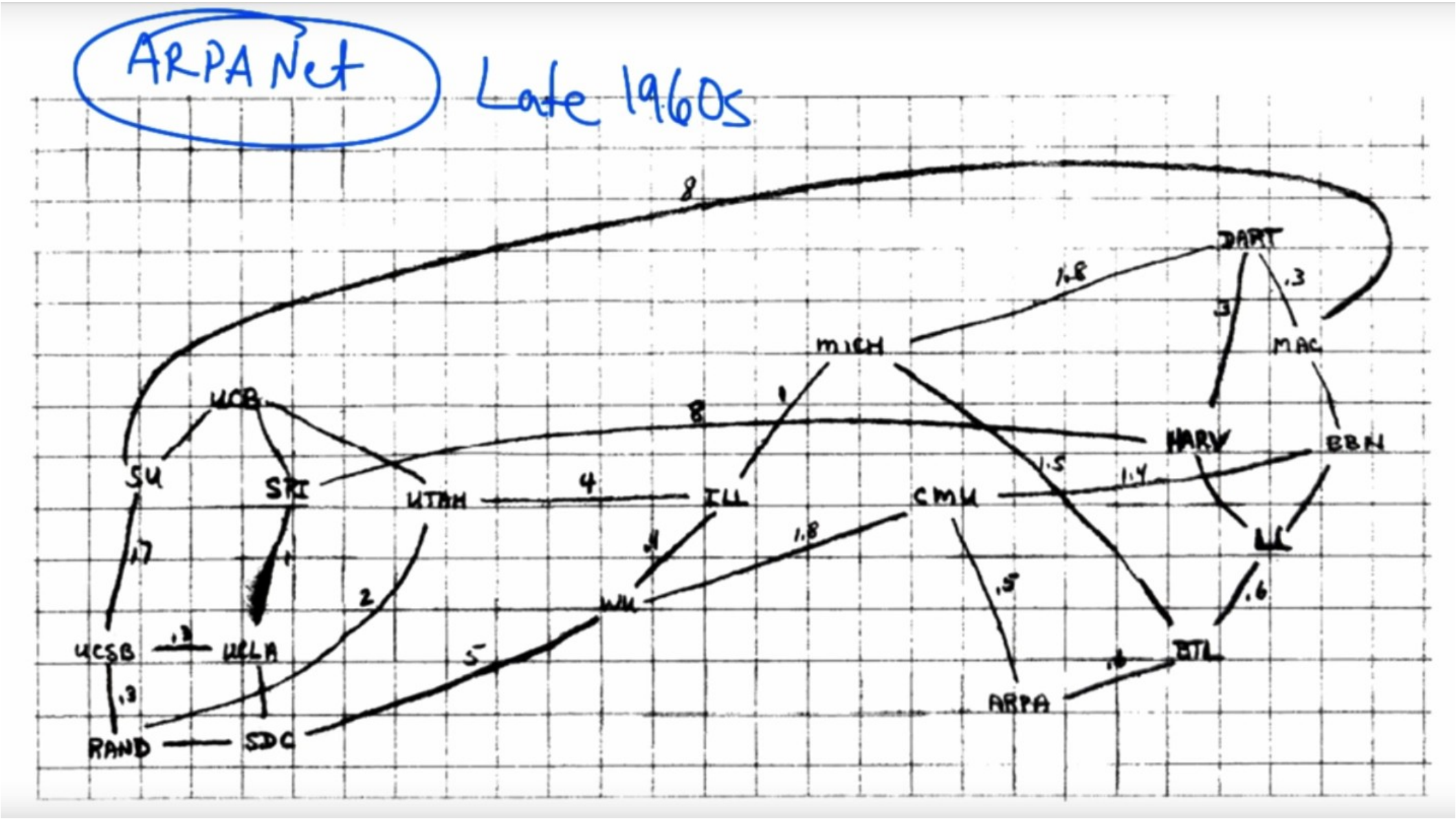
A Brief History of the Internet

- ARPANet (1966-1967) → UCLA, SRI, UCSB, Utah (1969)

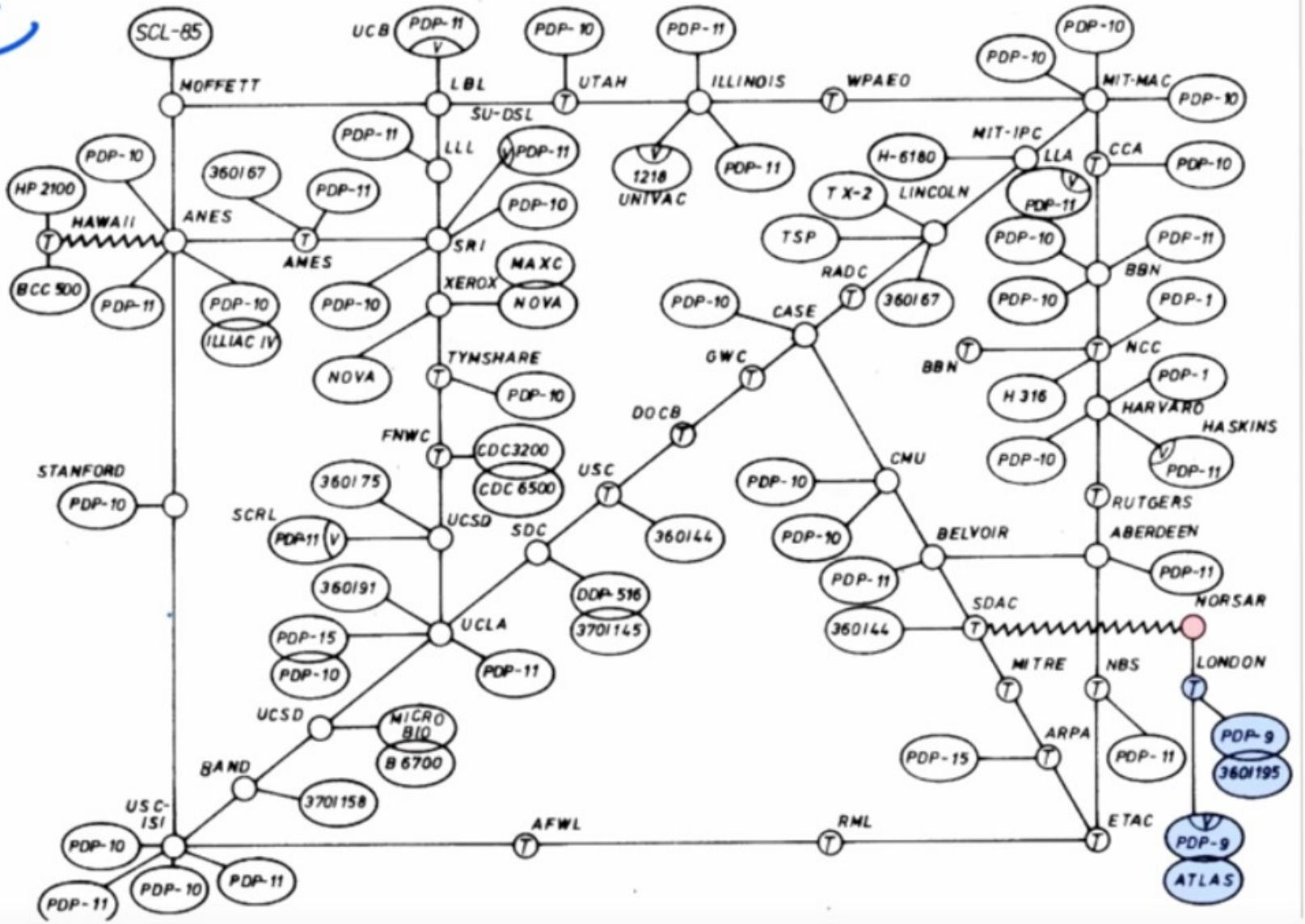
  Goal: Network academic computers

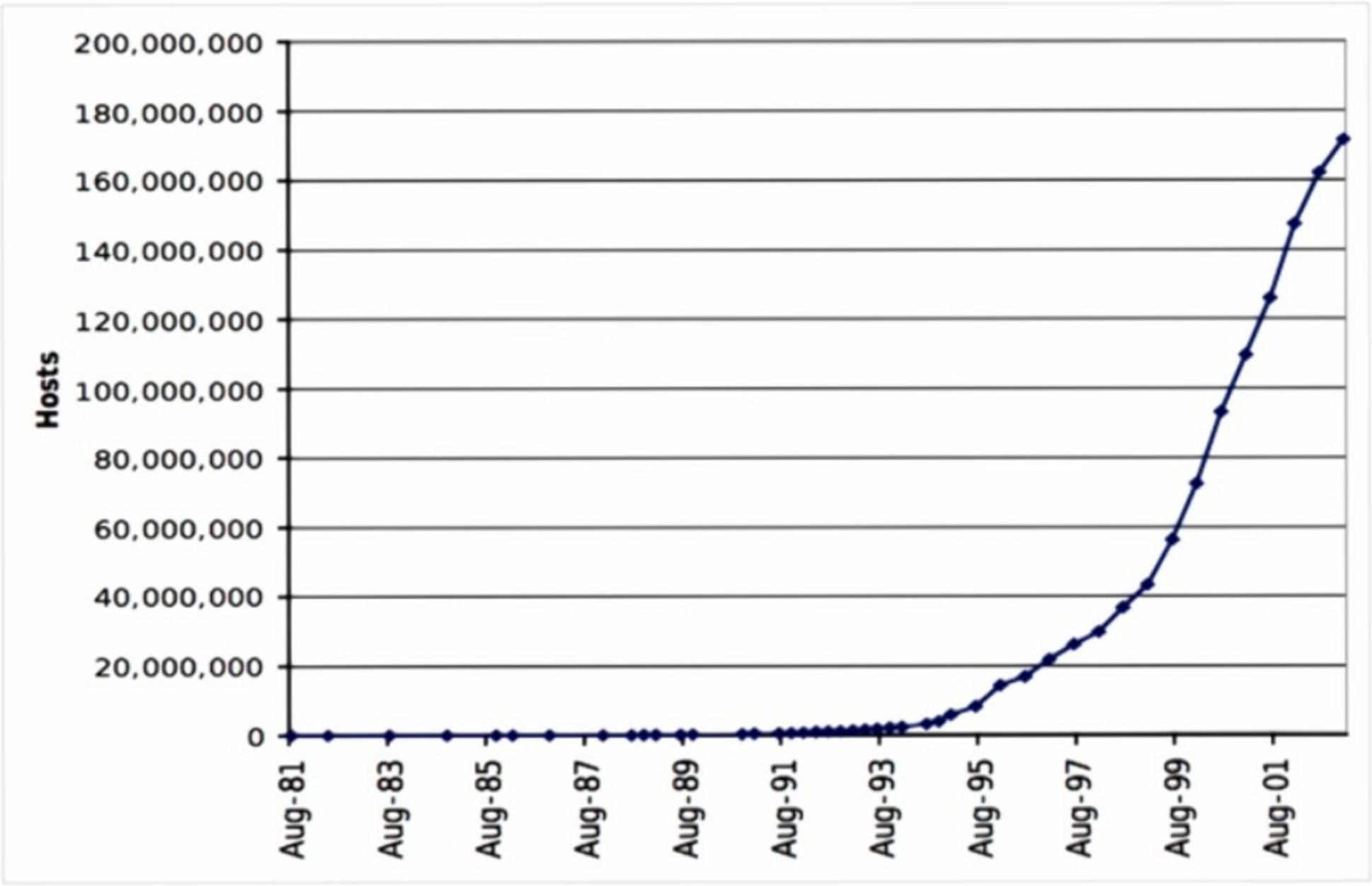
- NPL Net in UK around same time.

1971 → ~20 ARPANET Nodes

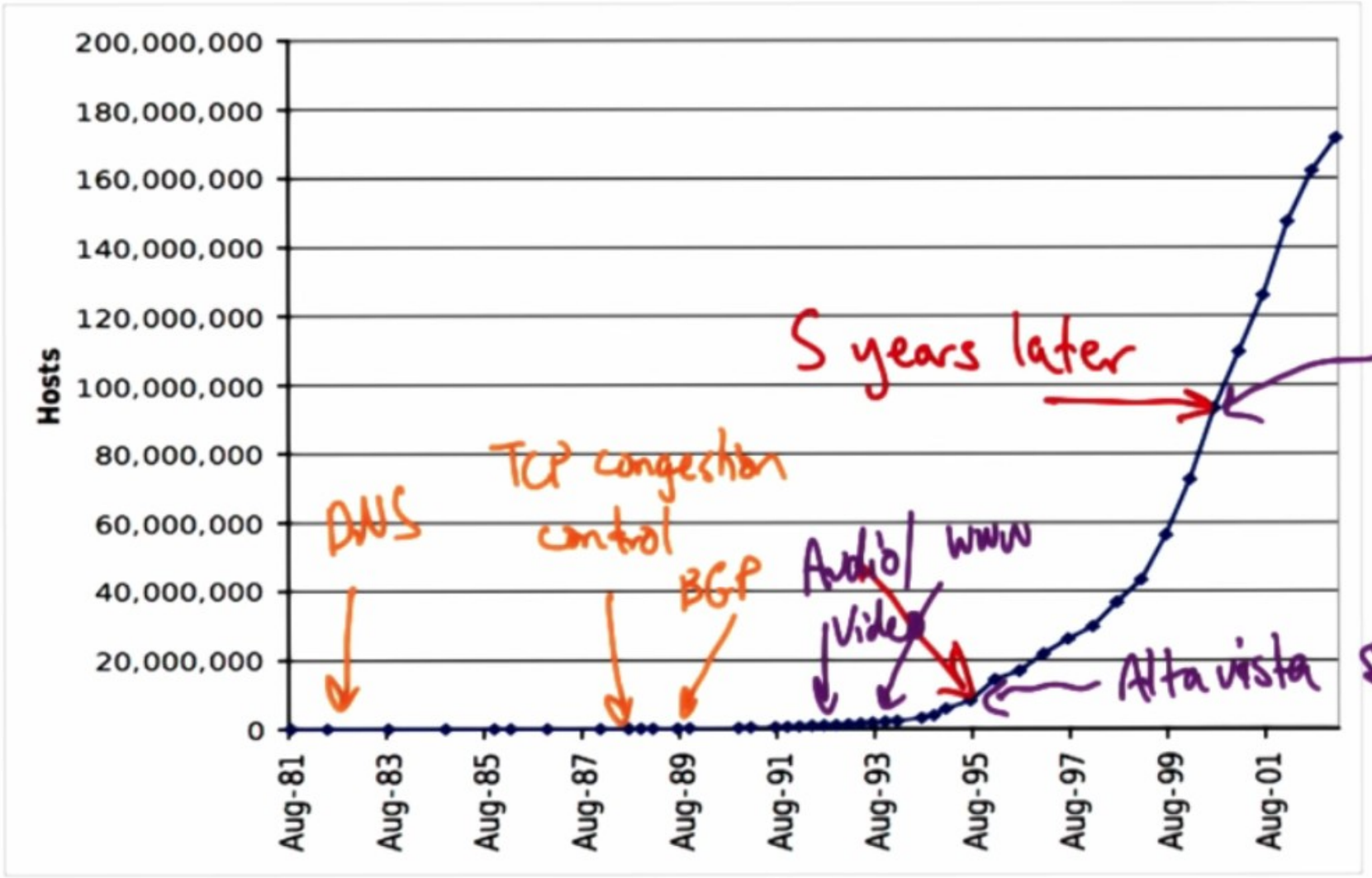

ARPANet
Late 1960s
8
DART
1.8
.3
3
MICH
MAC
UCB
8
1
HARV
BBN
SU
SRI
UTAH
4
ILL
CMU
1.5
1.4
LL
.7
1
.8
1.8
2
.5
.6
UCSB
.3
UCLA
5
.8
BTL
.3
ARPA
RAND
SDC

June 1974


SCL-85
MOFFETT
UCB
PDP-11
LBL
SU-DSL
PDP-10
UTAH
PDP-11
ILLINOIS
WPAFB
PDP-10
PDP-10
MIT-MAC
PDP-10
PDP-11
LLL
PDP-11
1218
UNIVAC
PDP-11
MIT-IPC
H-6180
LLA
CCA
PDP-10
PDP-10
360167
PDP-11
PDP-10
TX-2
LINCOLN
PDP-11
HP 2100
HAWAII
ANES
ANES
SRI
TSP
PDP-10
PDP-11
MAXC
XEROX
RADC
BBN
BCC 500
PDP-11
PDP-10
PDP-10
NOVA
360167
PDP-10
PDP-10
PDP-1
ILLIAC IV
CASE
NOVA
TYMSHARE
GWC
BBN
NCC
PDP-10
PDP-1
H 316
HARVARD
HASKINS
DOCB
FNWC
CDC3200
CDC 6500
CMU
PDP-10
PDP-11
STANFORD
PDP-10
360175
USC
360144
RUTGERS
SCRL
PDP-11
UCSD
SDC
PDP-10
BELVOIR
ABERDEEN
PDP-11
360191
DDP-516
3701145
SDAC
NORSAR
PDP-11
360144
UCLA
PDP-15
PDP-10
PDP-11
MITRE
NBS
LONDON
UCSD
MICRO 810
B 6700
PDP-9
3601195
ARPA
PDP-15
PDP-11
BAND
3701158
USC-ISI
AFWL
RML
ETAC
PDP-9
ATLAS
PDP-10
PDP-11
PDP-10
PDP-11



Source:Internet Software Consortium (http://www.isc.org/)



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Problems & Growing Pains

IPv4

All require changes to basic infrastructure!

1. Running out of addresses → only 2^{32} addresses.
2. Congestion Control → insufficient dynamic range (wireless, high-speed intercontinental paths)
3. Routing → no security, easily misconfigured, poor convergence, non-determinism.
4. Security → lack of key management, secure software deployment
5. Denial of service → too easy to send traffic to destination

Internet Design Principles

→ Design Philosophy of the DARPA Internet Protocols,
DAVE CLARK 1988.

