grant channel (AGCH): BTS informs an MS its allocation
  - Dedicated control channels
    - standalone dedicated control channel (SDCCH): signaling and short message between MS and an MS
- Traffic channels (TCH)

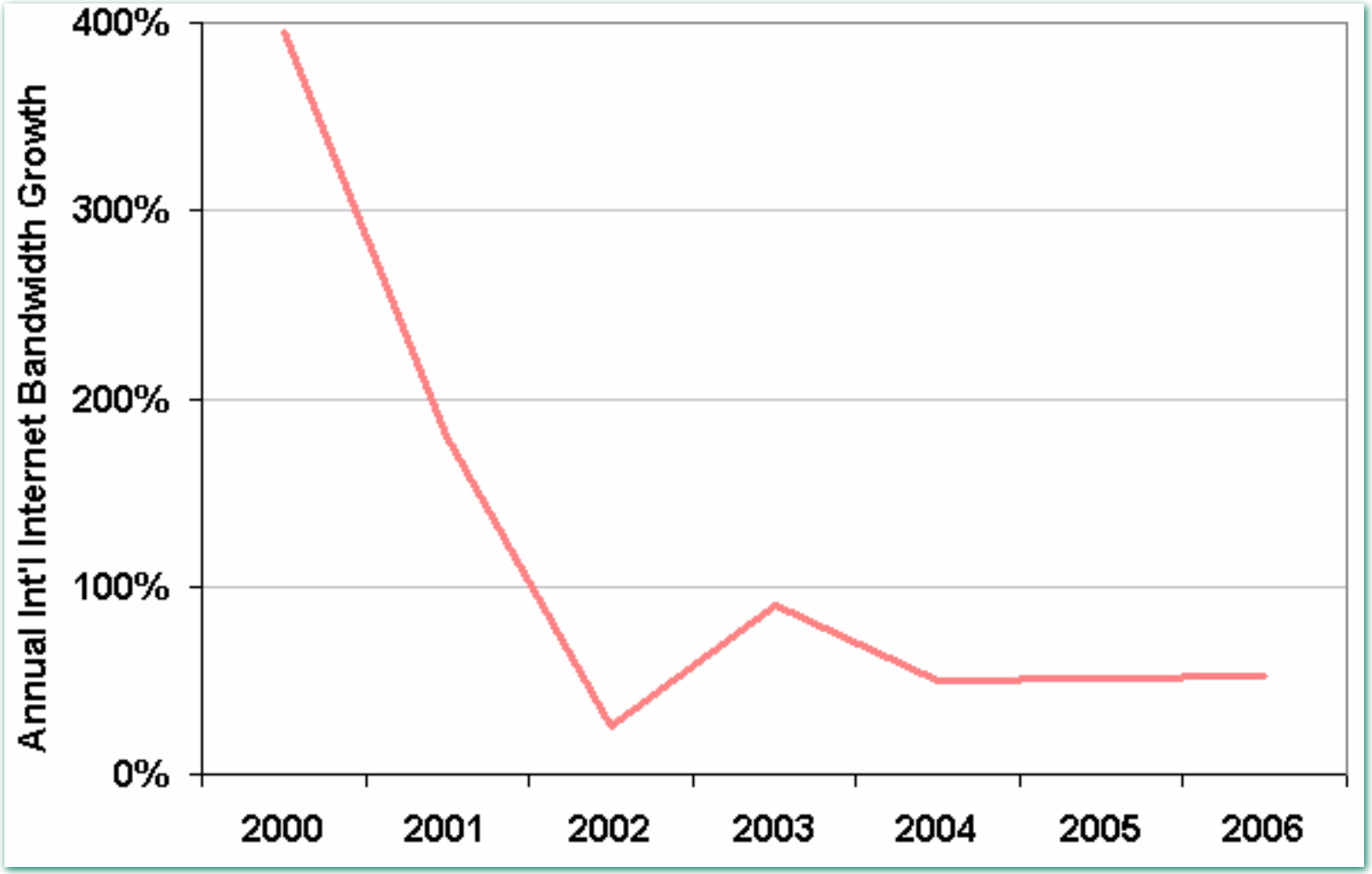
Discussions

- Advantages of channel partitioning over random access

- Advantages of random access over channel partitioning

Backup Slides: Physical Layer

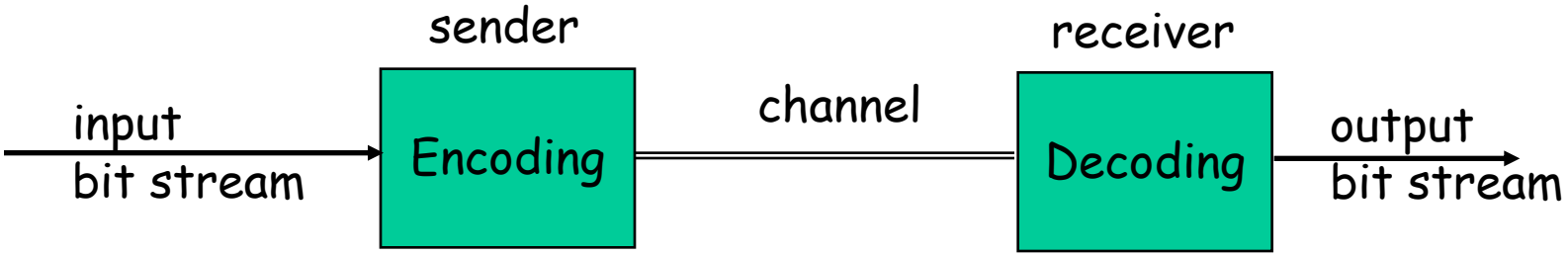
Internet Bandwidth Growth



Source: TeleGeograph Research

What Determines Transmission Rate?

- Service: transmit a bit stream from a sender to a receiver



Question to be addressed: how much can we send through the channel ?

Basic Theory: Channel Capacity

- The maximum number of bits that can be transmitted per second (bps) by a physical media is:

$$W \log_2 (1 + \frac{S}{N})$$

where W is the frequency range, S/N is the signal noise ratio. We assume Gaussian noise.

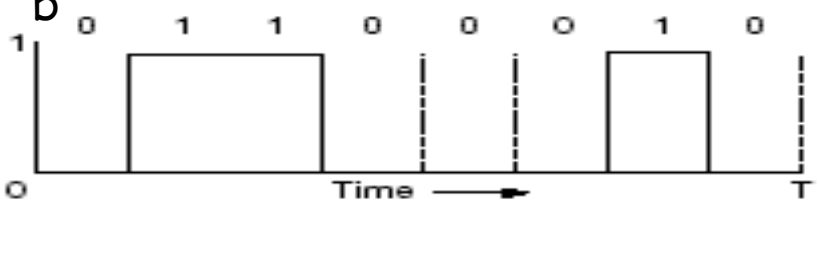
Fourier Transform

- Suppose the period of a data unit is f (=1/T), then the data unit can be represented as the sum of many harmonics (sin(), cos()) with frequencies f, 2f, 3f, 4f, …
- A reasonably behaved periodic function g(t), with minimal period T, can be constructed as the sum of a series of sines and cosines:

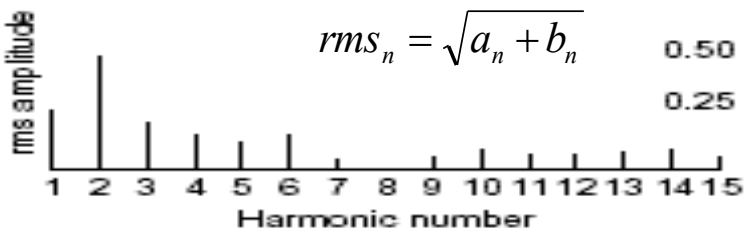
$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

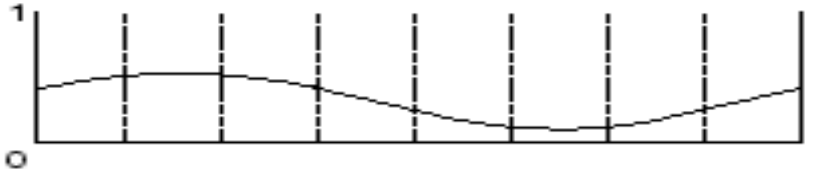
$$\begin{cases} f = 1/T \\ c = \frac{2}{T}\int_0^T g(t)dt \\ a_n = \frac{2}{T}\int_0^T g(t)\sin(2\pi nft)dt \\ b_n = \frac{2}{T}\int_0^T g(t)\cos(2\pi nft)dt \end{cases}$$

char “b”


0 1 1 0 0 0 1 0
1
0
Time
T

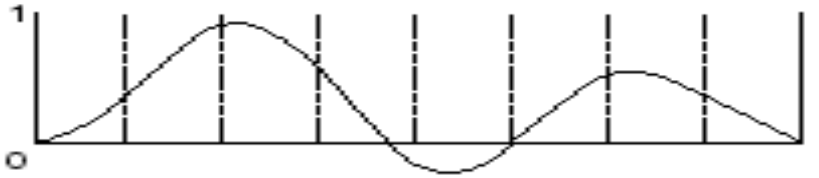
(a)


$rms_n = \sqrt{a_n + b_n}$
rms amplitude
0.50
0.25
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Harmonic number

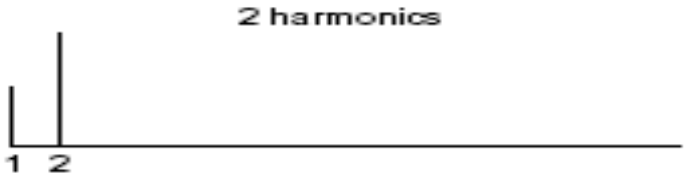

1
0

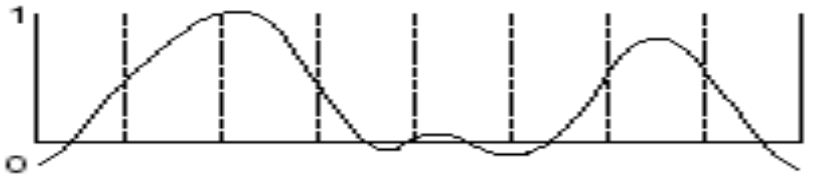
(b)


1 harmonic
1

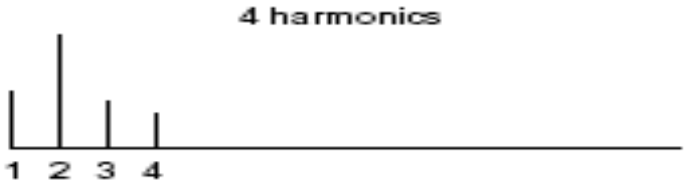

1
0

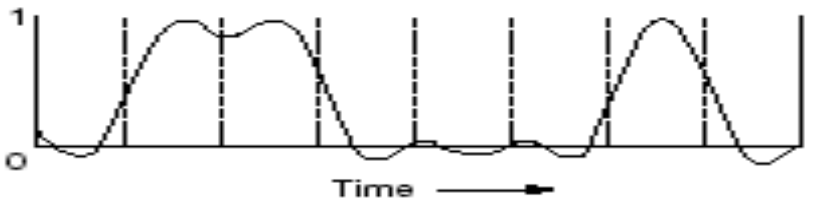
(c)

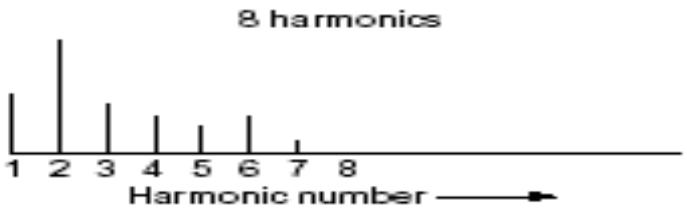

2 harmonics
1 2


1
0

(d)