Conceptual Lessons → Principles designed for a certain type of network

Technical Lessons → ① Packet switching
② Fate sharing

Goal: "multiplexed utilization of existing interconnected networks"

sharing

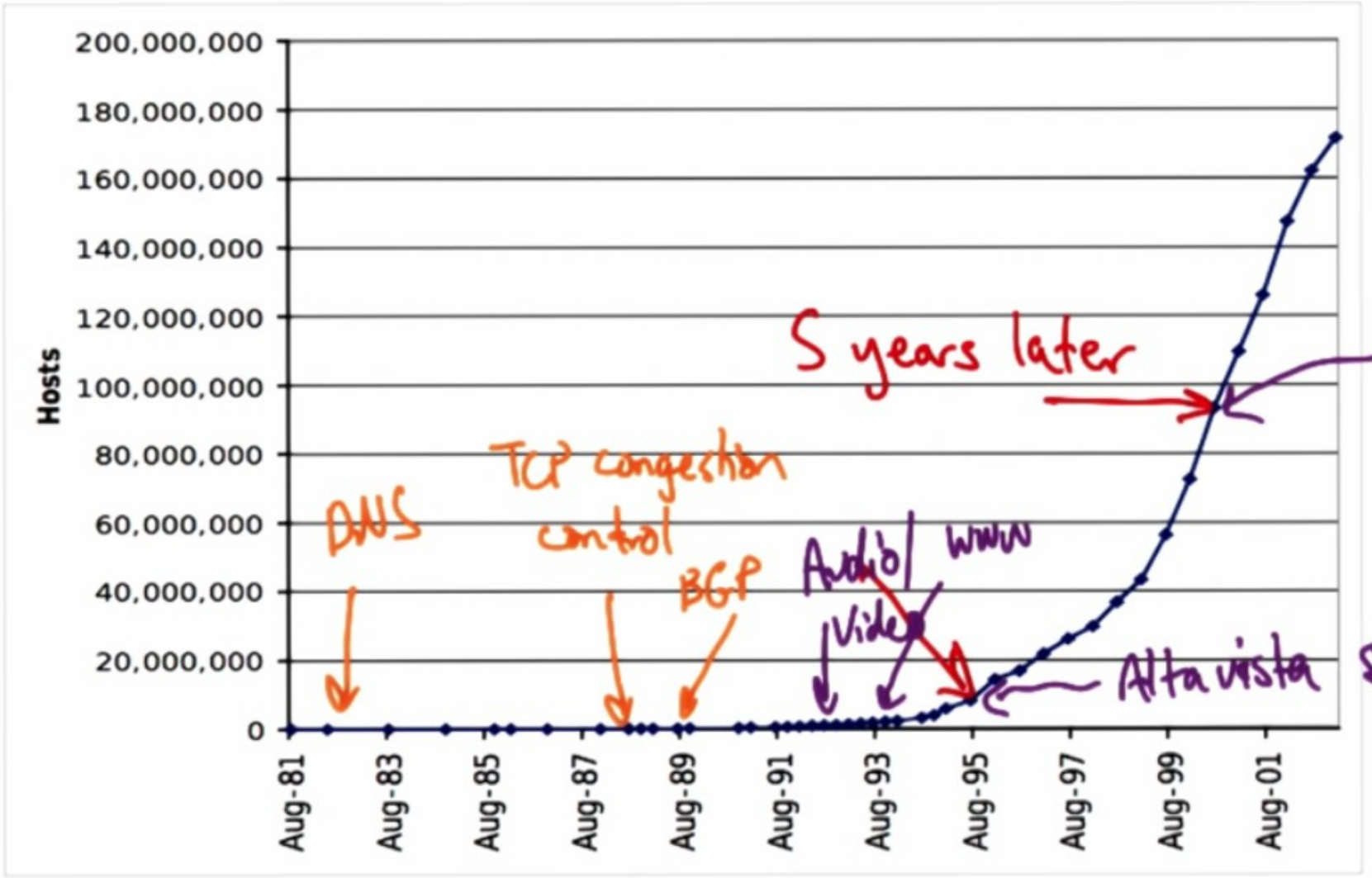
⇓

statistical multiplexing /
→ packet switching

interconnection

⇓

"narrow waist"



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Packet Switching

- Information for forwarding traffic contained in destination address of packet.

Packet Switching

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- "Best effort" service

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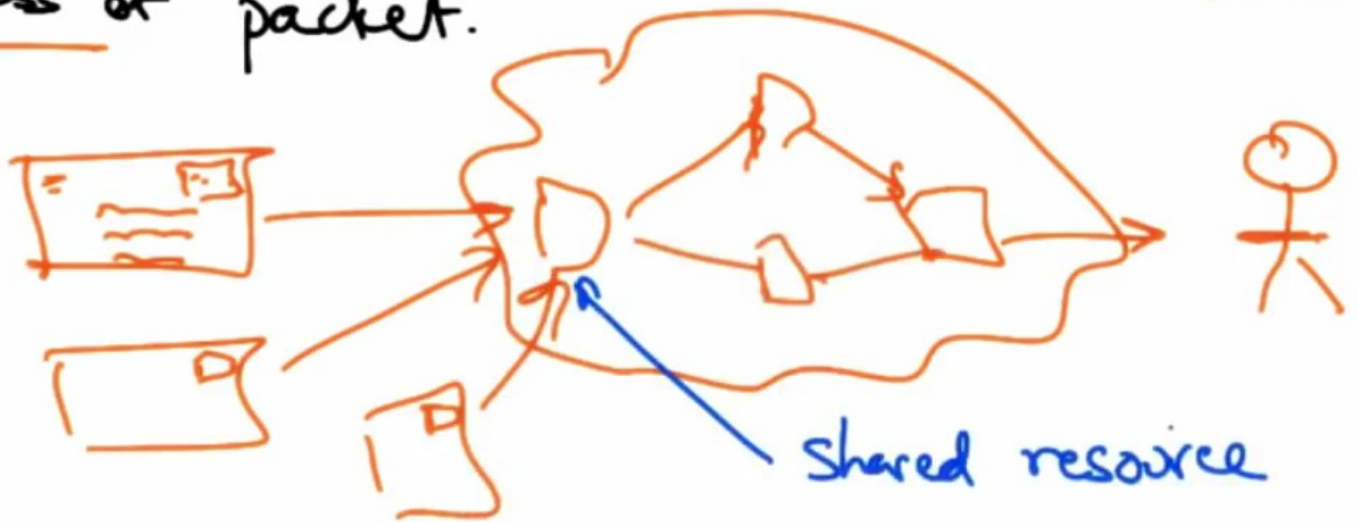

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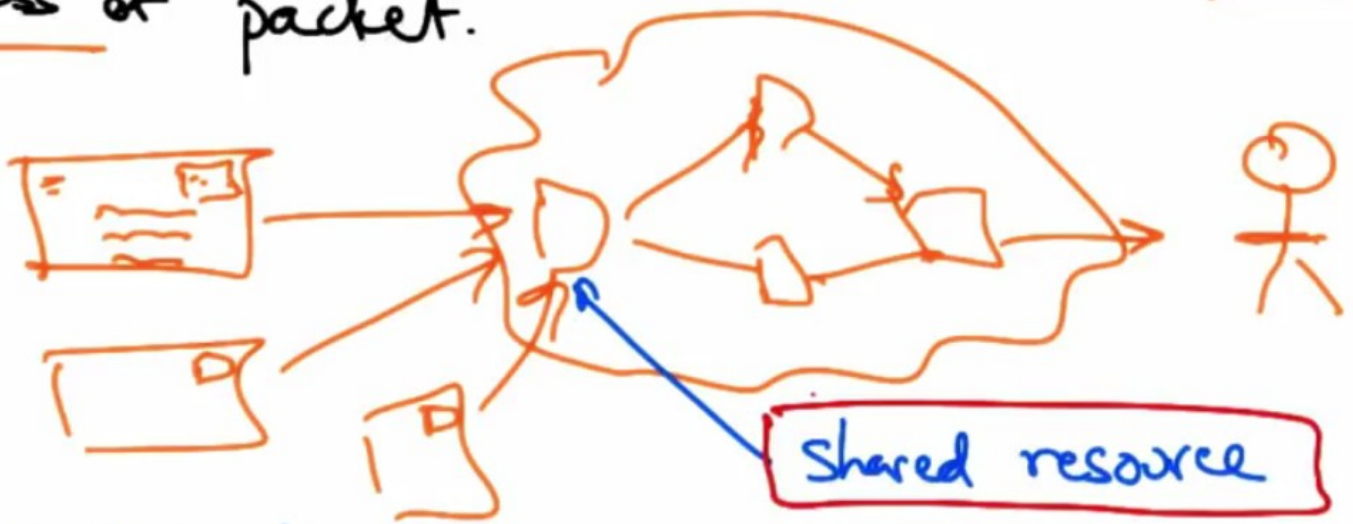

- In contrast to "circuit switching" → out-of-band signaling sets up dedicated path

Quiz: Packet Switching vs. Circuit Switching

PS	CS	
☐	☐	Variable Delay
☐	☐	"Busy signals"
☐	☐	Sharing of network resources
☐	☐	Dedicated resources between sender & receiver

Quiz: Packet Switching vs. Circuit Switching

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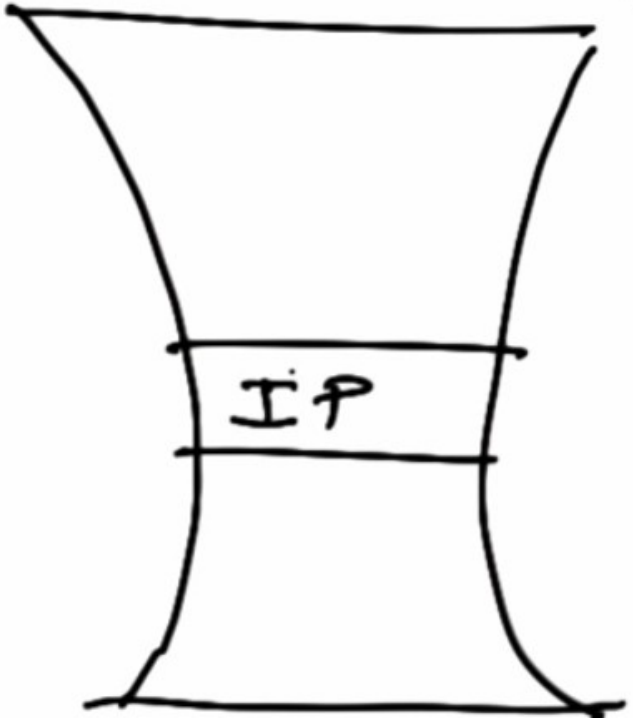
Interconnection: Narrow Waist

Goal: Interconnect many existing networks.
Hide underlying technology from applications



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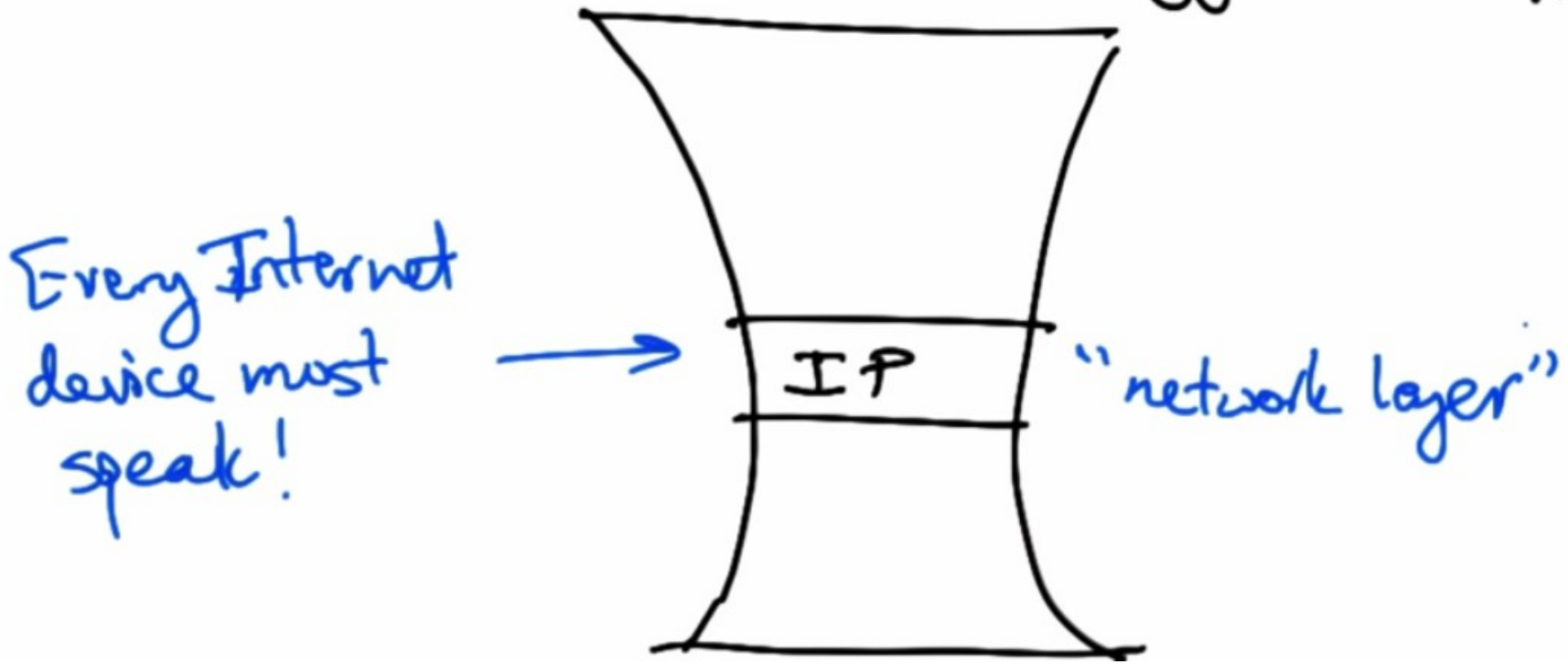

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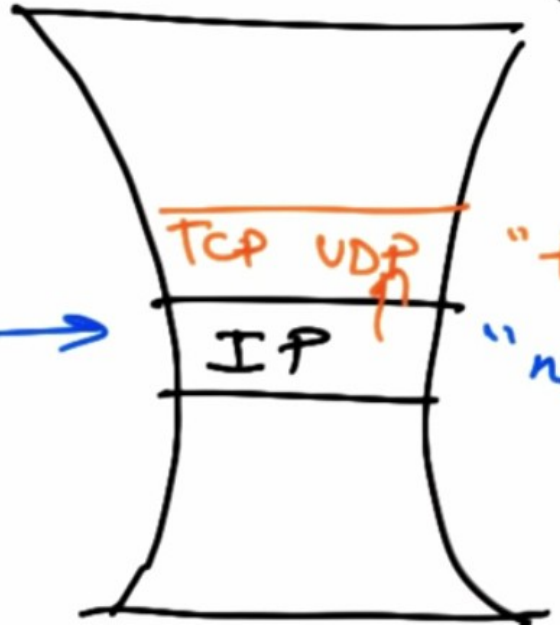

Every Internet device must speak!

"transport layer"

"network layer"

} e2e connectivity

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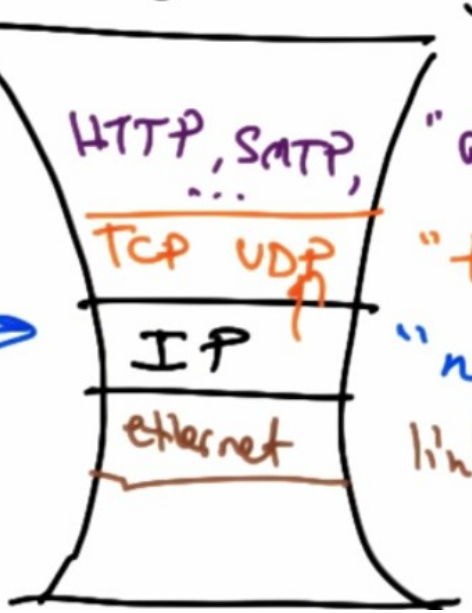

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"application layer" } reliable transport, congestion control

"transport layer" } e2e connectivity

"network layer"

link layer } p2p connectivity

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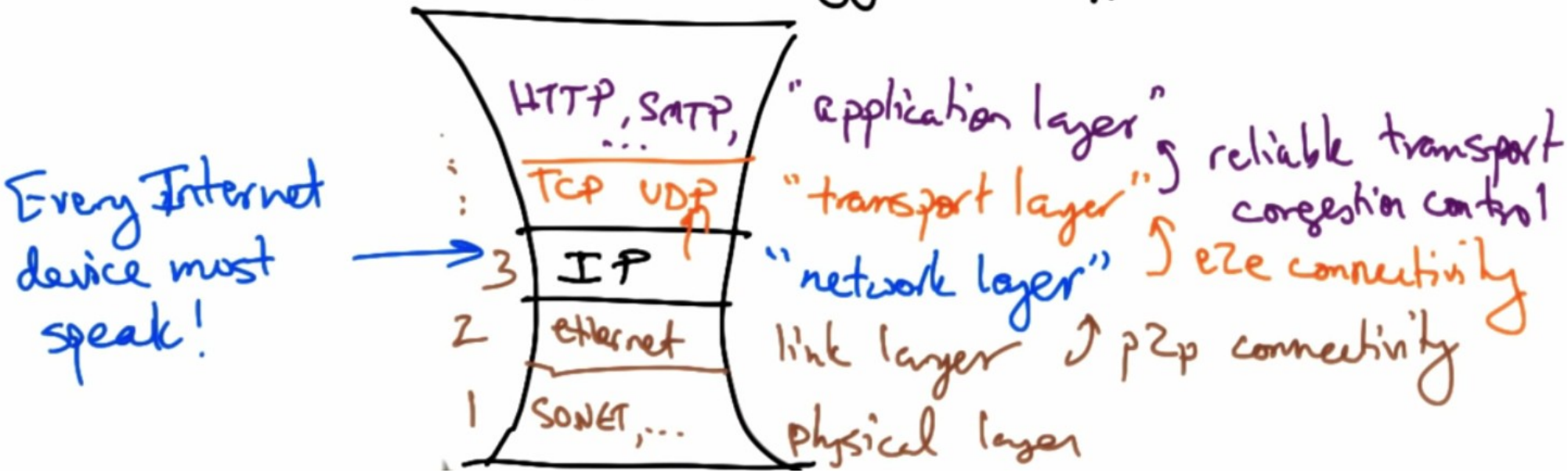

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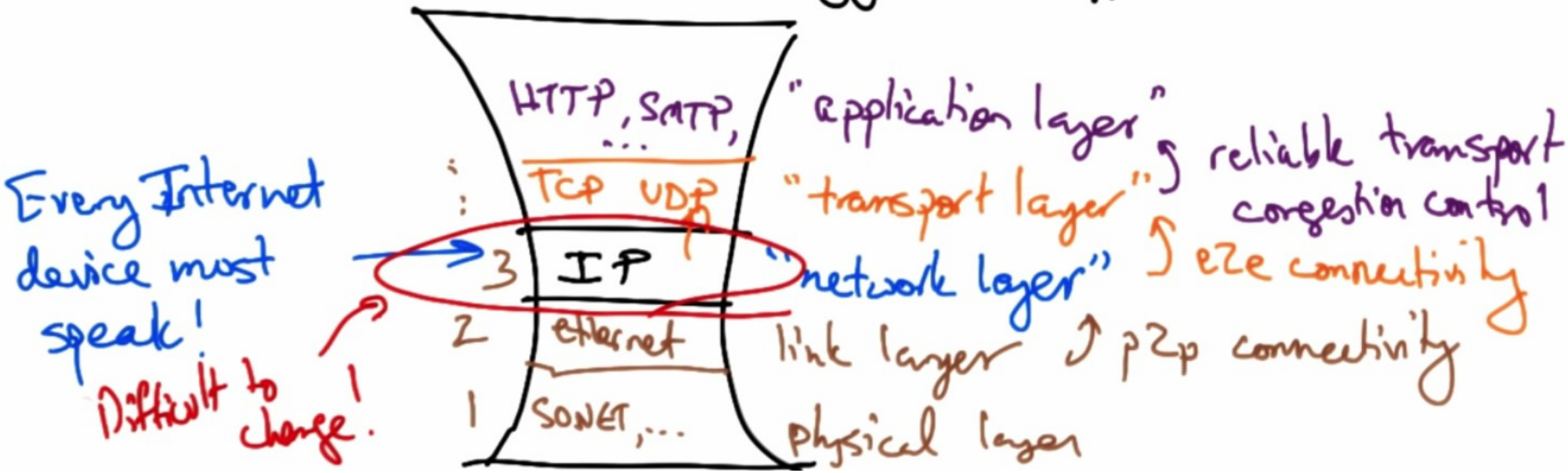

Goals

- ✓ Interconnection
- ✓ Sharing

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✓ Interconnection

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→ replication

→ fate sharing (???)
- → easier to withstand complex failure
- → easier engineering

✓ Heterogeneity: ① ~~TCP~~ IP ② "Best effort"
+ simple
× debugging is hard

~~TCP~~: streaming, DNS

✓ Distributed Management:
+ organic growth
+ stable management
× no "owner"

Addressing
Naming (DNS)
Routing (BGP)

✓ Cost
- Ease of attachment
- Accountability

What's Missing?

- × Security
- × Availability
- × Mobility
- × Scaling
- ⋮

Quiz

- [ ] Security
- [ ] Heterogeneity
- [ ] Interconnection
- [ ] Sharing
- [ ] Mobility

Quiz

- [ ] Security
- [x] Heterogeneity
- [x] Interconnection
- [x] Sharing
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End-to-End Argument

Saltzer, Reed, Clark (1981)

"The function in question can completely and correctly be implemented only with the knowledge and help of the application standing at the end points of the communication system. Therefore, providing that questioned function as a feature of the communication system itself is not possible. (Sometimes an incomplete version of the function provided by the communication system may be useful as a performance enhancement.)"

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1. Error handling in file transfer
2. End-to-end encryption
3. TCP/IP split in error handling

→ "Dumb network, intelligent endpoints"

File Transfer

(1) Read file from disk

(2) Communication system sends file

(3) Transmits packets

(4) Give file to file transfer program

(5) Write to disk

File Transfer

What can go wrong?

1. Read/write
2. Breaking up/assembling
3. Communication system

× ① Read file from disk

× ② Communication system sends file

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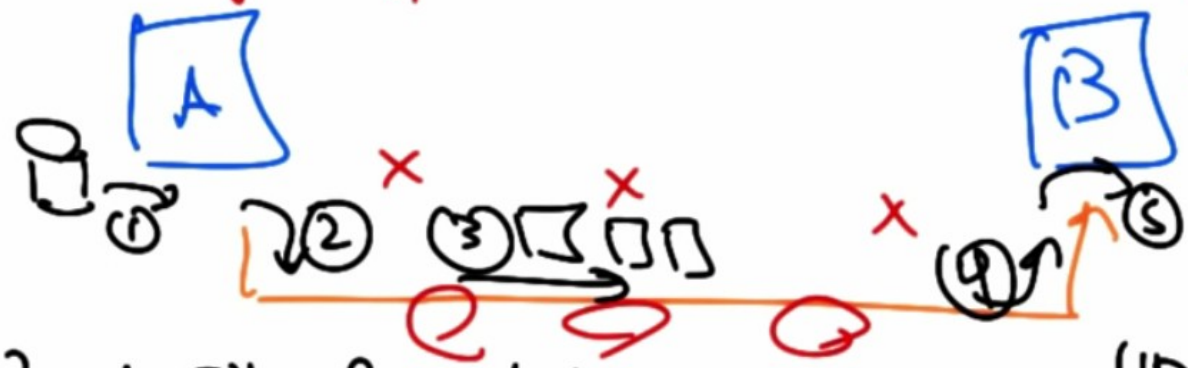
× ④ Give file to file transfer program

× ⑤ Write to disk

File Transfer

All solutions require app level checks!



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End-to-End Argument

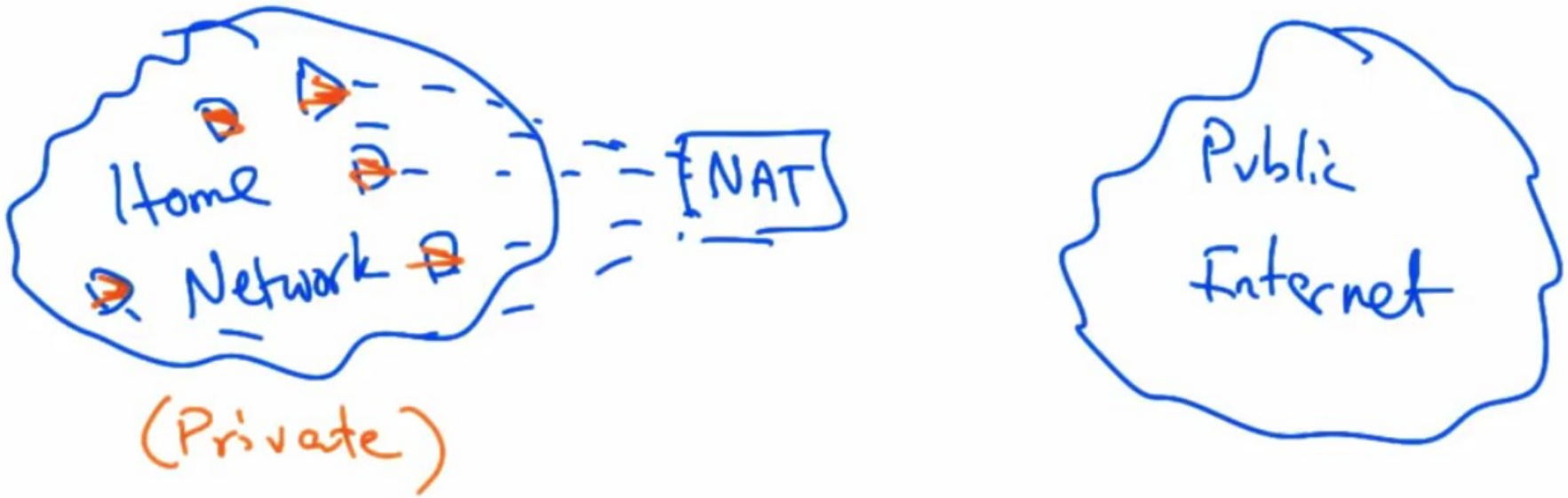
Violations:

- NAT
- VPN tunnels
- TCP splitting
- Spam → What about spam filters?
- P2P systems
- Caches

Questions:

- What's in/out?
  - Routing
  - Multicast
  - QoS
  - NAT
  - :

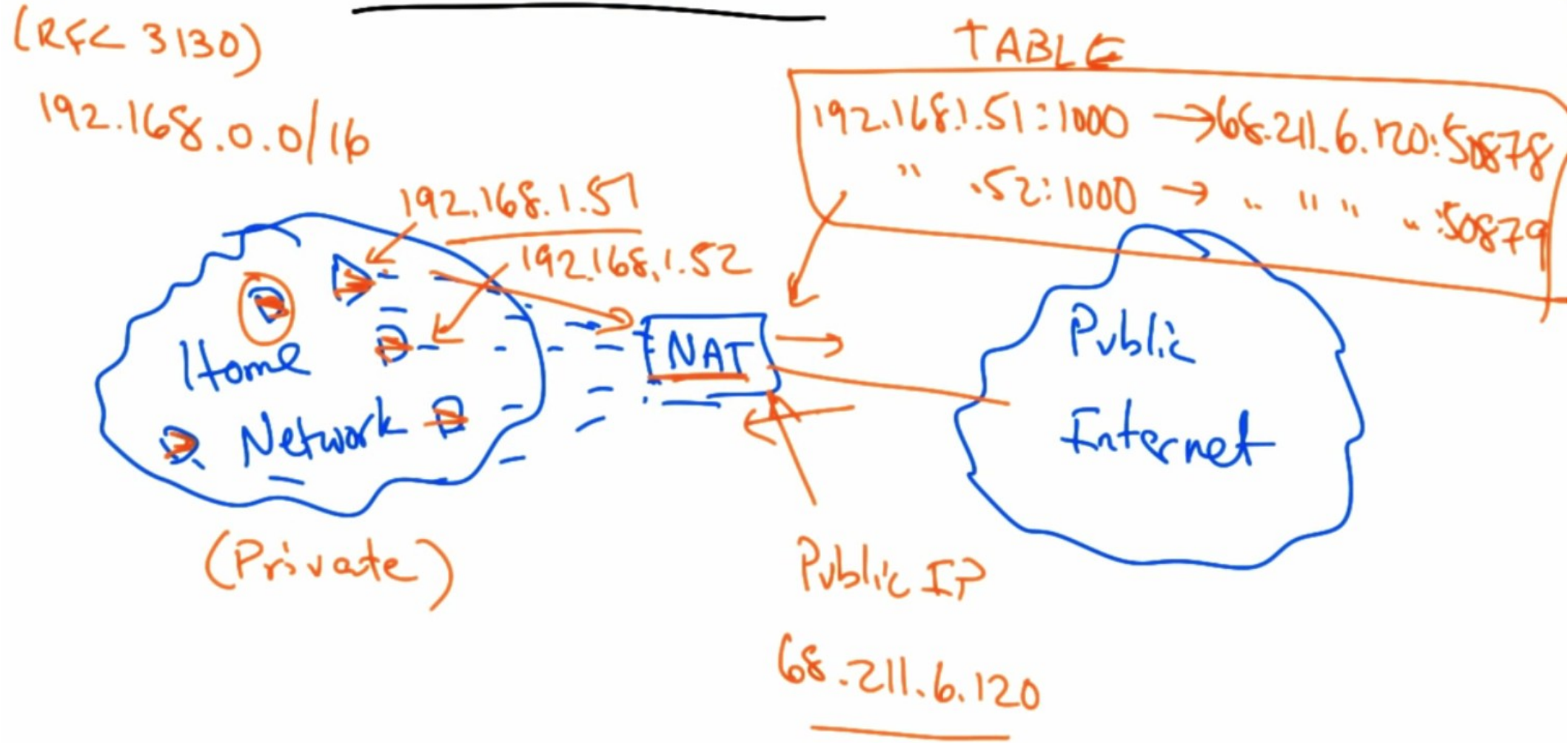
Violation: NAT



Violation: NAT

(RFC 3130)

192.168.0.0/16



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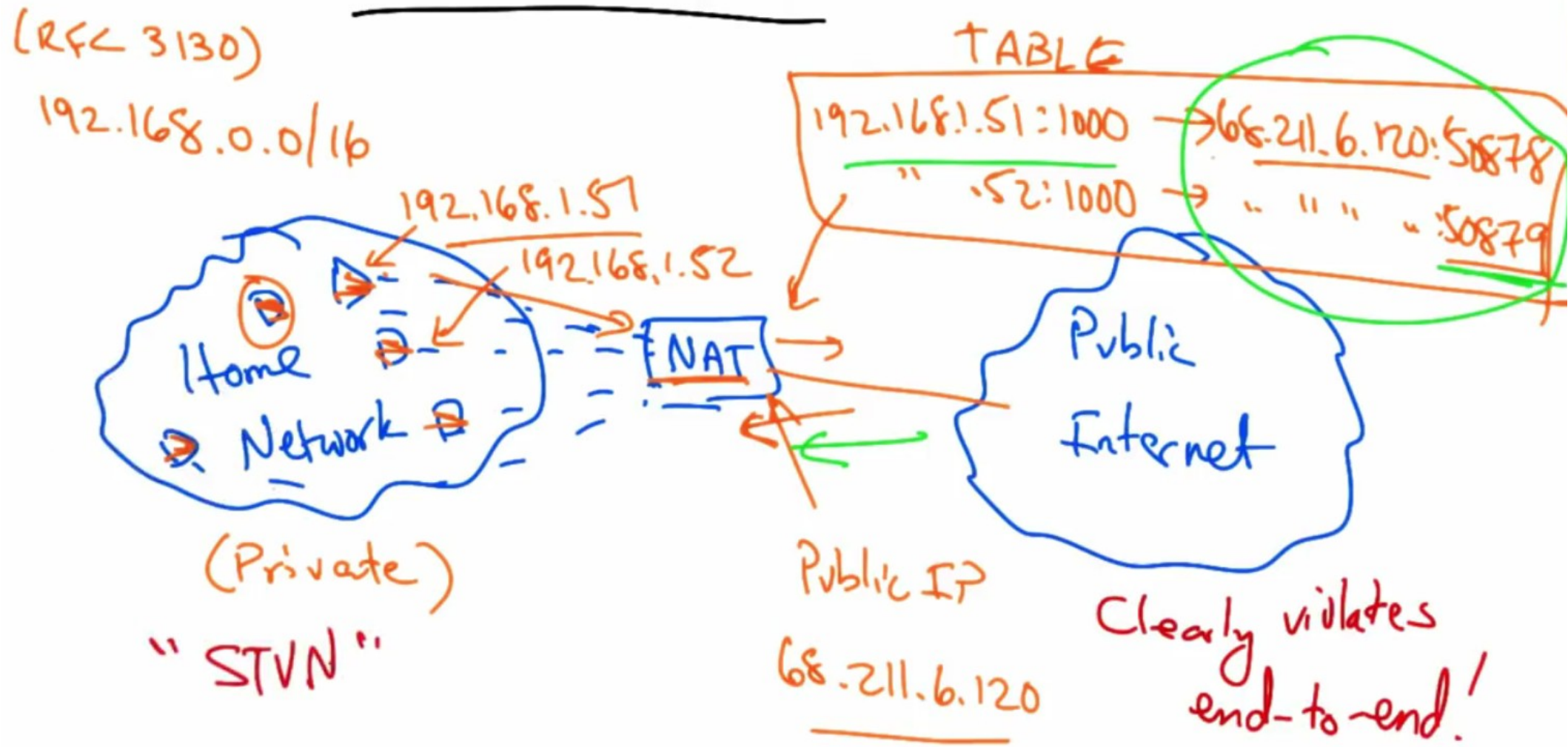


Switching and Bridging

Problem: How hosts find each other on a subnet.

How subnets are interconnected

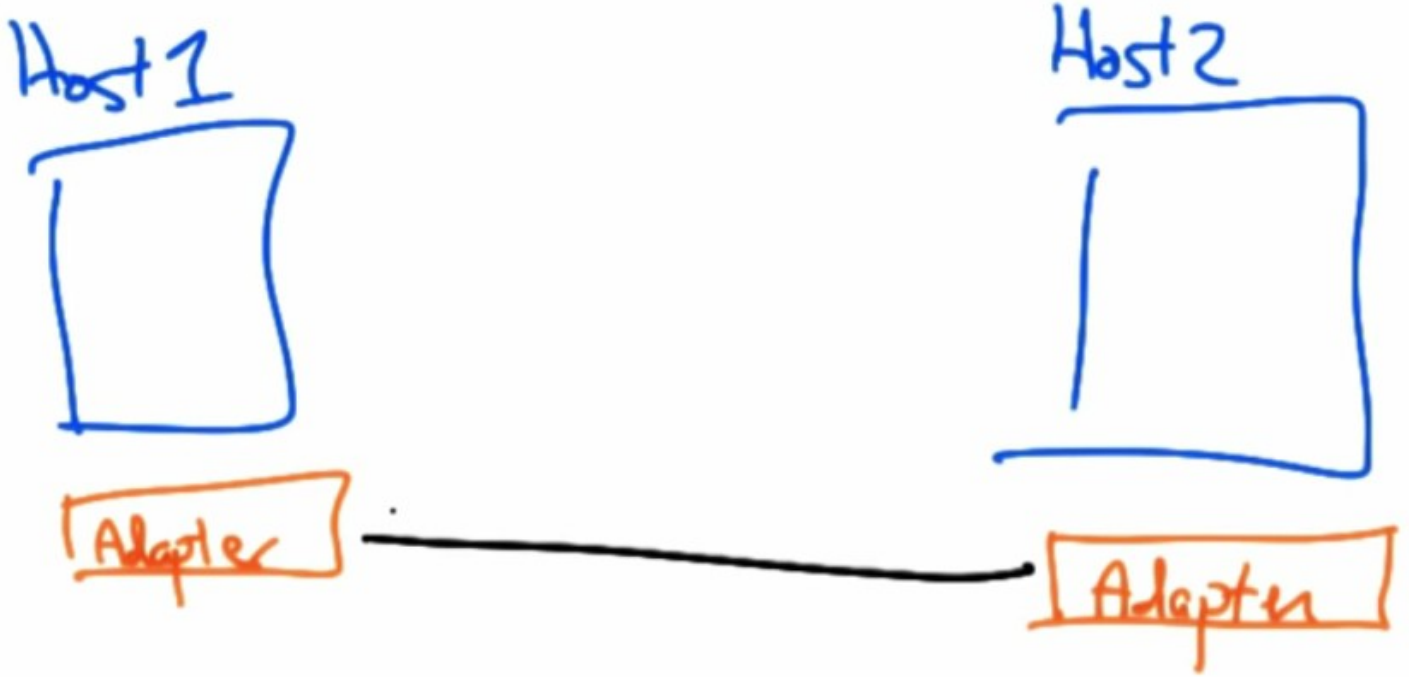
Also:

Switches vs. hubs

Switches vs. routers

How to scale Ethernet

Bootstrapping: Networking Two Hosts



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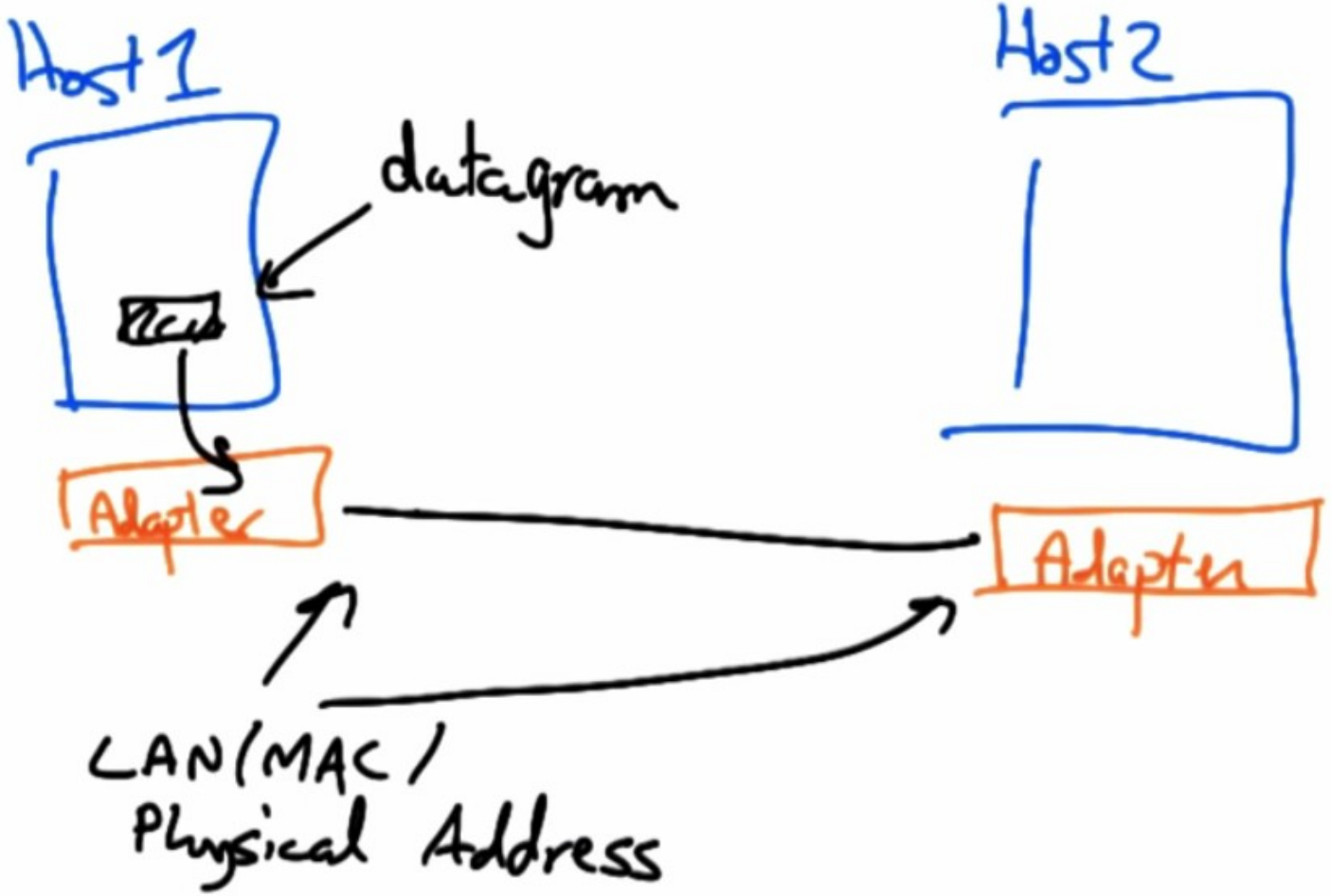

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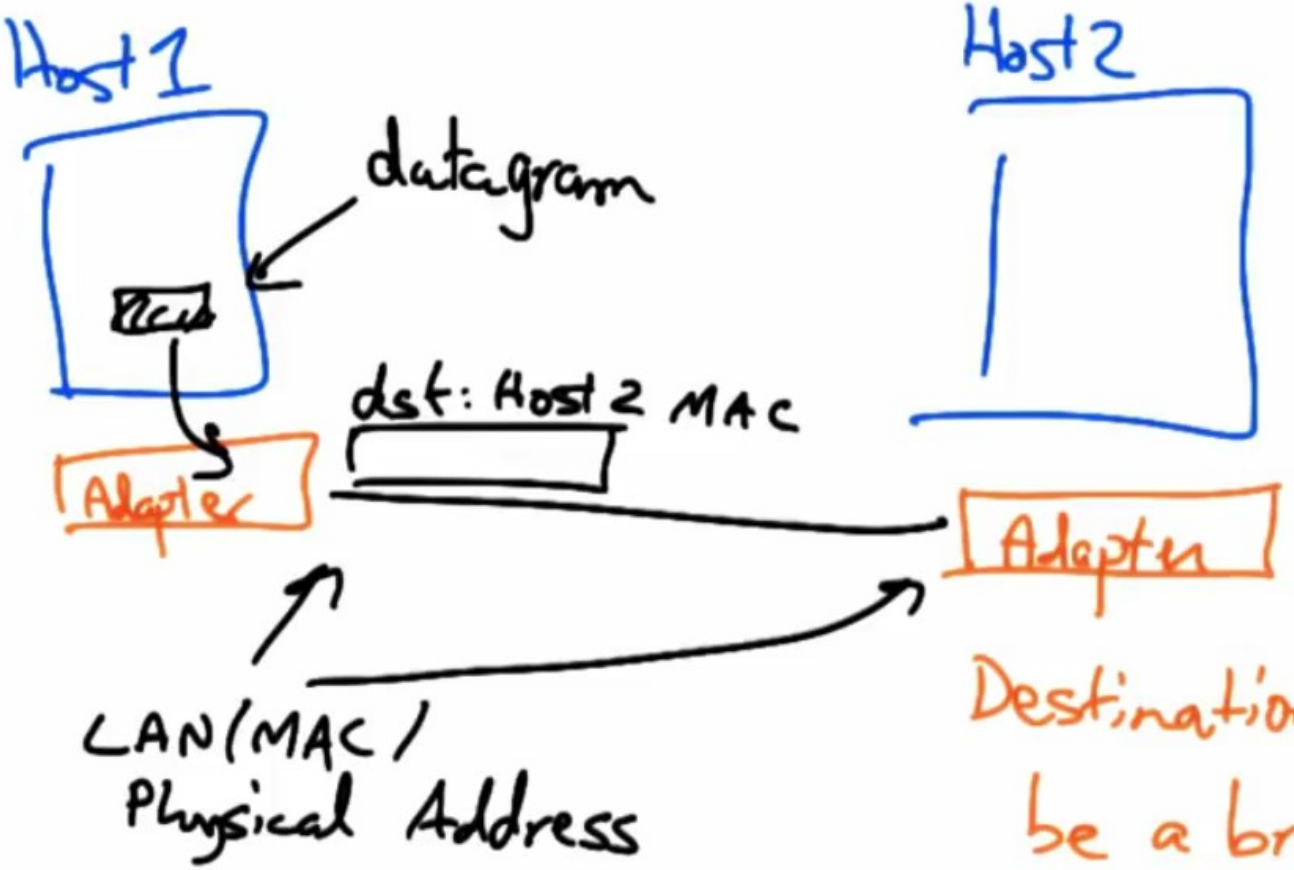
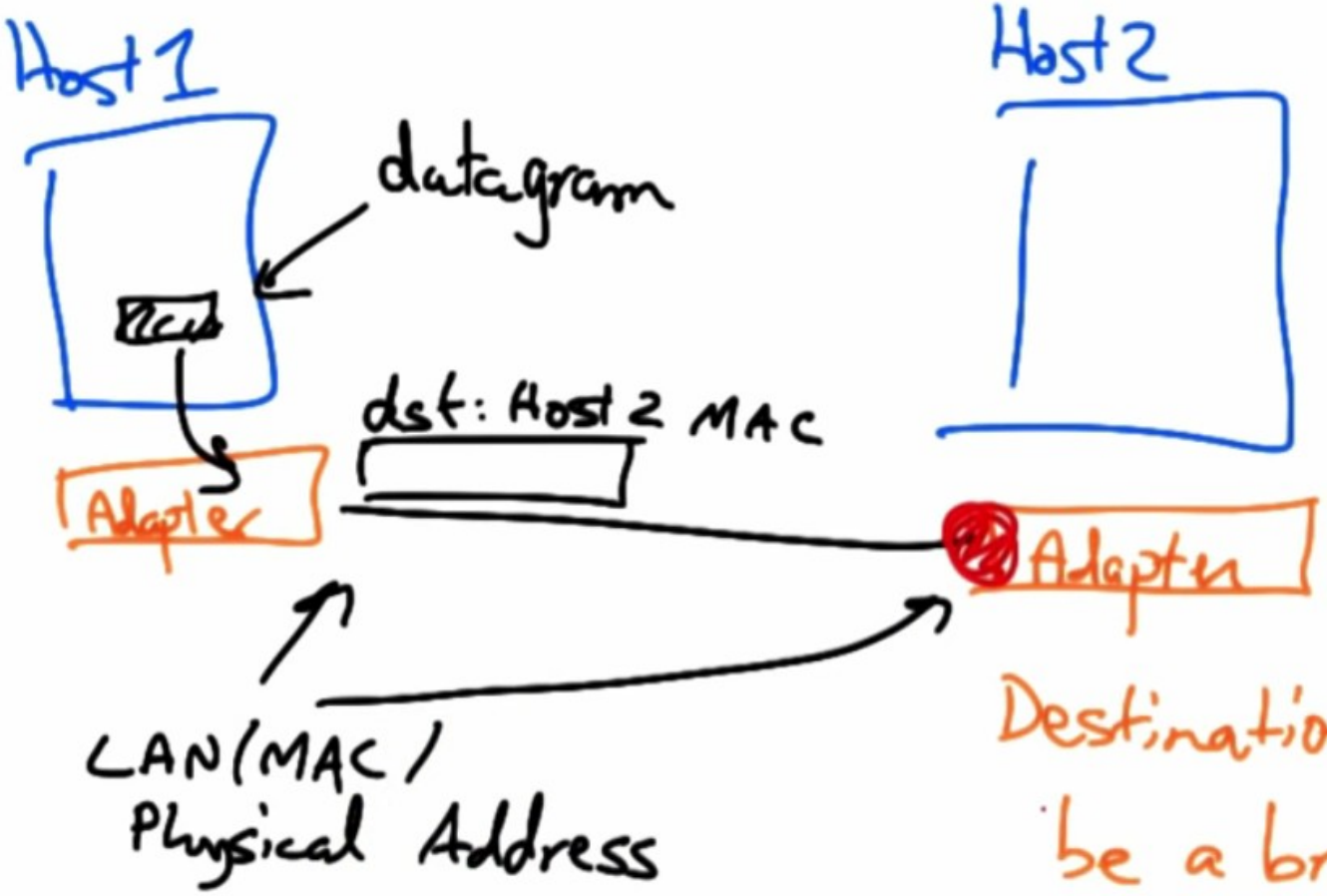


Destination can also be a broadcast MAC address.

Bootstrapping: Networking Two Hosts

How does a host learn the MAC address of another host?



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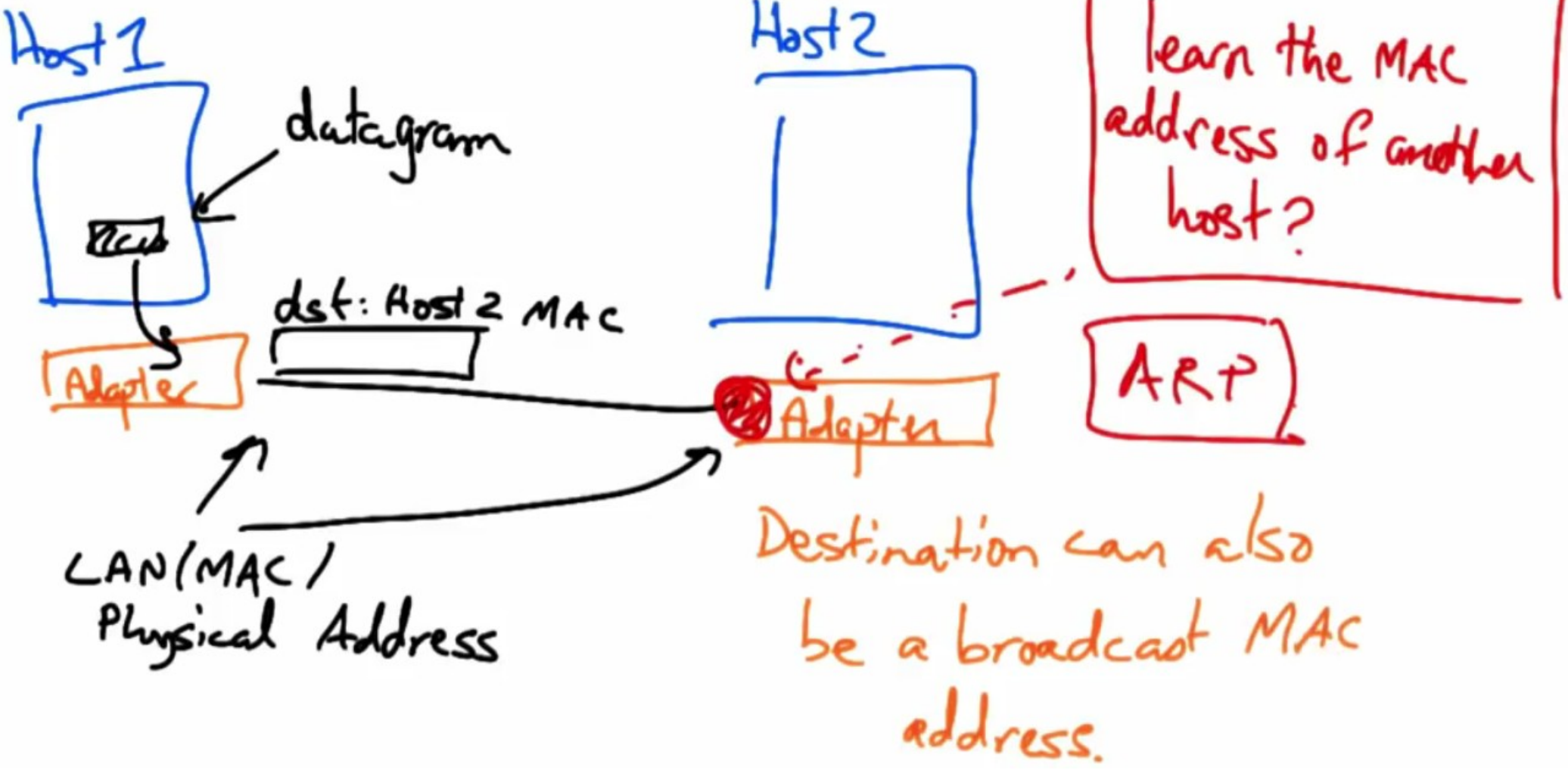

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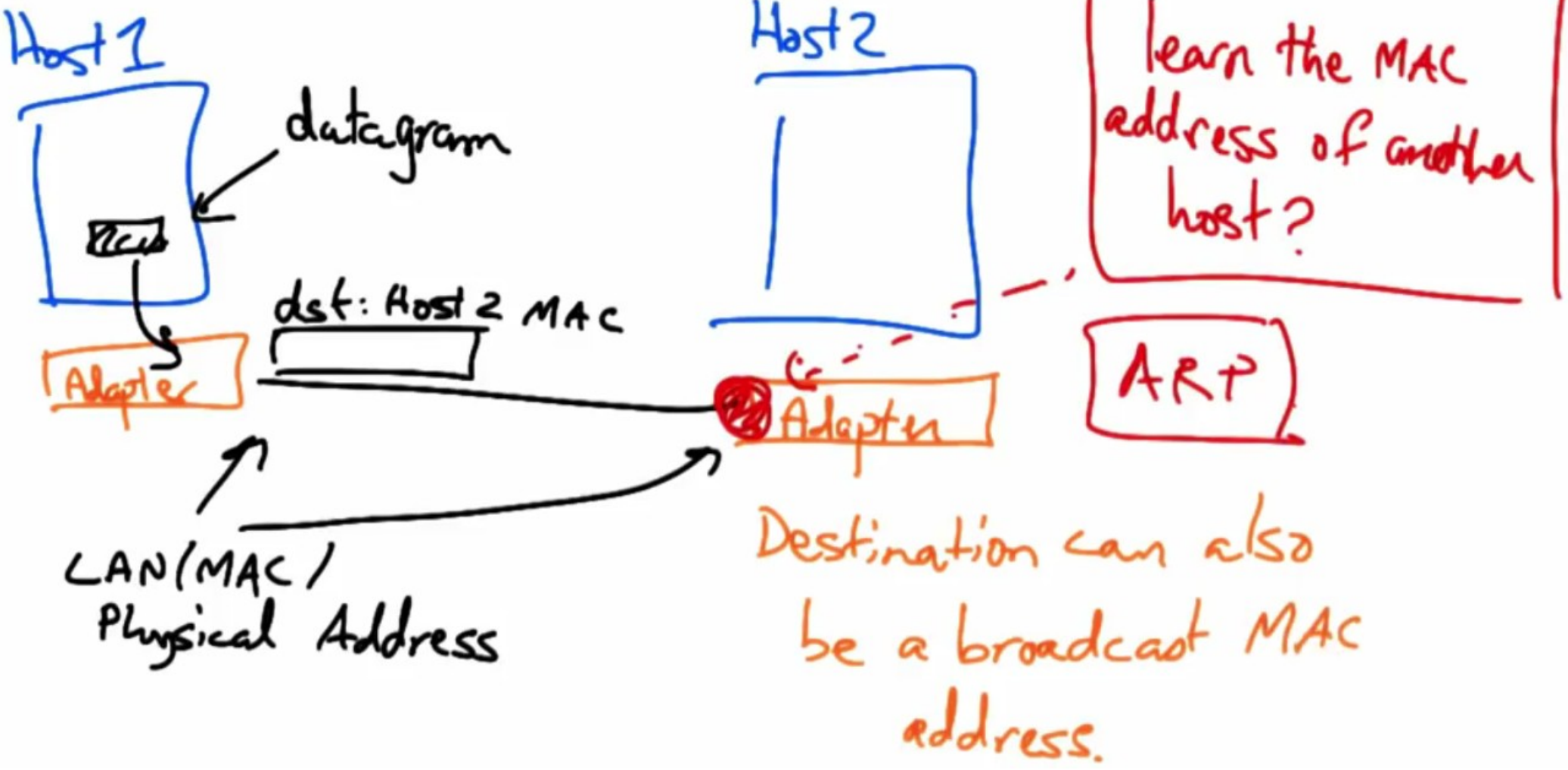
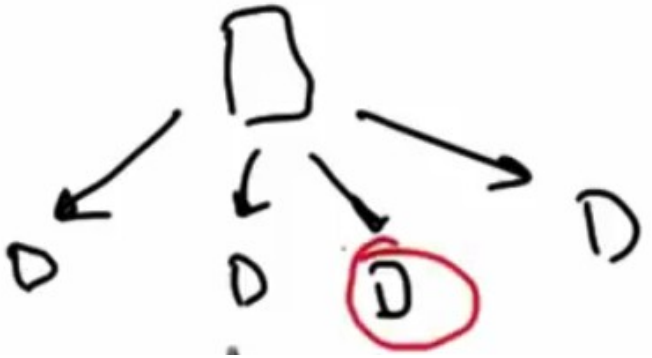


ARP: Address Resolution Protocol

Host queries with an IP address:

"Who has IP address 130.207.160.47?"