4 harmonics
1 2 3 4

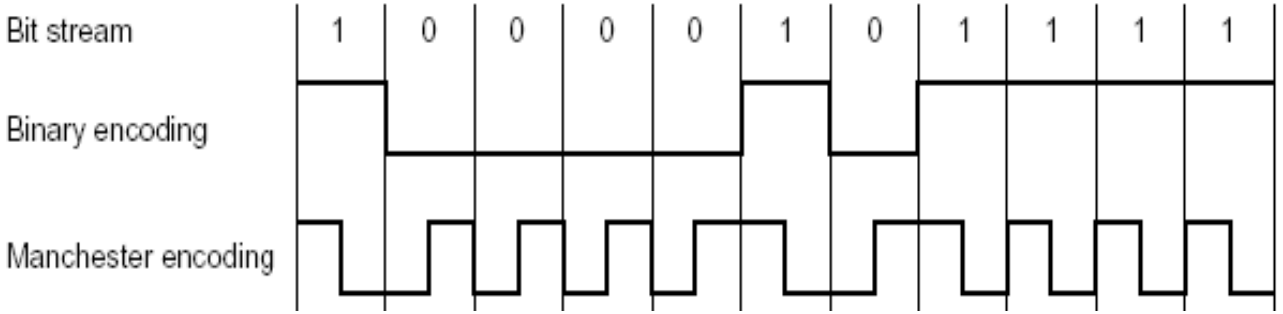

1
0
Time

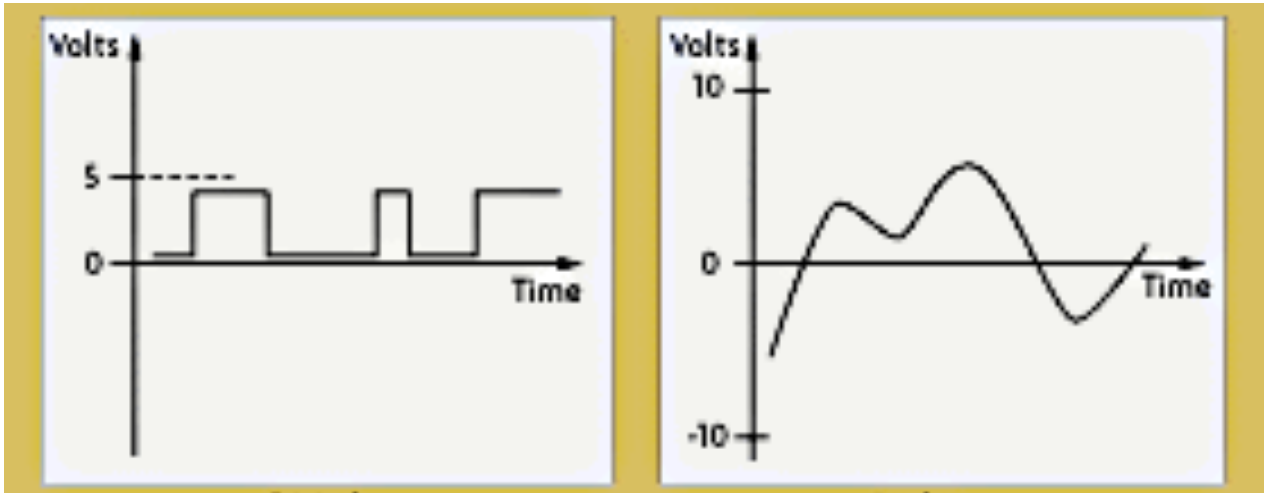

8 harmonics
1 2 3 4 5 6 7 8
Harmonic number

Signal Attenuation

$$W \log_2(1+\frac{S}{N})$$

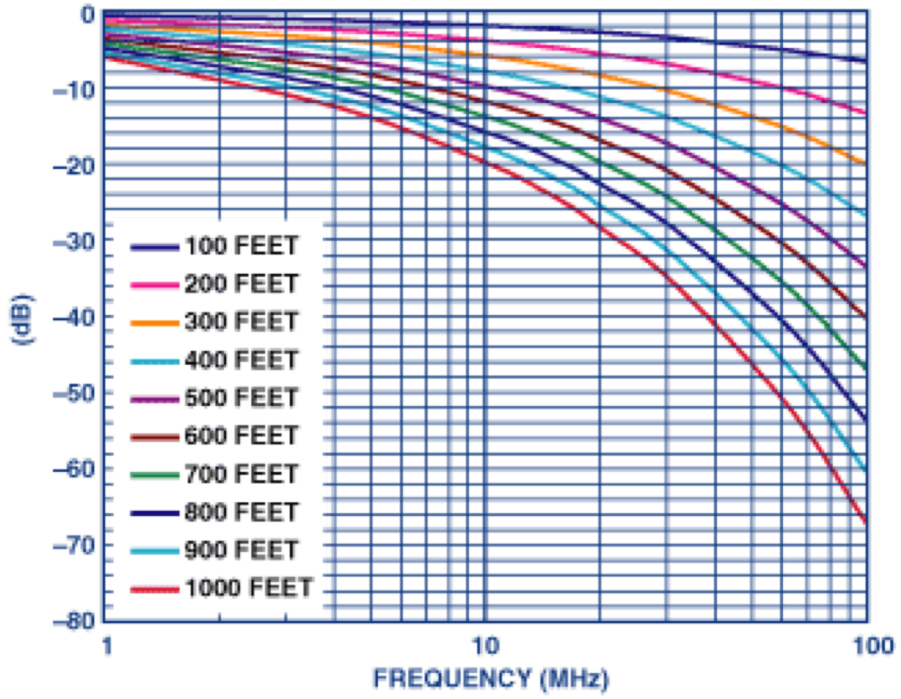
- The quality of signal will degrade when it travels
  - loss, frequency passing





Frequency Dependent Attenuation

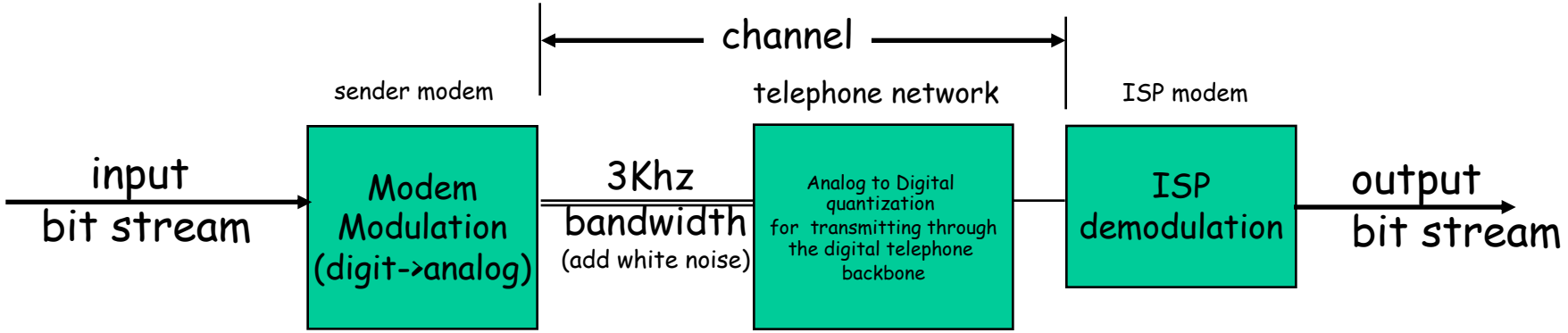
- The received signal will be distorted even when there is no interference and the transmitted signal is "perfect" square waveform



Example: Voltage-attenuation magnitude ratios of Category 5 cable. For example, 500 feet of cable attenuates a 10-MHz, 1-V signal to 0.32 V, which corresponds to about –9.90 dB (= 20 log 1/0.32)

Example

V.34 (33.6kbps Dialup Modem)



Example: W=3000Hz, S/N ≈ 4000

$$\max bandwidth = 3000\log_2(1+4000) \approx 36kbps$$

Example: ADSL

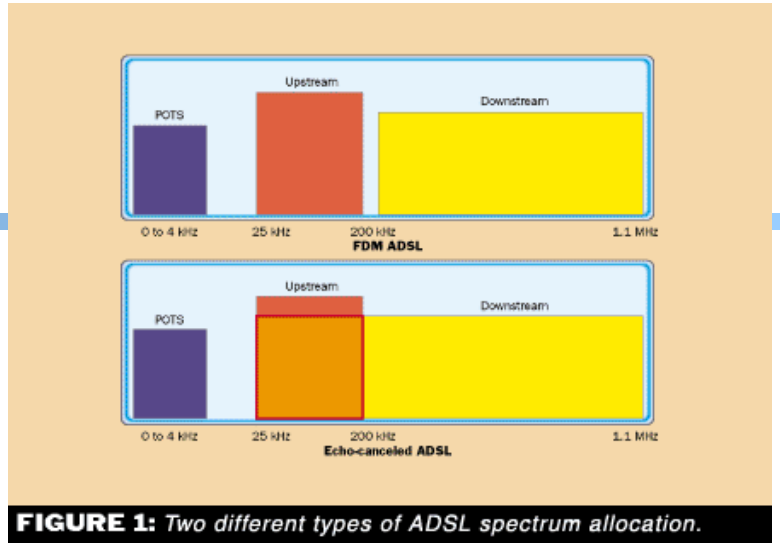


FIGURE 1: *Two different types of ADSL spectrum allocation.*

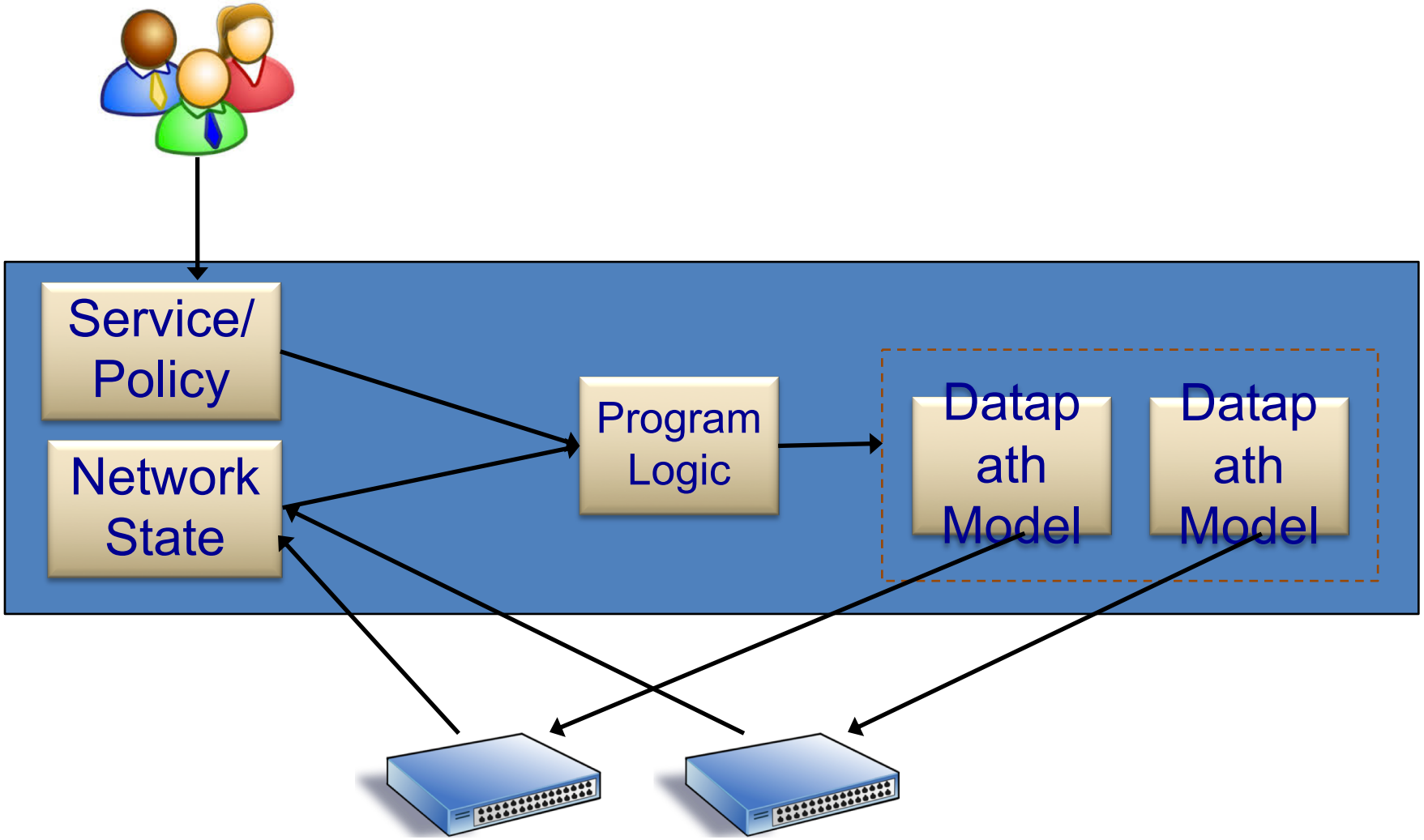
- Spectrum allocation: divided into a total of 256 downstream and 32 upstream tones, where each tone is a standard 4kHz voice channel
- During initial negotiation, a tone is used only if the S/N is above 6 db (≈4)

$$down = 256 * 4000 \log_2(1+4) \approx 2.4 Mbps$$

$$up = 32 * 4000 \log_2(1+4) \approx 297 kbps$$

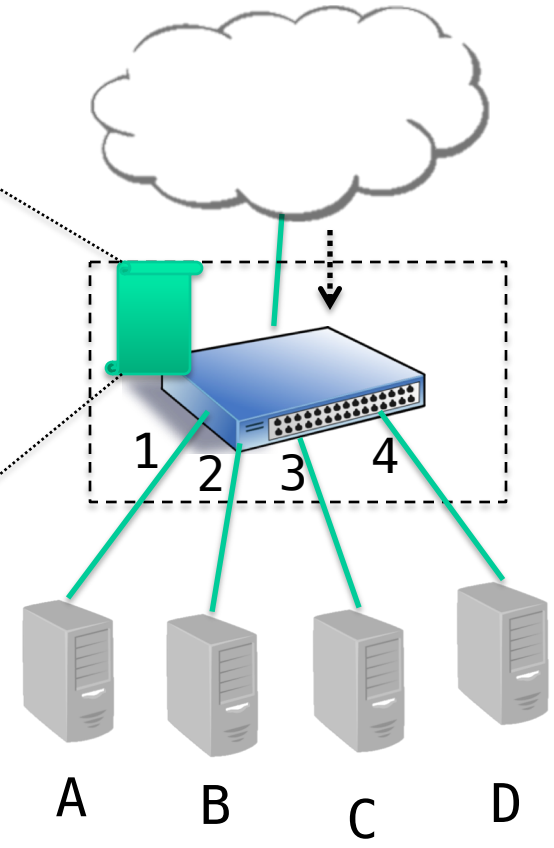
Backup Slides: SDN Control Programming

SDN Programming Model



An Example: A Simple SDN Controller

```
badPort = 22          // policy
hostTbl = {A:1,B:2,
           C:3,D:4} // net view

def onPacketIn(p):
  if badPort == p.tcp_dst:
    drop
  else:
    forward([hostTbl(p.eth_dst)])
```



Assume only packets to A,B,C,D can appear.

Controller Program with Flow Table Management

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({‘match':{'tcp_dst':22},
         ‘action’:[]})

  else:
   forward([hostTbl(p.eth_dst)])