Broadcast

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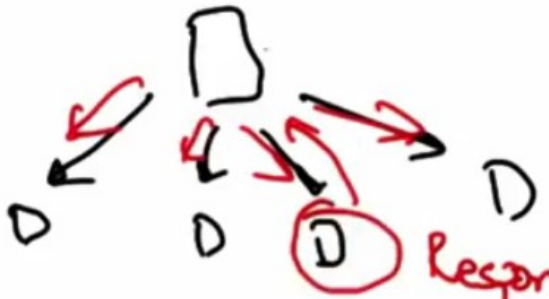

Broadcast

Response is the MAC address corresponding to 130.207.160.47

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ARP Table

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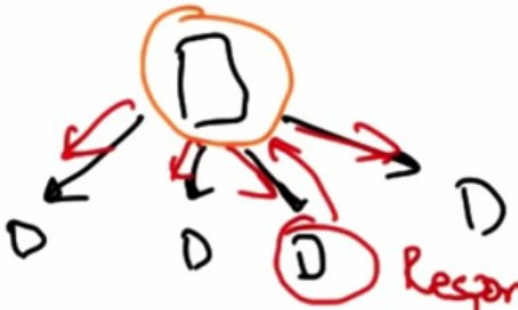

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Encapsulation

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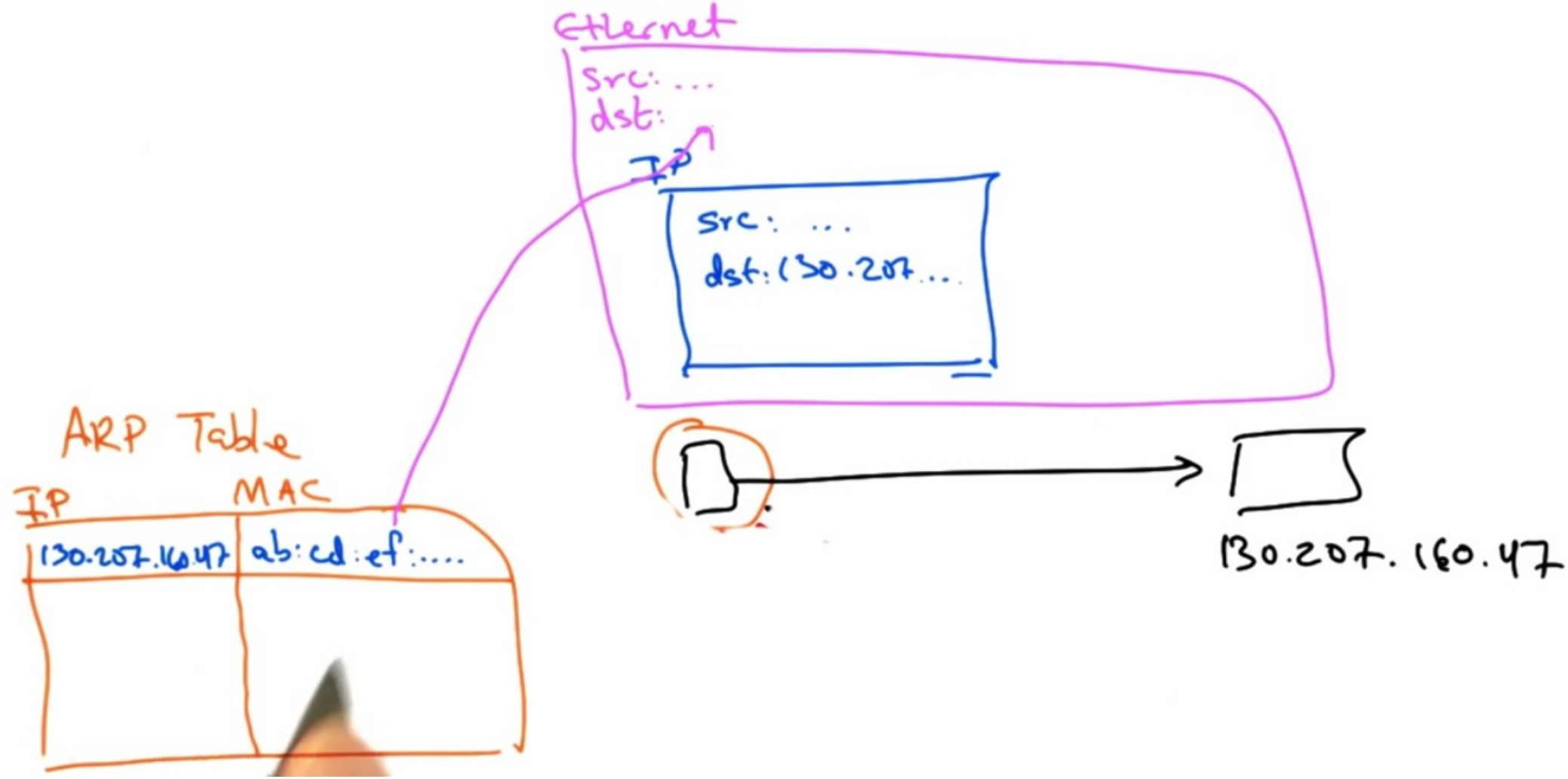

Quiz: ARP

What are the queries and responses in ARP?

- ☐ Query: Broadcast asking about IP
  Response: Unicast with MAC address
- ☐ Query: Unicast asking about IP
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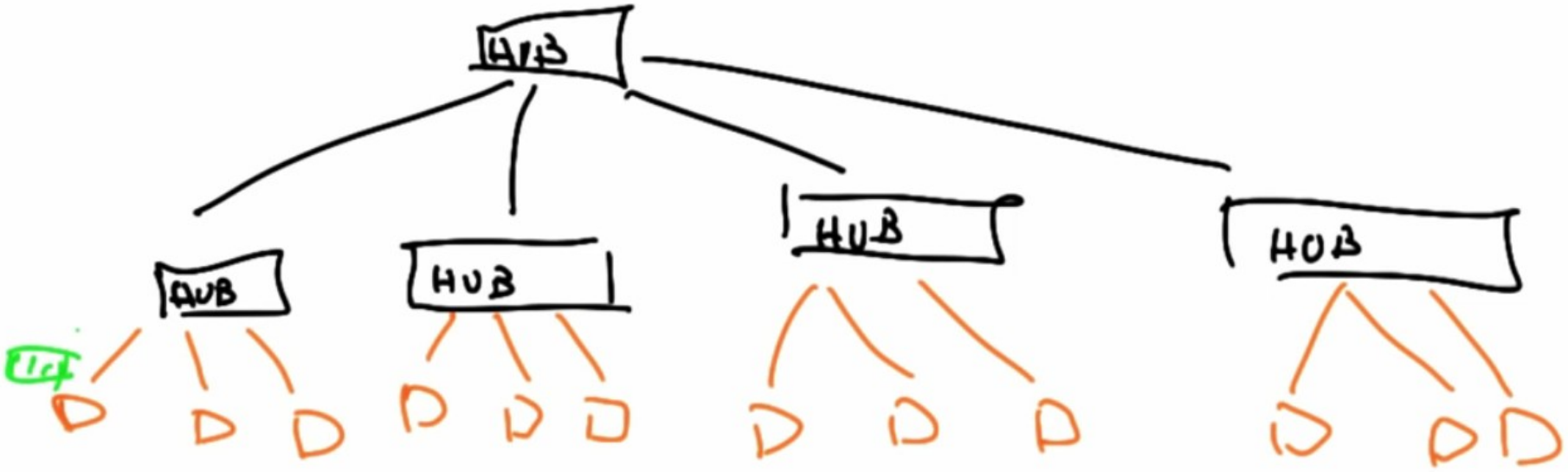
Interconnecting LANs with Hubs

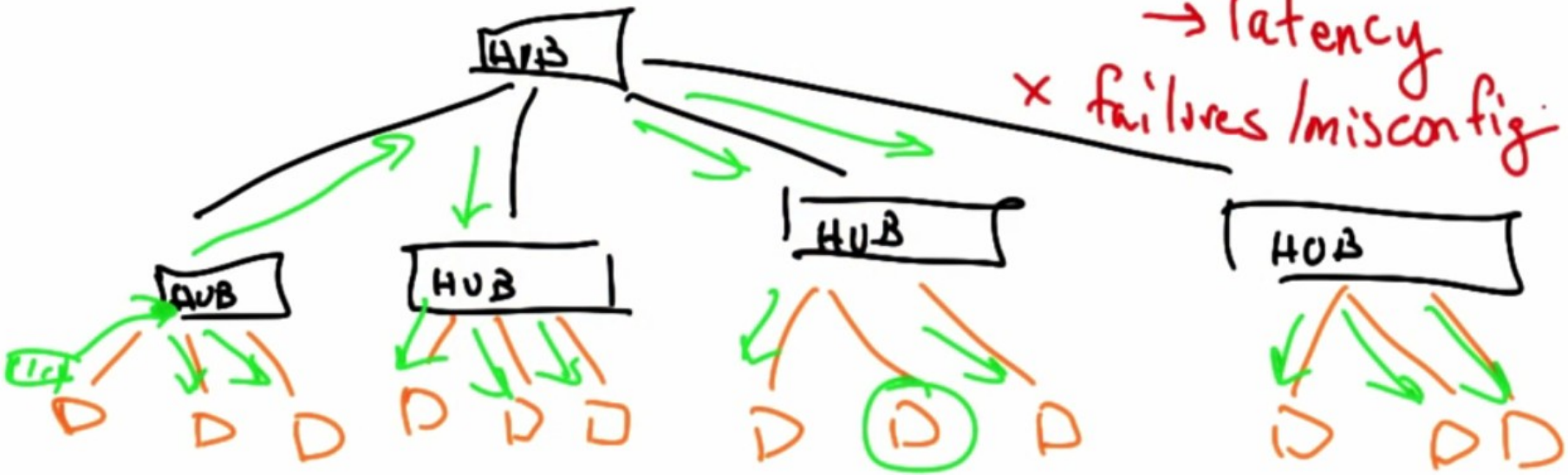
Hub: Broadcast medium



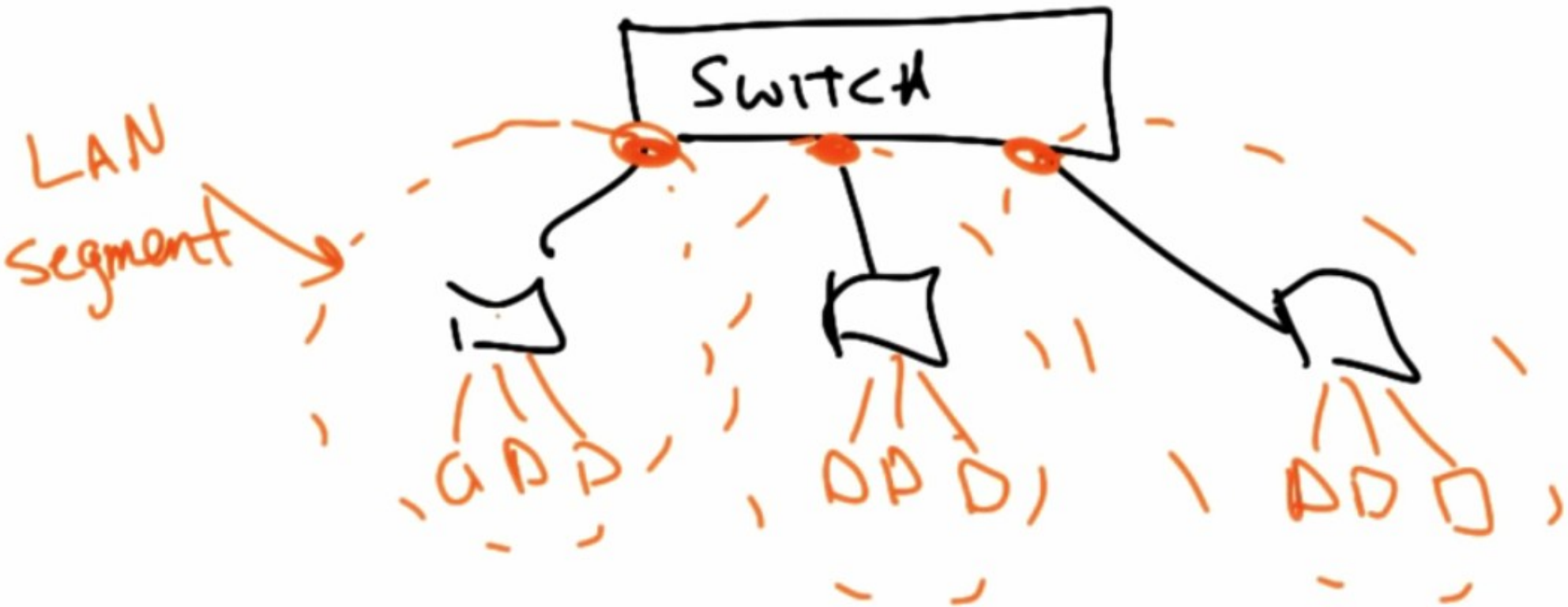
Interconnecting LANs with Hubs

Hub: Broadcast medium

× flooding
× collisions of frames
→ latency
× failures / misconfig.



Switches: Traffic Isolation



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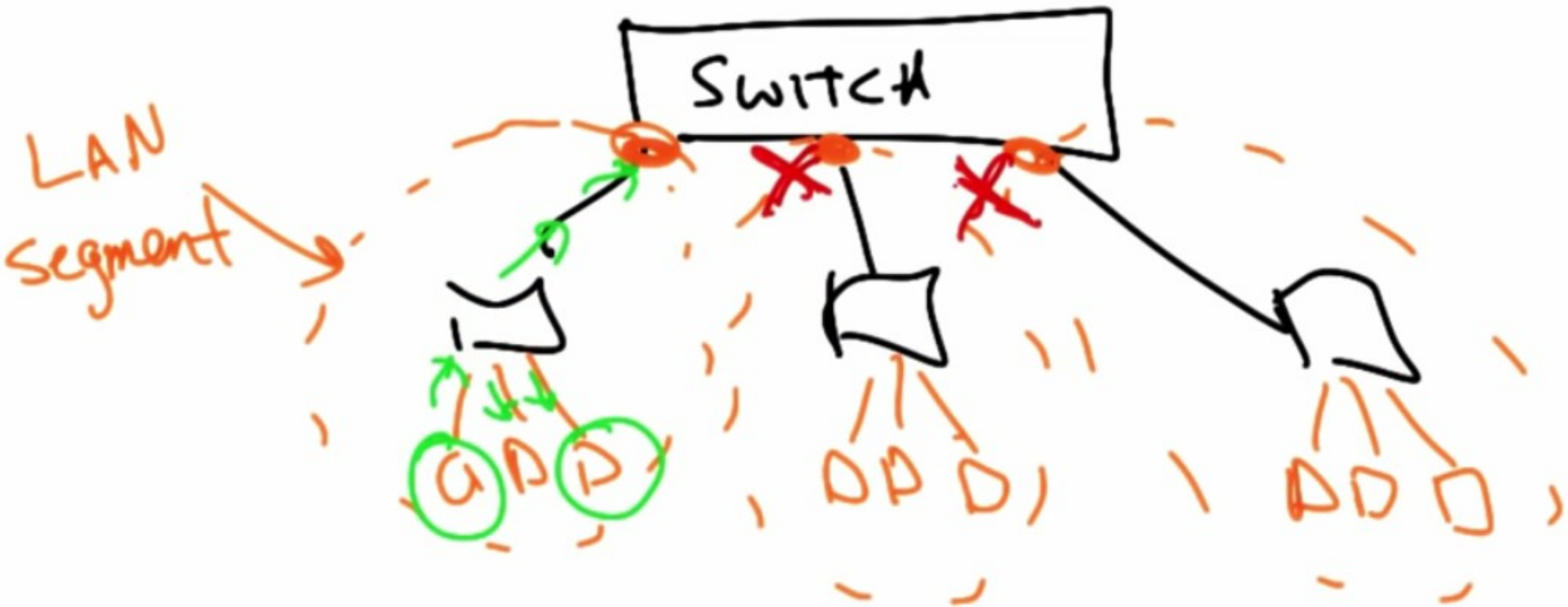