 installRule({‘match’: {‘eth_dst’:p.eth_dst,
              ’tcp_dst’!=22},
        ‘action’:[hostTbl(p.eth_dst)]})
```

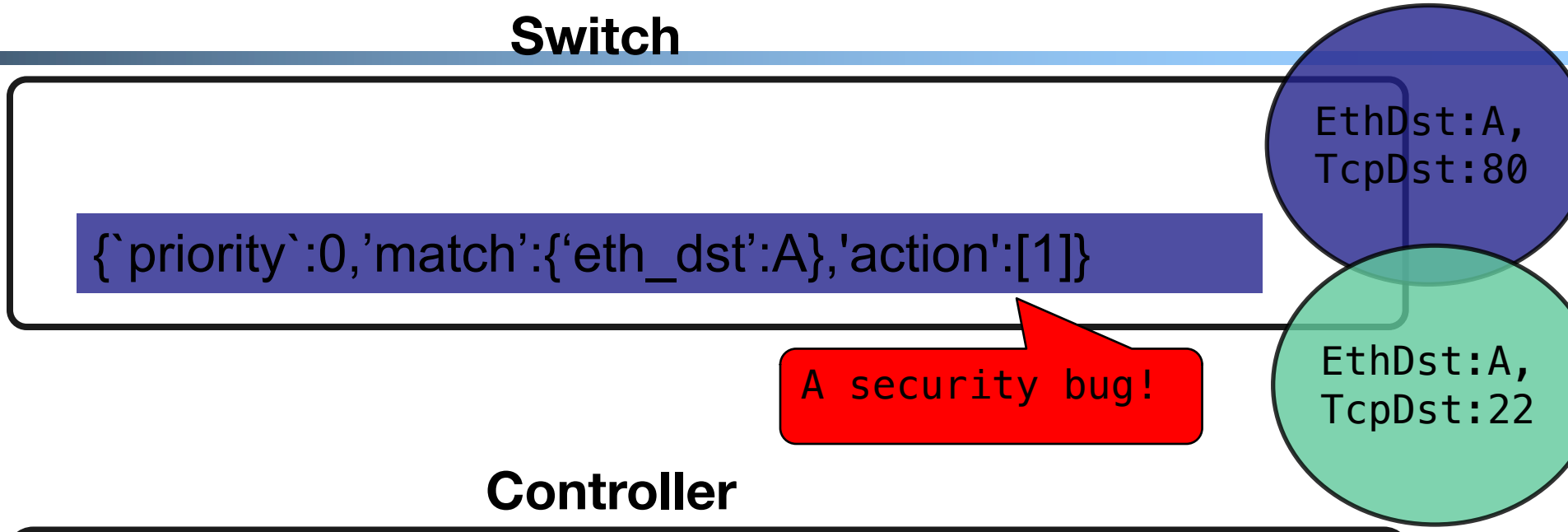
match does not support logic negation

Controller Program with Flow Table Management

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({'priority':1,
        'match':{'tcp_dst':22},
        'action':[]})

  else:
    forward([hostTbl(p.eth_dst)])

  installRule({'priority':0,
        'match': {'eth_dst':p.eth_dst},
        'action':[hostTbl(p.eth_dst)]})
```

Does the Program Work?

Switch



Controller

```
def onPacketIn(p):
  if 22 == p.tcp_dst:
   drop
   installRule({`priority`:1,'match':{'tcp_dst':22},'action':[]})
  else:
   installRule({`priority`:0,'match':{'eth_dst':p.eth_dst},
                'action':[hostTbl(p.eth_dst)]})
   forward([hostTbl(p.eth_dst)])
```

OVS Approach: Using Exact Match

```
hostTbl = {A:1,B:2,C:3,D:4}

def onPacketIn(p):
  if 22 == p.tcp_dst:
    drop

  installRule({'priority':1,
        'match':exactMatch(p),
        'action':[]})

  else:
    forward([hostTbl(p.eth_dst)])

  installRule({'priority':0,
        'match':exactMatch(p),
        'action':[hostTbl(p.eth_dst)]})
```

Problems of OVS Approach

	Match									
Priority	inport	MAC src	MAC dst	MAC proto	IP src	IP dst	TCP src	TCP dst	…	Action
0	1	B	A	0x0806	12…	78…	…	22		drop
0	1	B	A	0x0806	12…	78…	9881	80		port 1
0	1	B	A	0x0806	12…	78…	…	7231		port 1
0	2	C	A	0x0806	32…	78…	…	7232		port 1
0	1	A	B	0x0806	78…	12…	80	9881		port 2

- Each new TCP flow delayed for flow setup (10-100 ms)
- Number of flow table rules may exceed capacity (typically a few thousands)

Outline

- Admin and recap
- Link layer
- Software defined networking
  - Motivation: from simple forwarding to network functions
  - Design overview
  - Data path (OpenFlow)
  - Control path (programming model)
    - Problems
    - Algorithmic network programming

Goal of SDN Programming

Let programmers write the most obvious (=> data path independent) code:

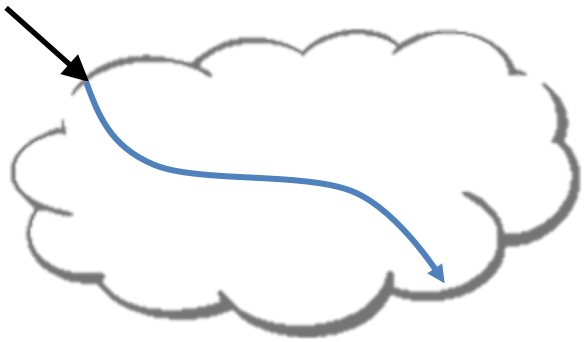
```
def onPacketIn(p)
  if 22 == p.tcp_dst:
    drop
  else:
   forward([hostTbl(p.eth_dst)])
```

Design a system that can automatically generate correct, highly-optimized data path.

Algorithmic SDN Programming Abstraction: Programmer's View

- **Conceptually programmer's network control function f is invoked on every packet entering the network.**
- f expressed in an **existing**, **general purpose language (e.g., Java, Python)**, describing how a packet should be routed, **not** how data path flow tables are configured

f: packet ⟶ route



Example Algorithmic Policy in Java

```
Route f(Packet p) {
  if (p.tcpDstIs(22)) return null();
  else {
    Location sloc = hostTable(p.ethSrc());
    Location dloc = hostTable(p.ethDst());
    Route path    = myRoutingAlg(topology(),
                                 sloc,dloc);
    return path;
  }
}
Route myRoutingAlg(Topology topo,
                   Location sLoc, Location dloc) {
   if ( isSensitive(sLoc) || isSensitive(dLoc) )
      return secureRoutingAlg(topo, sloc, dloc);
   else
      return standardRoutingAlg(topo, sloc, dloc);
}
```

Does not specify anything on flow tables!

More Complex Example: ACL+Routing

```
void insert(ACLItem acl, int pos,
            List<ACLItem> acls) {
  acls.add(pos, acl);
}

void delete(int pos,
            List<ACLItem> acls) {
  acls.remove(pos);
}
```

```
boolean permit(Packet p,
               List<ACLItem> acls) {
  for (ACLItem item : acls) {
    if ( match(p, item)){
   return item.action == PERMIT;
  }
 }
 return false;
}
```

```
List<ACLItem> acls;
Route f(Packet p) {
 if ( ! permit(p, acls) ) {
   return null();
 }
   Location sloc = hostTable(p.ethSrc());
   Location dloc = hostTable(p.ethDst());
   Route path = myRoutingAlg(topology(),sloc,dloc);
   return path;
}
```

Challenge and Basic Idea

- Challenge: How to derive datapath (flow-tables) from a datapath-oblivious SDN controller function f?

- Basic idea of handling the challenge w/o a compiler:
  - There are two representations of computation
    - A sequence of instructions (whitebox)
    - Memorization tables (blackbox)
  - Although the decision function f does **not** specify how flow tables are configured, if for a given decision (e.g., drop), one know the dependency of the decision, one can construct the flow tables (aka. memorization tables).

Basic Idea

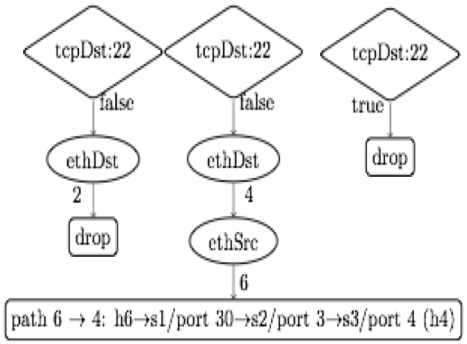
- Only requirement: Program f uses a simple library to access pkt attr

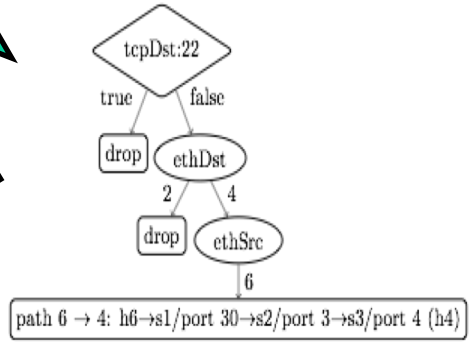
```
readPacketField :: Field -> Value
testEqual       :: (Field,Value) -> Bool
ipSrcInPrefix   :: IPPrefix -> Bool
ipDstInPrefix   :: IPPrefix -> Bool
```

- Library provides both convenience and more importantly, decision dependency!

Dynamic Tracing: Abstraction to Flow Tables

1. **Observes decision dependency** of f on pkt attributes.





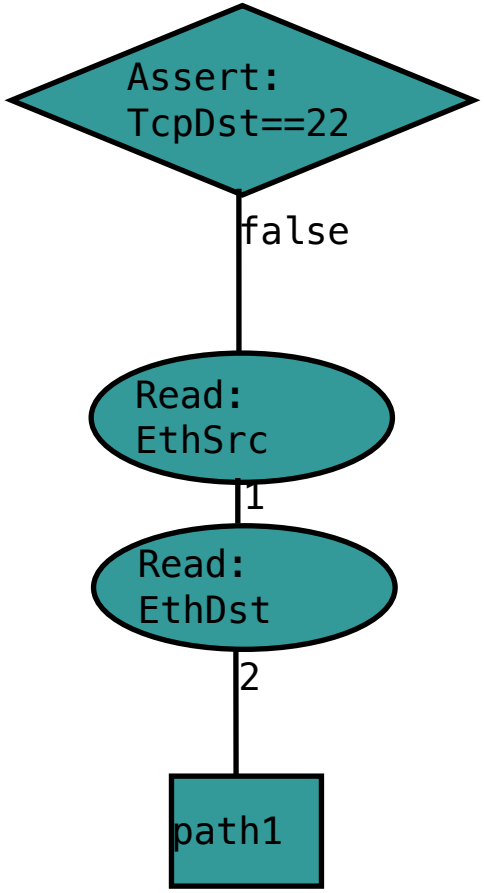
Prio	Match	Action
1	tcpDst:22	ToControl
0	ethDst:2	discard
0	ethDst:4,	port 30

2. Builds a **trace tree (TT)**, a universal (general), partial decision tree representation of any f.

3. **Compile** trace tree to generate flow tables (FTs).

Policy

```
Route f(Packet p) {

  if (p.tcpDstIs(22))


    return null();

  else {

    Location sloc =
      hostTable(p.ethSrc());

    Location dloc =
      hostTable(p.ethDst());


    Route path    =
      myRoutingAlg(
        topology(),sloc,dloc);
    return path;
  }
}
```



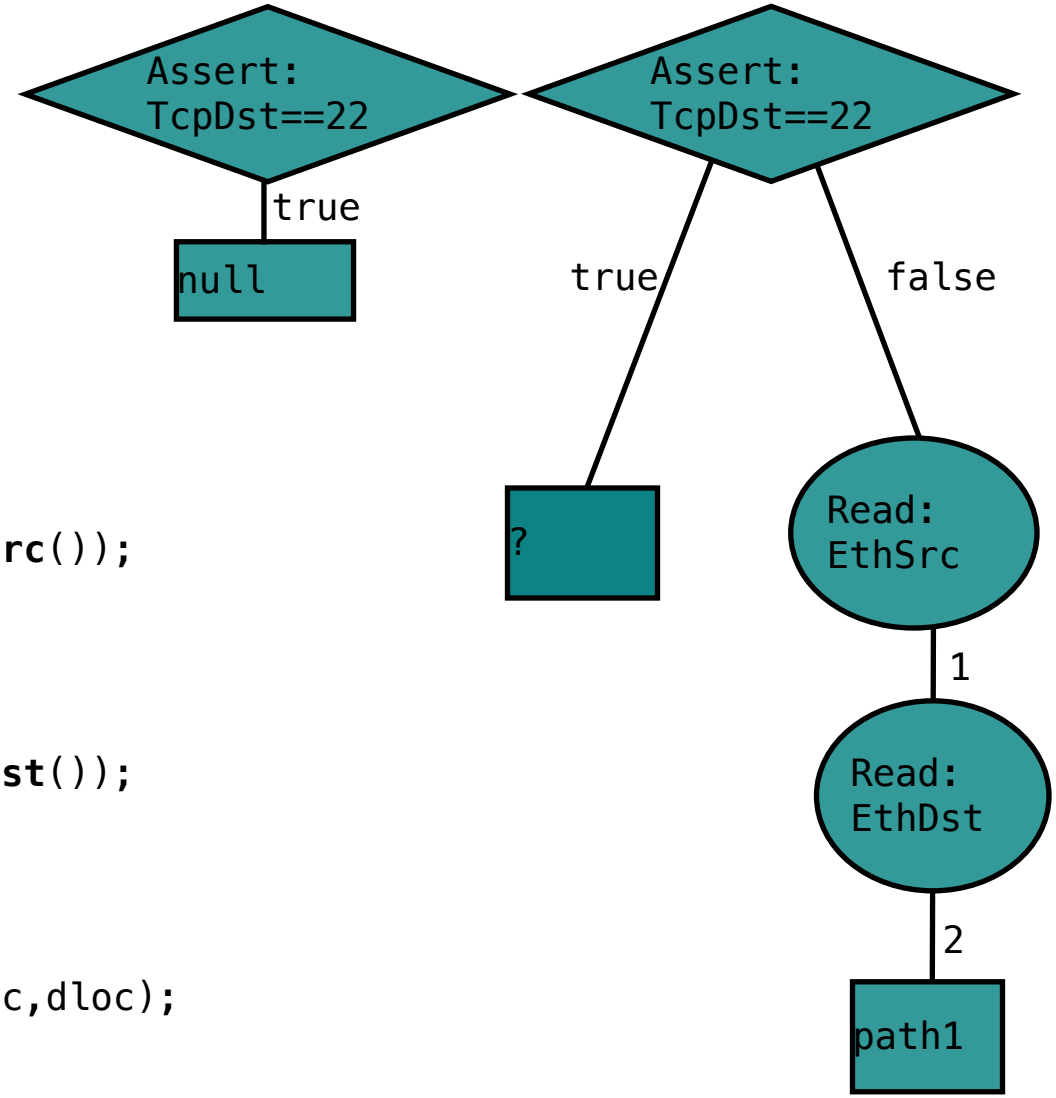
EthSrc:1,
EthDst:2,
TcpDst:80

Policy

Trace Tree

EthDst:1,
TcpDst:22

```
Route f(Packet p) {

  if (p.tcpDstIs(22))

    return null();

  else {

    Location sloc =
      hostTable(p.ethSrc());

    Location dloc =
      hostTable(p.ethDst());

    Route path    =
      myRoutingAlg(
        topology(),sloc,dloc);
    return path;
  }
}
```