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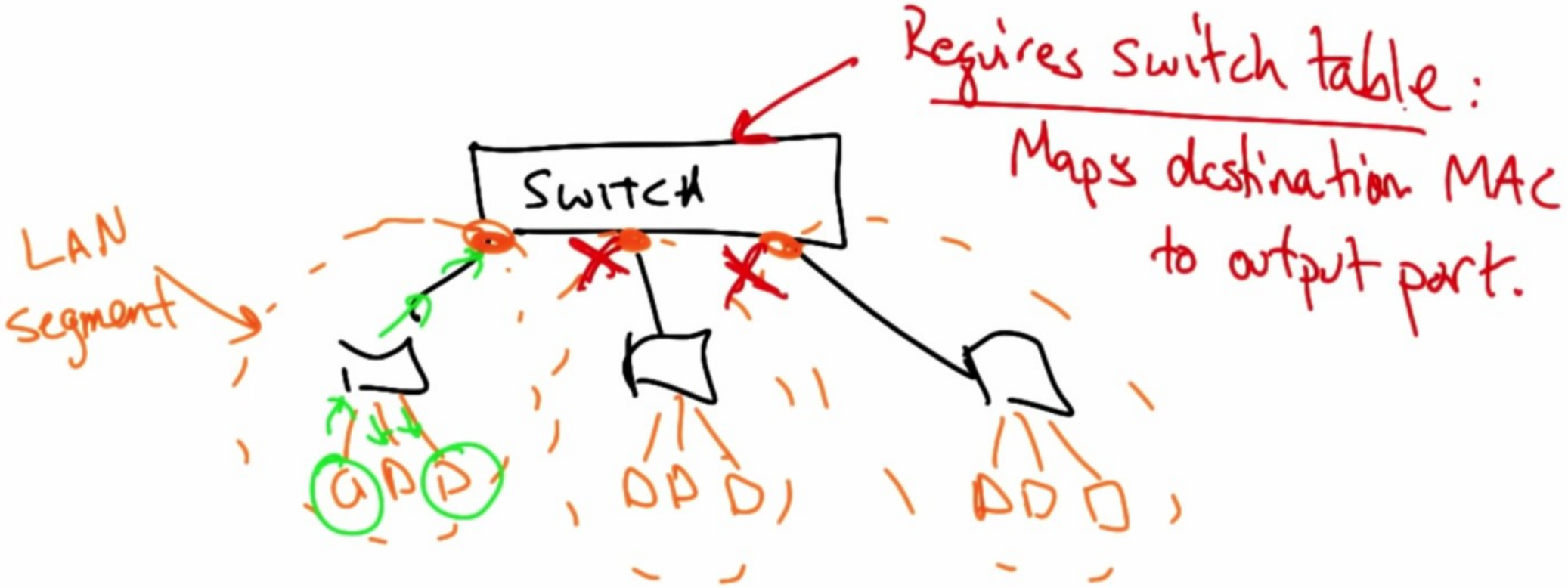
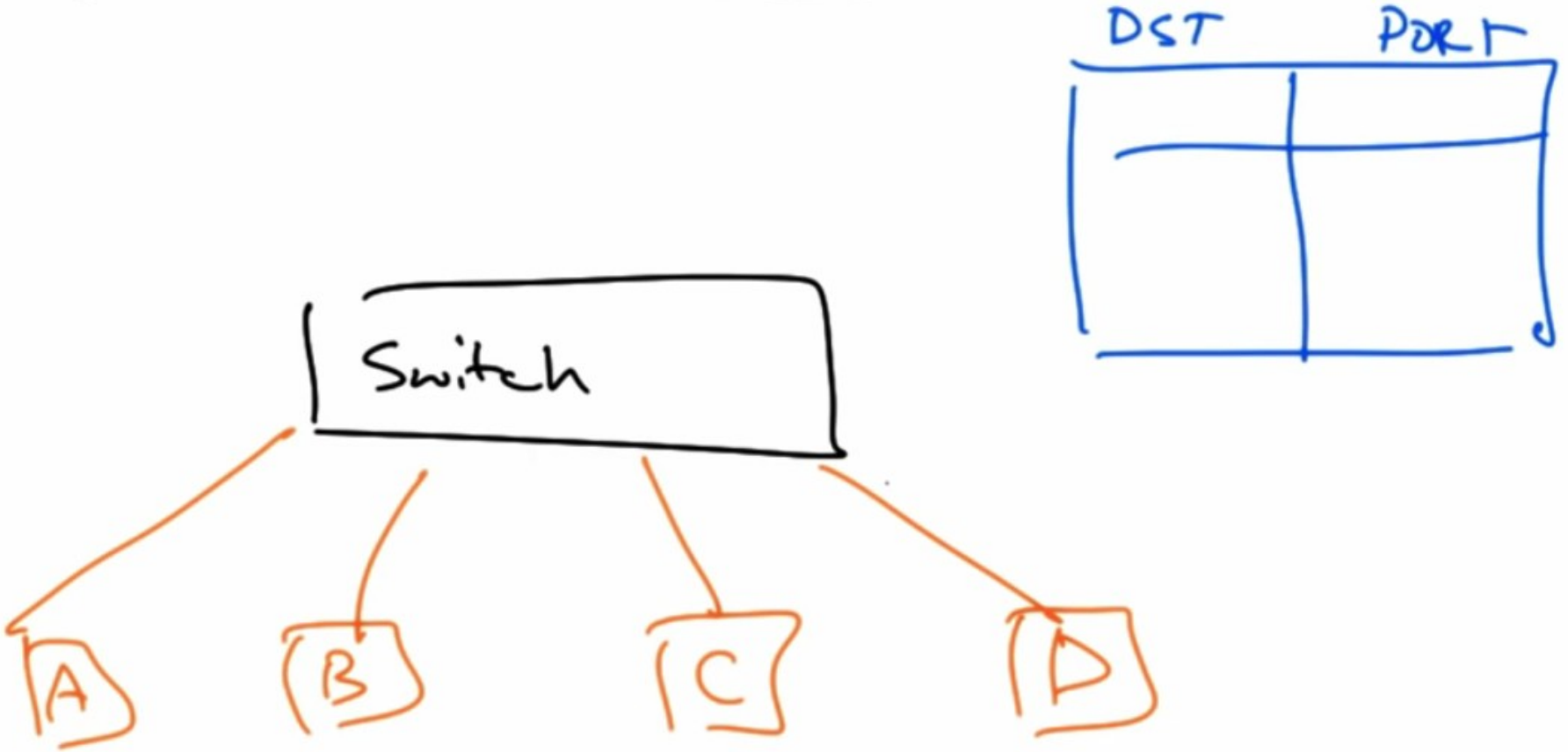
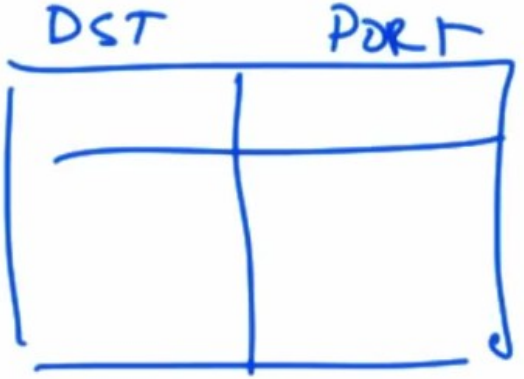


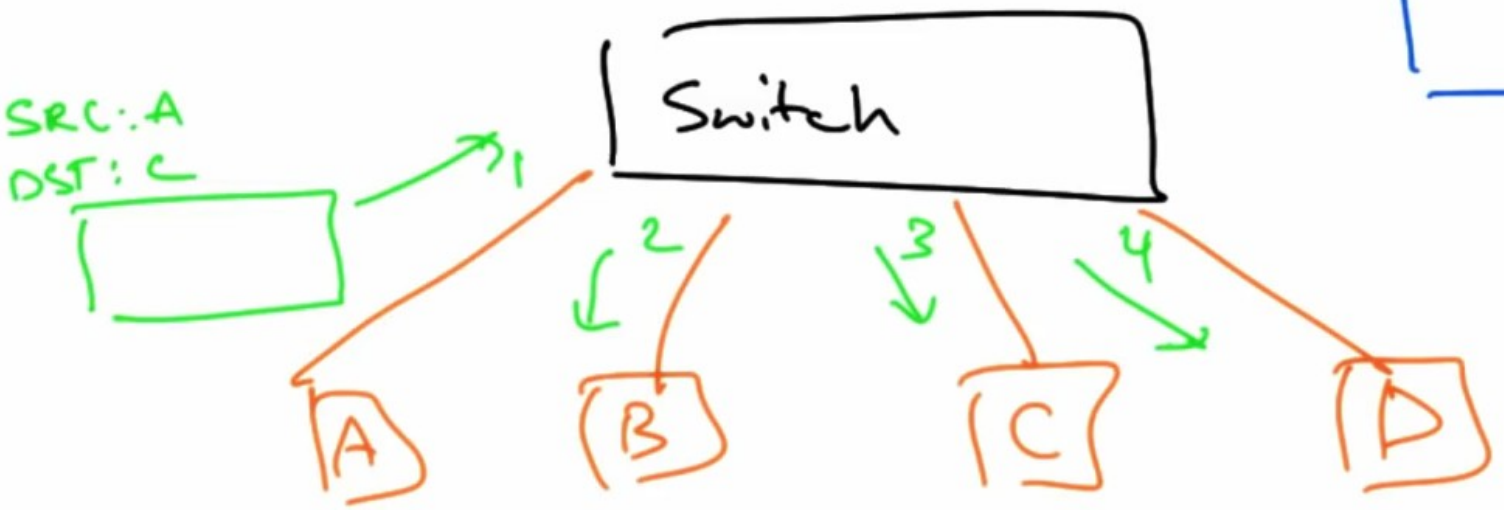
Learning Switches



Learning Switches

① If no entry in forwarding table ⇒ FLOOD

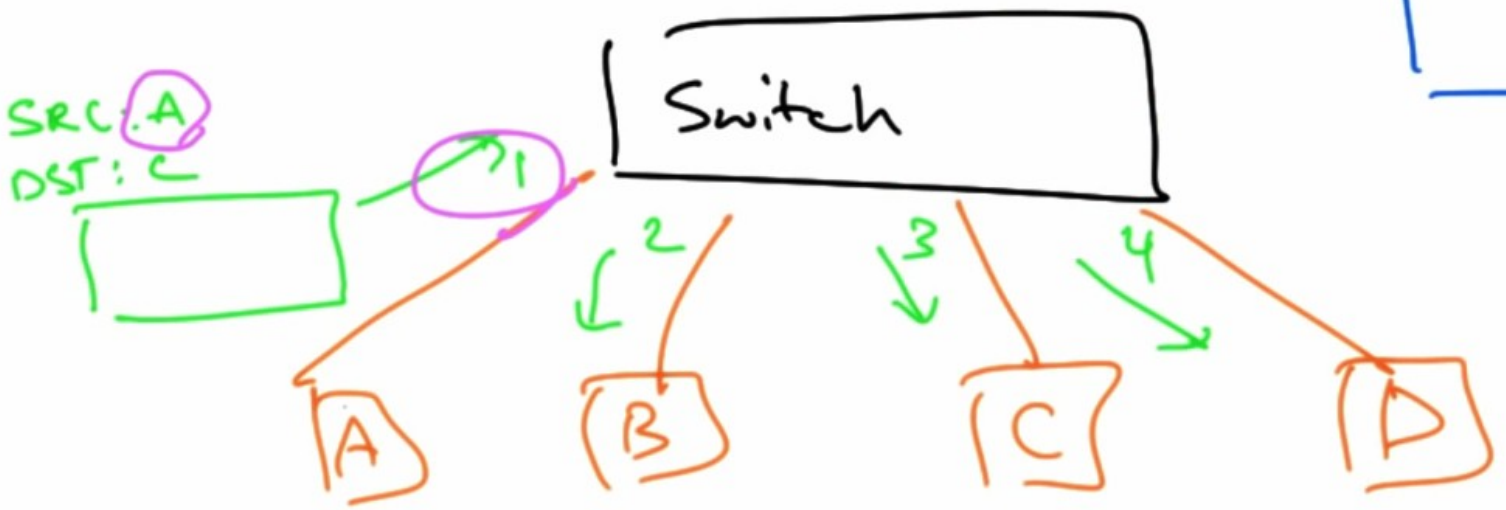




Learning Switches

DST	PORT
A	1

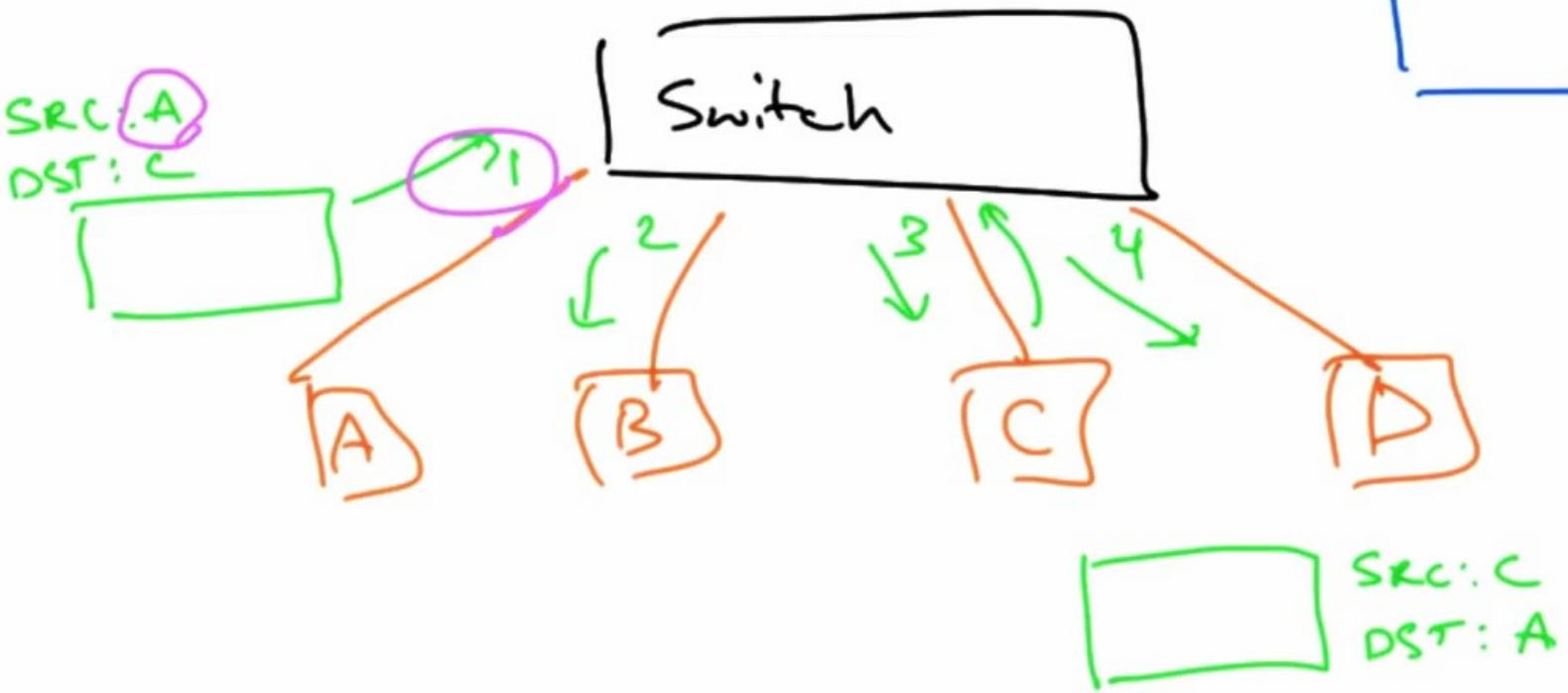
(1) If no entry in forwarding table => FLOOD



Learning Switches

(1) If no entry in forwarding table ⇒ FLOOD

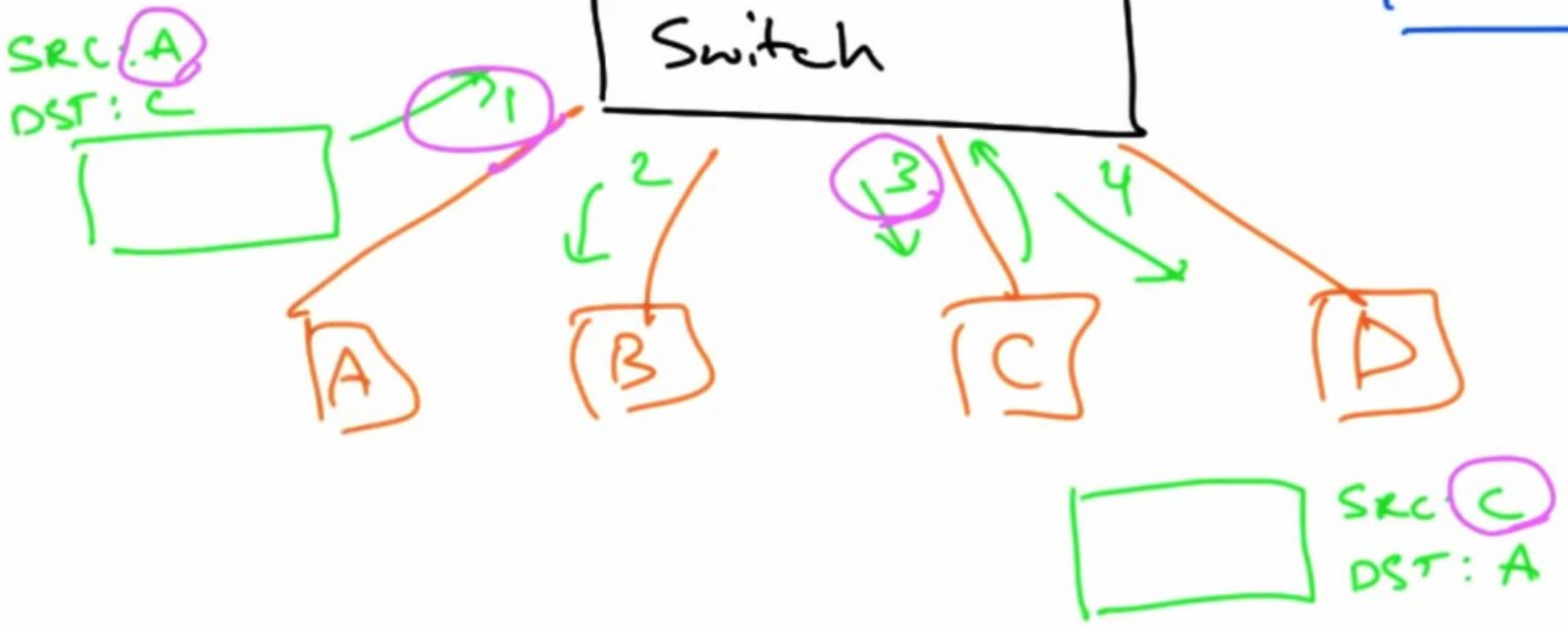
DST	PORT
A	1



Learning Switches

1. If no entry in forwarding table ⇒ FLOOD
2. Otherwise, send to output port in table

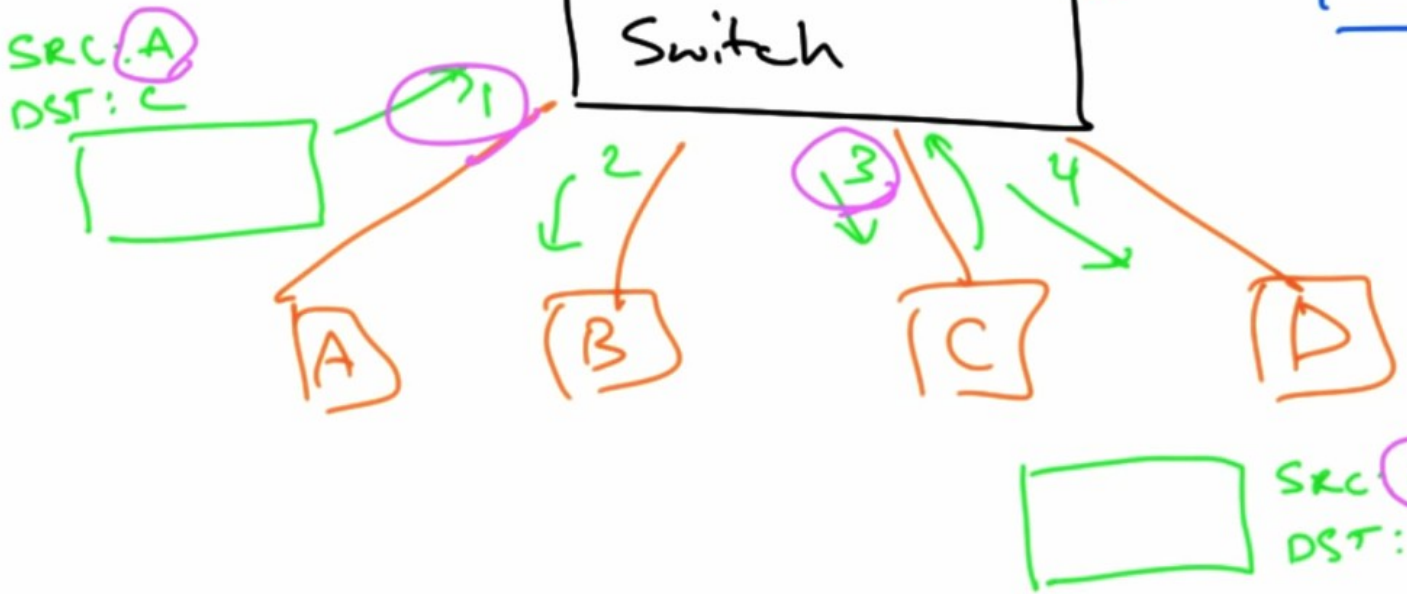
DST	PORT
A	1
C	3



Learning Switches

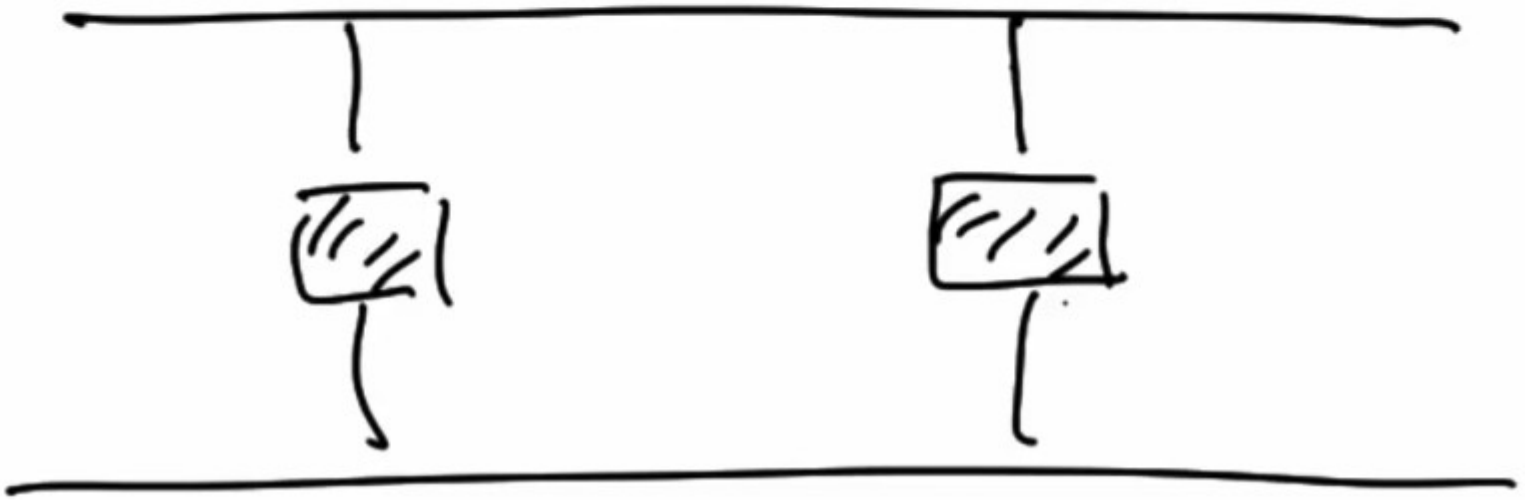
1. If no entry in forwarding table ⇒ FLOOD
2. Otherwise, send to output port in table

DST	PORT
A	1
C	3



+ Broadcast frames (e.g., ARP)

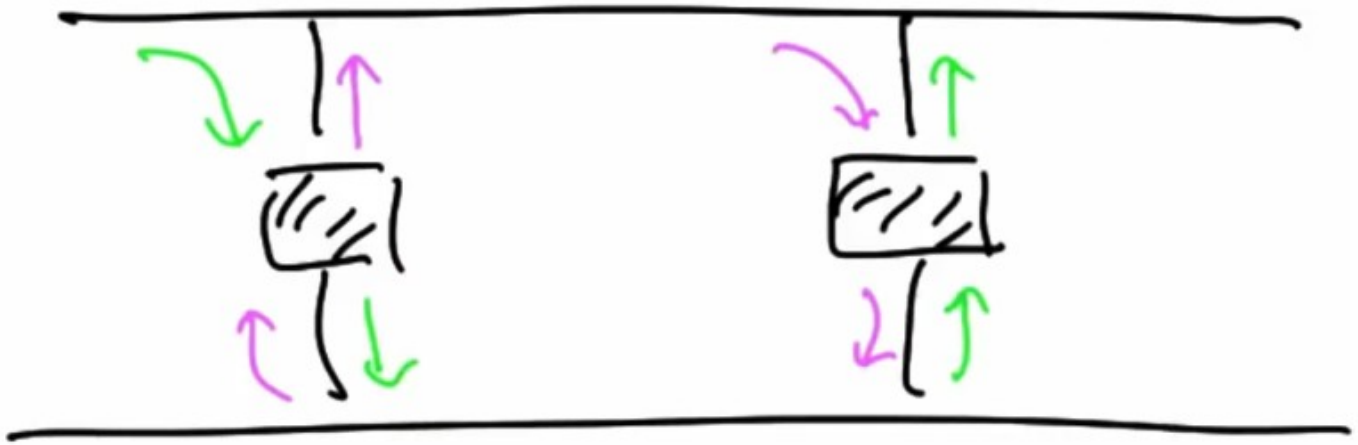
Loops & Broadcasts



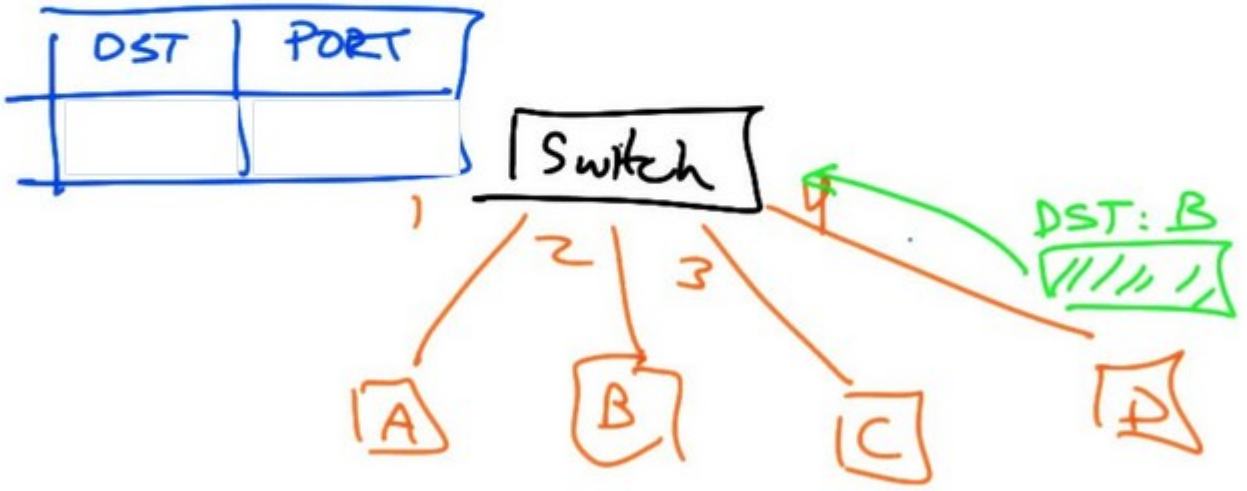
Loops & Broadcasts

Cycles ⇒

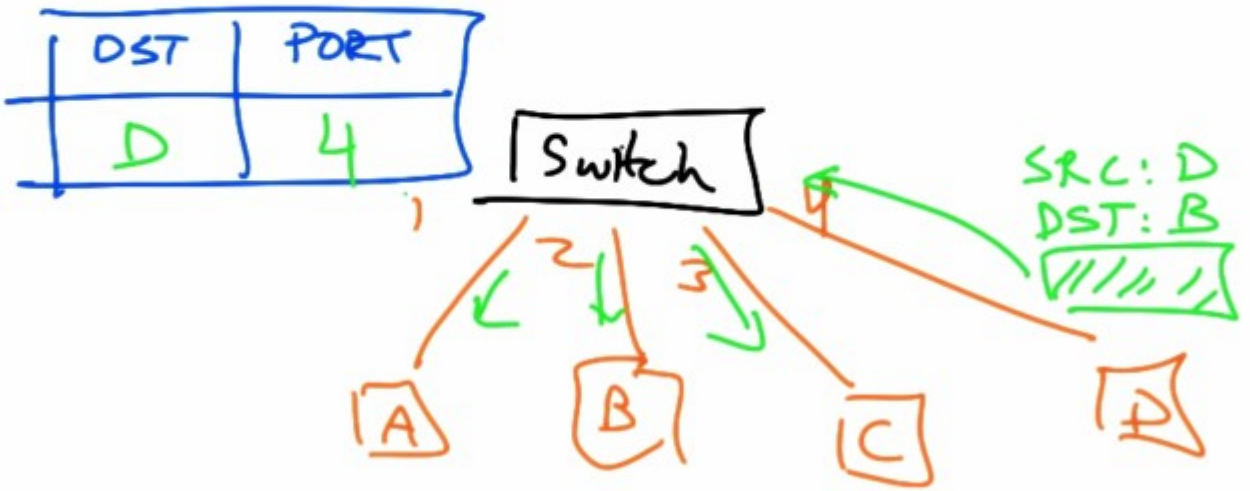
1. Loops
2. Broadcast storms



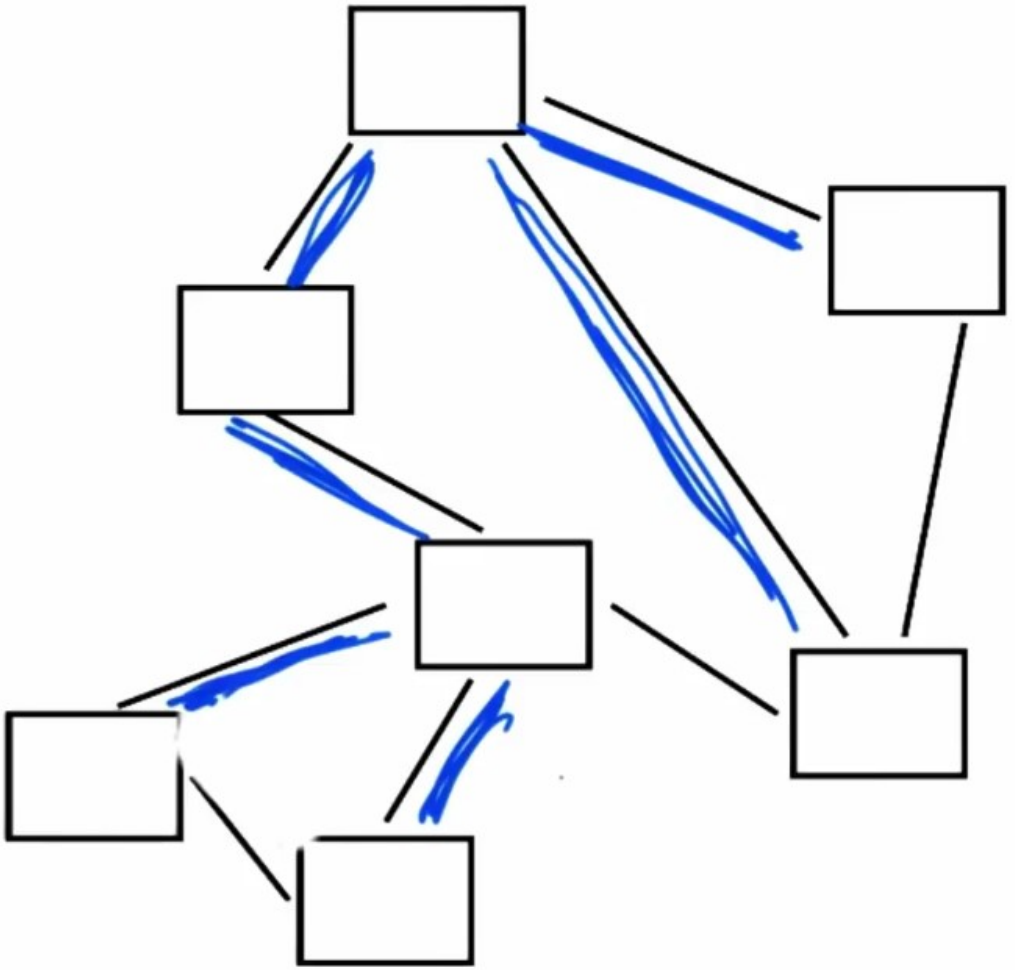
Quiz: Learning Switches



Quiz: Learning Switches

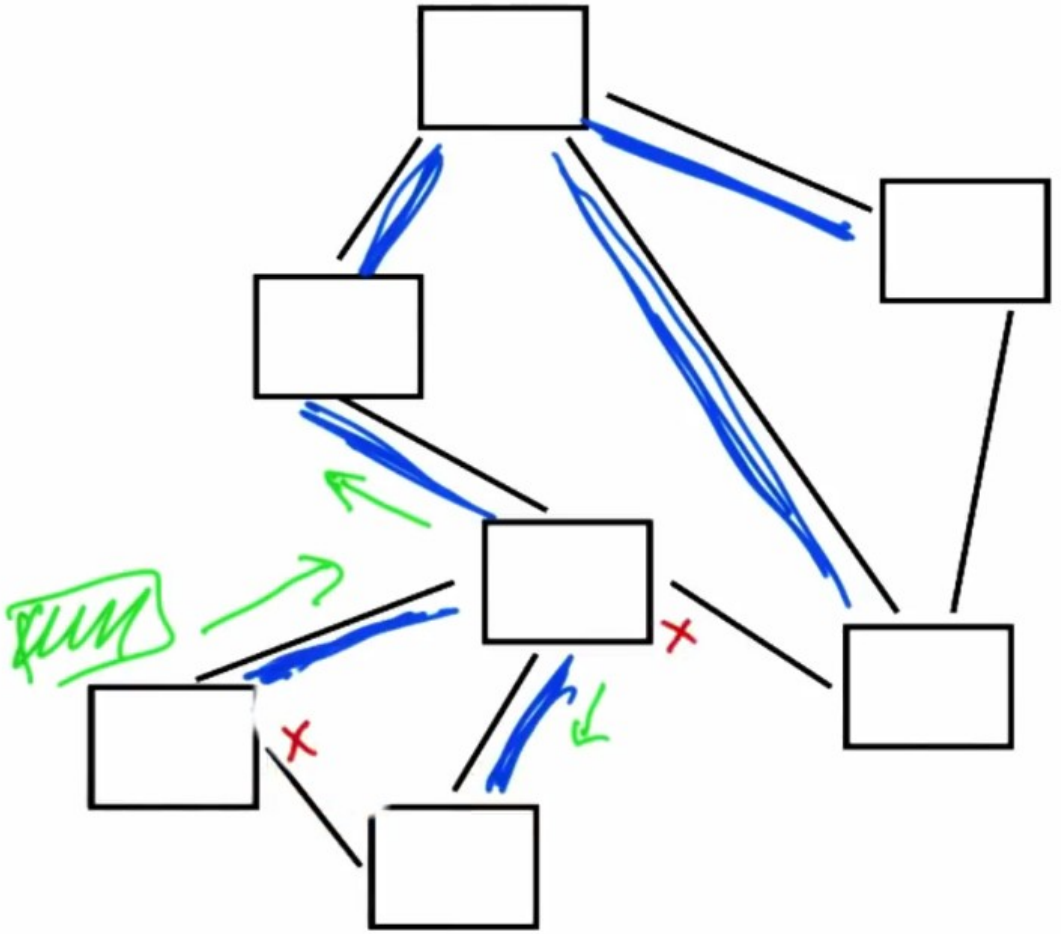


Spanning Tree



Allow loop-free forwarding on a topology that may contain cycles.