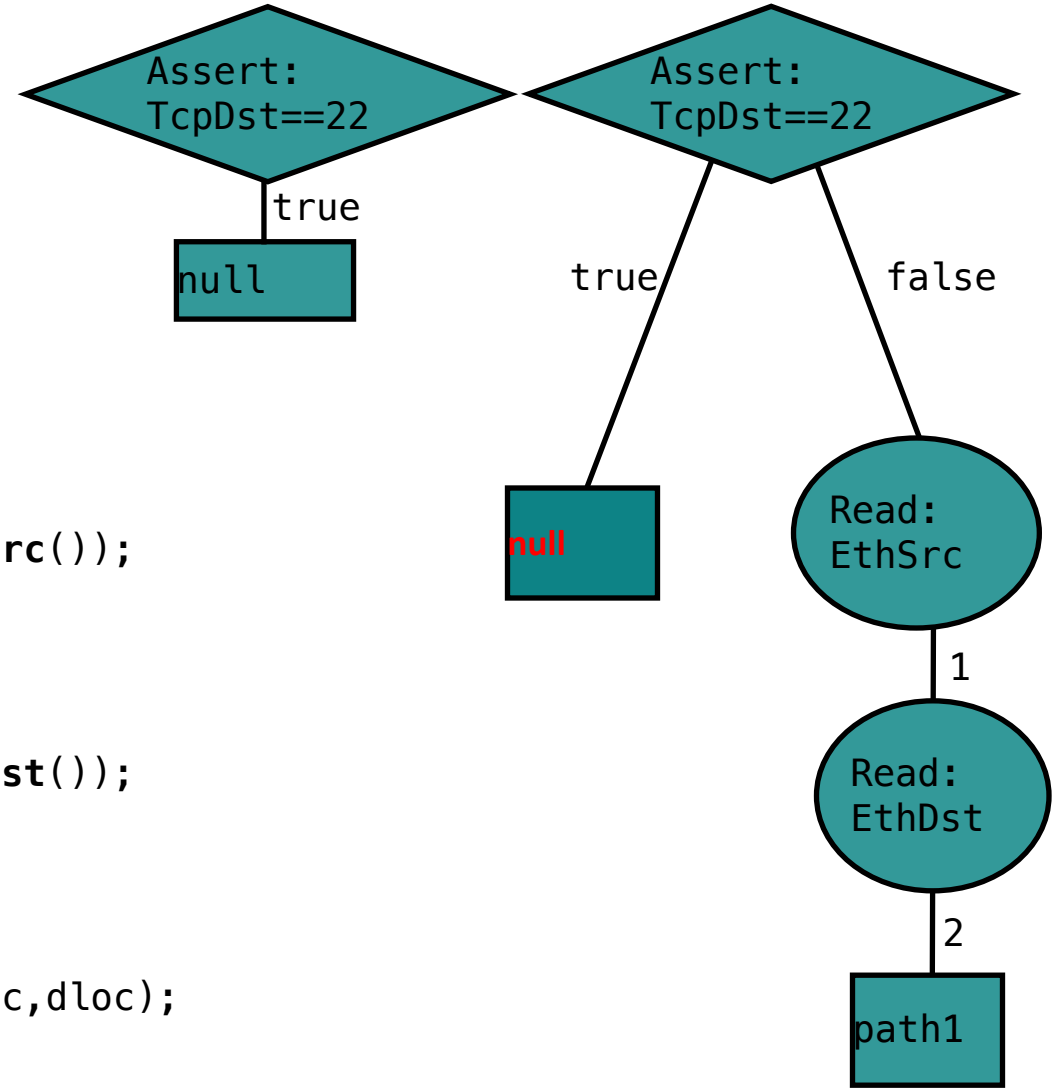


Policy

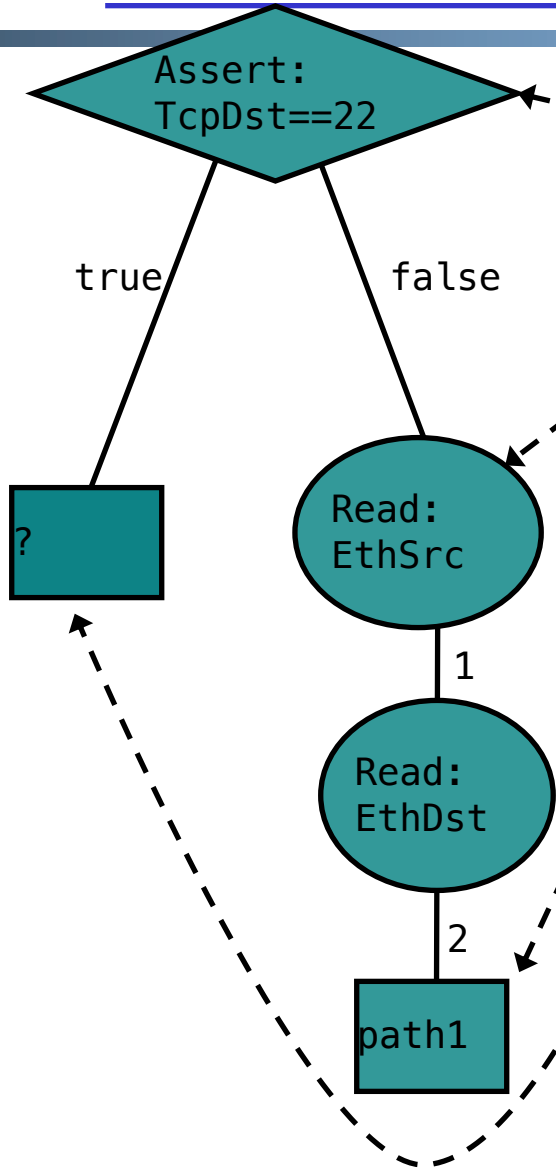
Trace Tree

EthDst:1,
TcpDst:22

```
Route f(Packet p) {

  if (p.tcpDstIs(22))


    return null();

  else {


    Location sloc =
      hostTable(p.ethSrc());



    Location dloc =
      hostTable(p.ethDst());


    Route path    =
      myRoutingAlg(
        topology(),sloc,dloc);
    return path;
  }
}
```

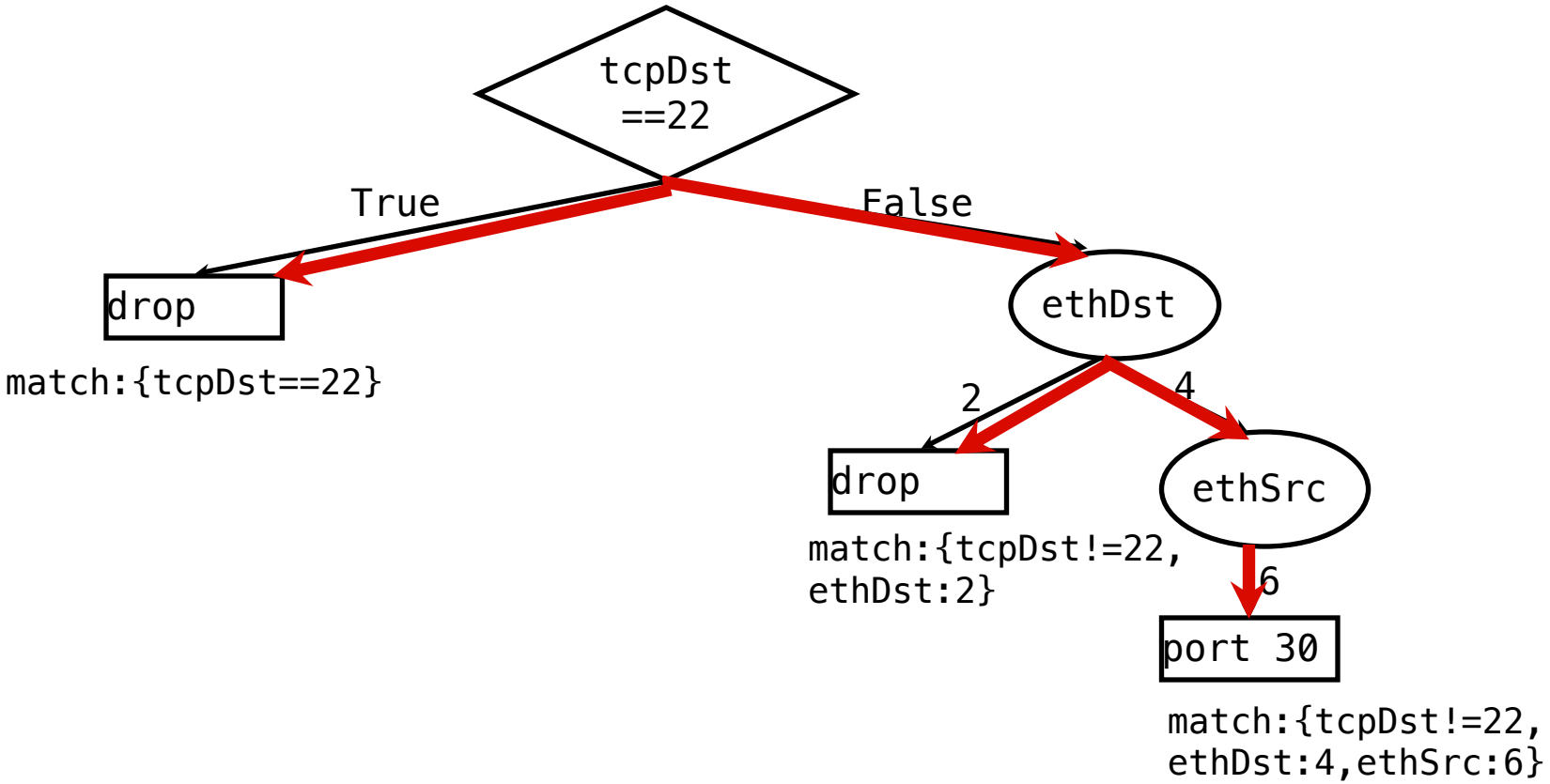


Trace Tree Formal Spec

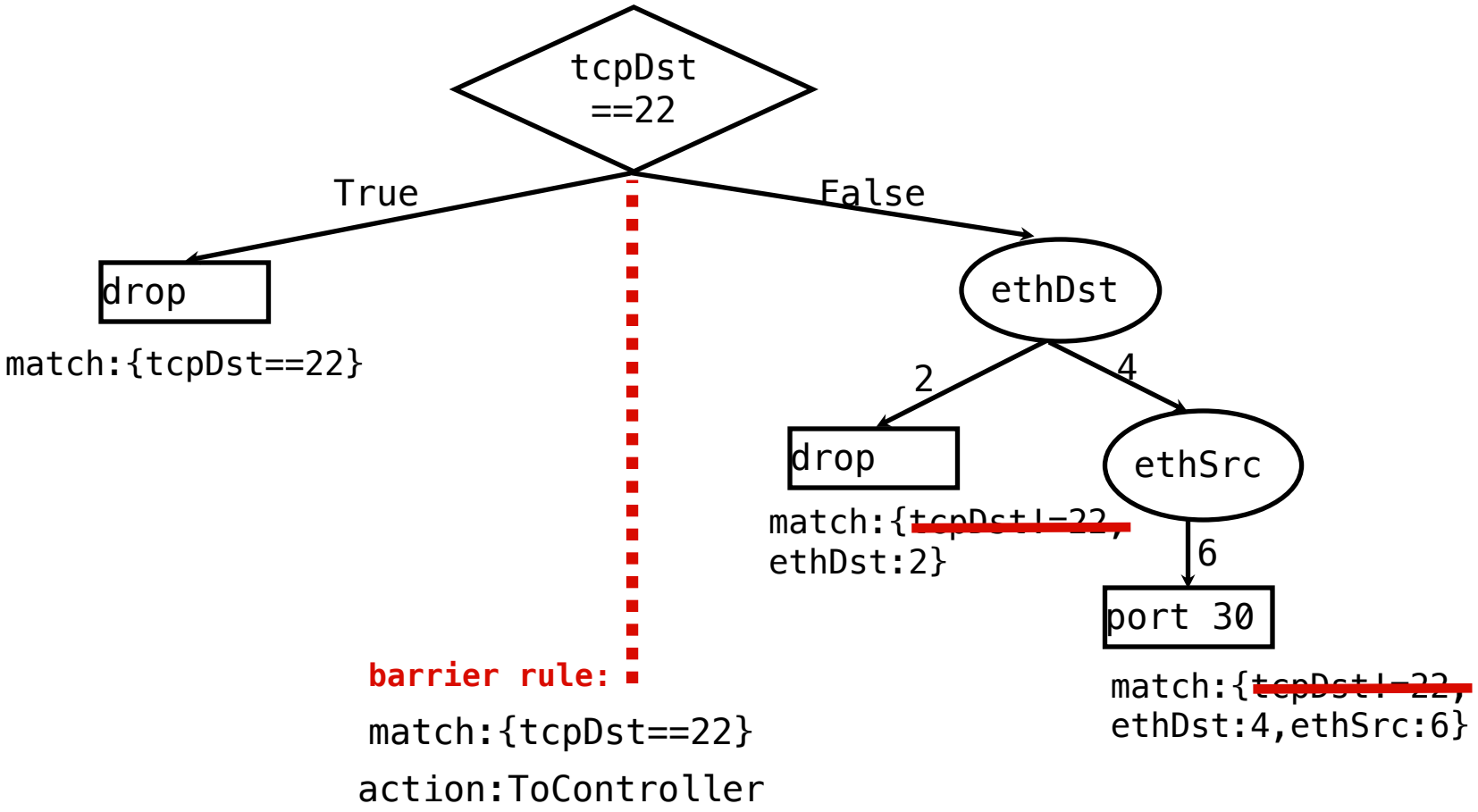


- A tree w/ 4 types of nodes
  - **T** node: assertion on packet attributes
  - **V** node: multi-way branching on a packet attribute
  - **L** node: leaf node labeled w/ action
  - **?** node: unknown
- **TT search**: traverse tree for a given packet to determine action or no answer
- **TT correctness**: if TT records an answer for a given packet

Trace Tree => Flow Table



Trace Tree => Flow Table



Trace Tree => Flow Table

Simple, classical in-order tree traversal generates flow table rules!