Spanning Tree



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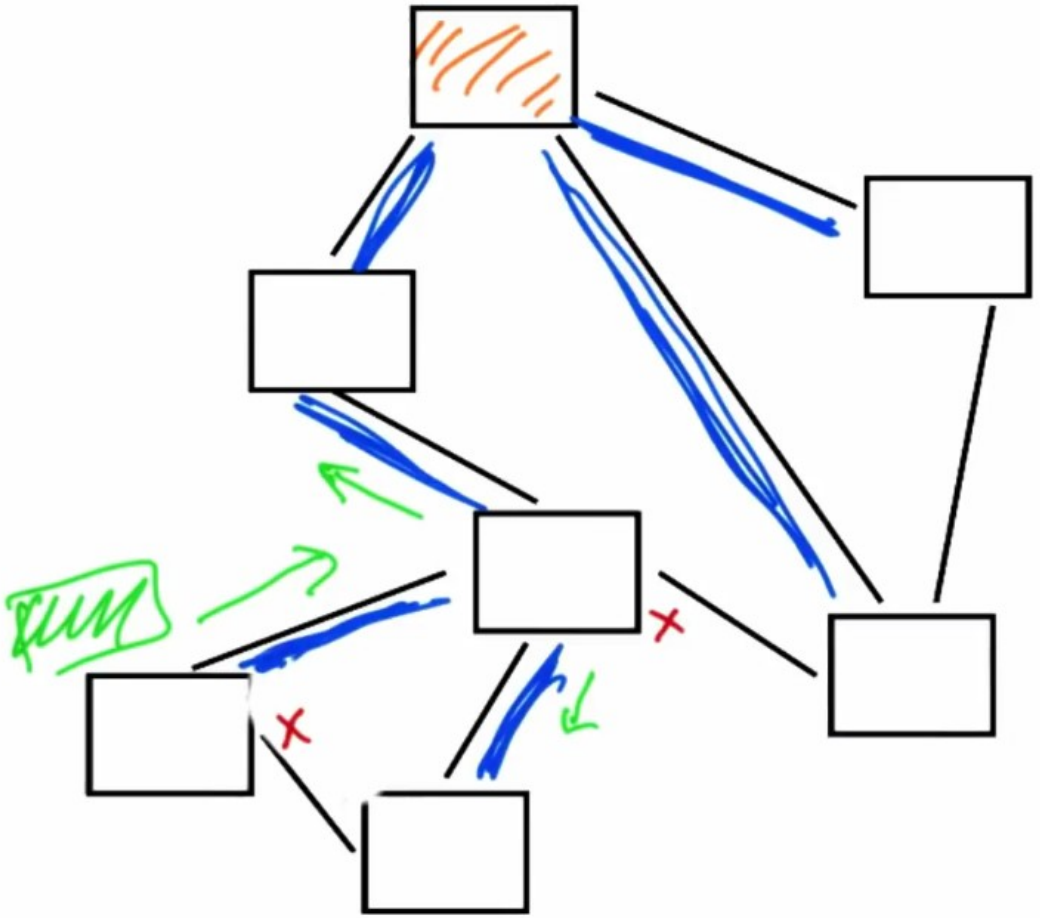
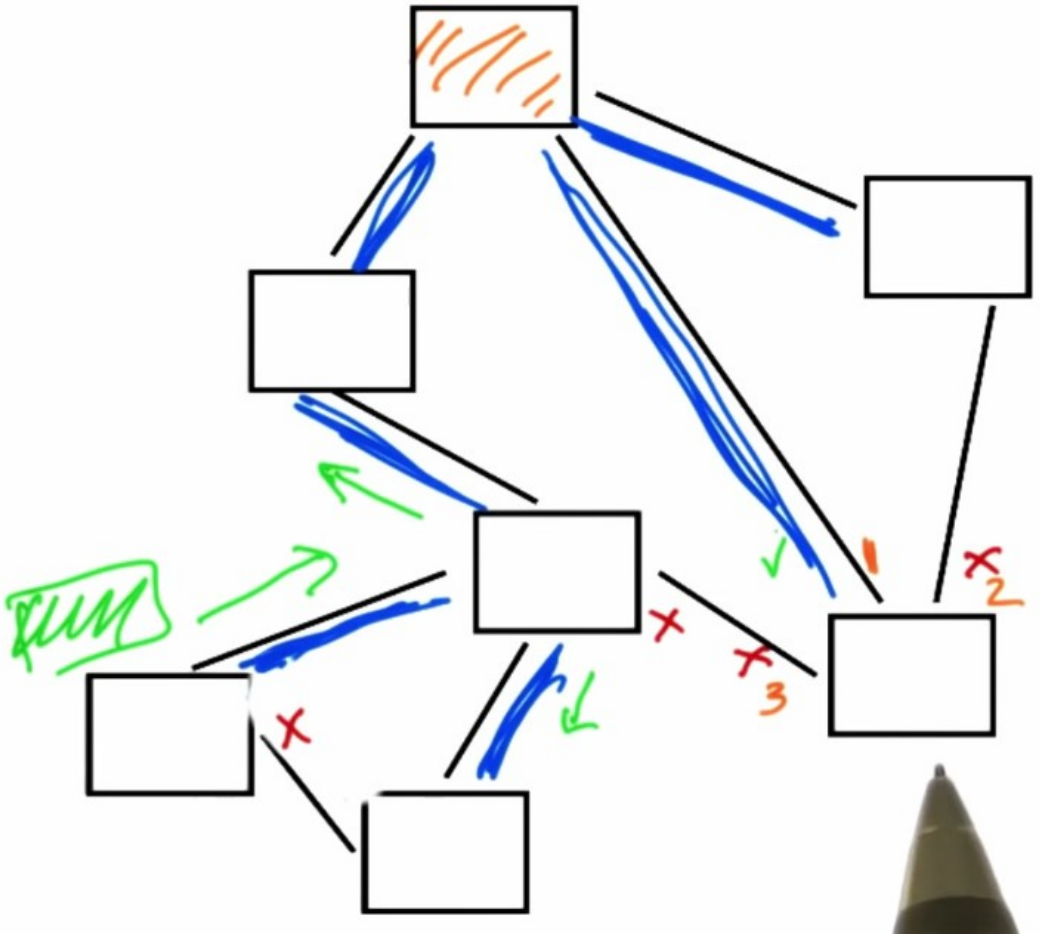


Construct Spanning Tree

1. Elect root (e.g., switch w/ smallest ID)
2. At each switch:

exclude link if not on shortest path to root.

Spanning Tree



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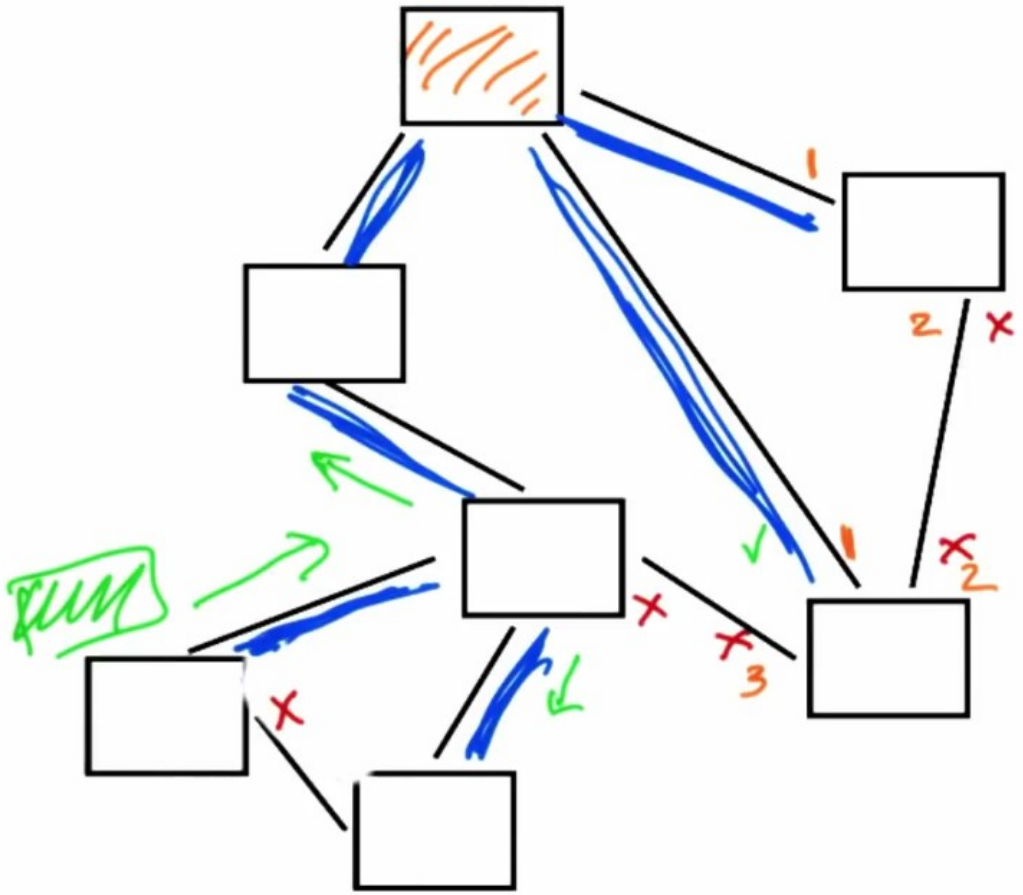


Construct Spanning Tree

(1) Elect root (e.g., switch w/ smallest ID)

(2) At each switch:

exclude link if not on shortest path to root.

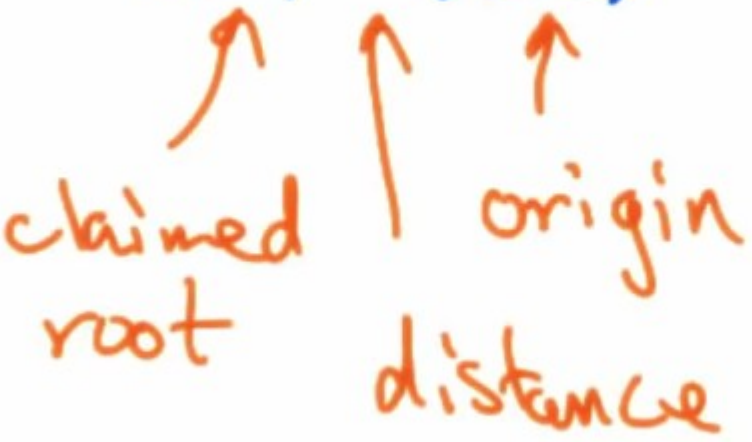
Initially: every node thinks it is the root!

→ (1) update view of root

(2) compute distance to new root

Example

Format: (Y, d, X)



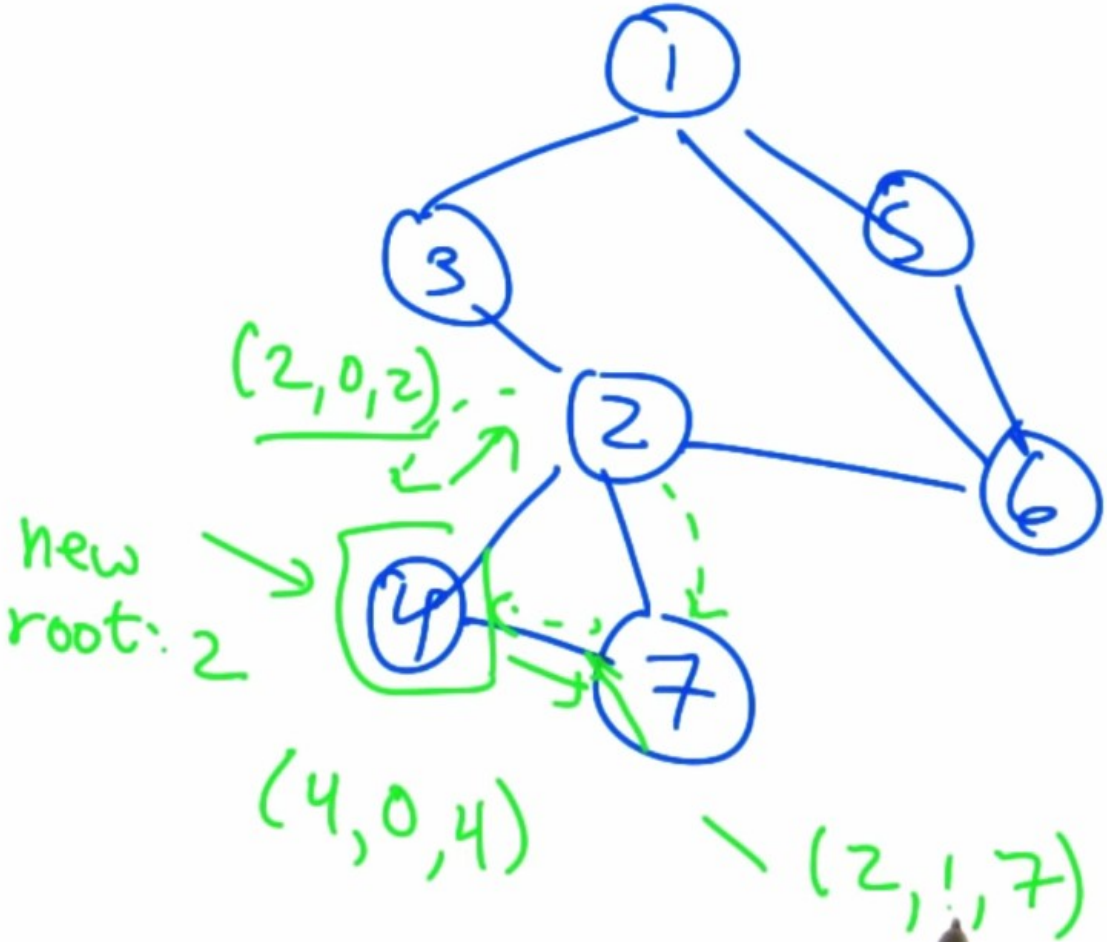
Initially: "$(x, 0, x)$"

Example

Format: (Y, d, X)

- Y: claimed root
- d: distance
- X: origin

Initially: "$(x, 0, x)$"



Example

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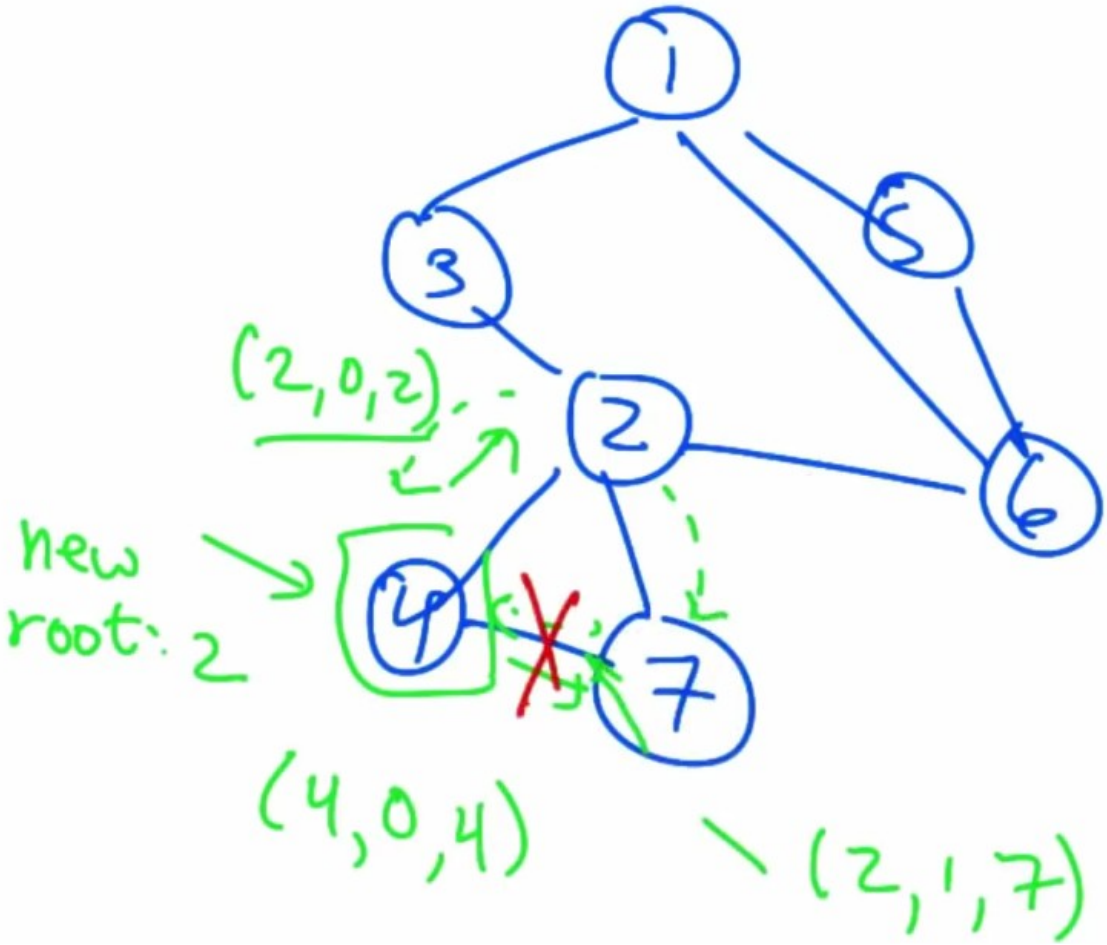
Initially: "$(x, 0, x)$"



Switches vs. Routers

Switches (Layer 2 / "Ethernet")

- Auto-configuring
- Forwarding tends to be fast

Routers (Layer 3 / IP)

- Not restricted to spanning tree

Major limitation

Broadcast

- spanning tree
- ARP queries

SDN

Buffer Sizing

Question: How much buffering do routers/switches need?

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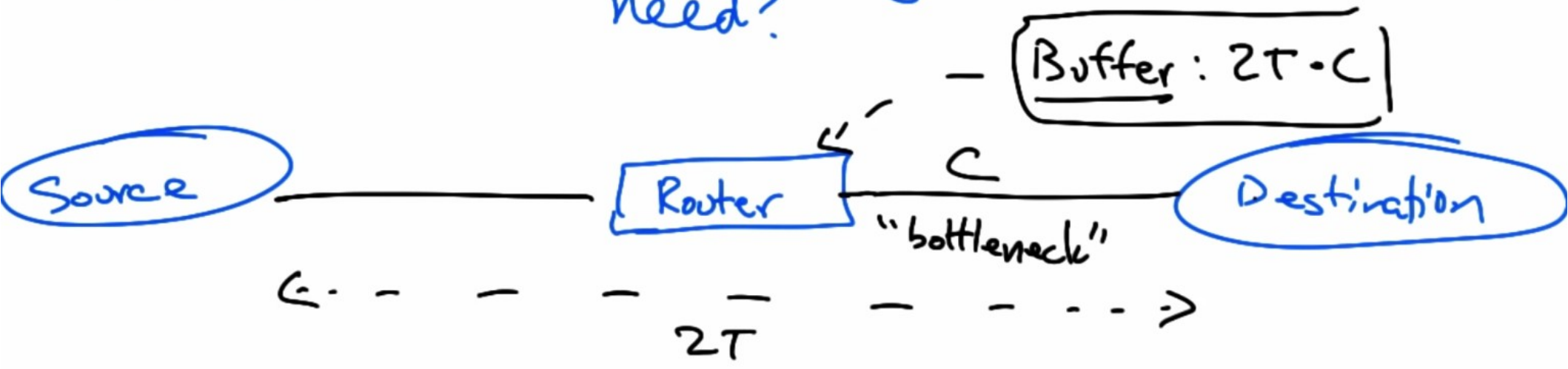

Buffer Sizing

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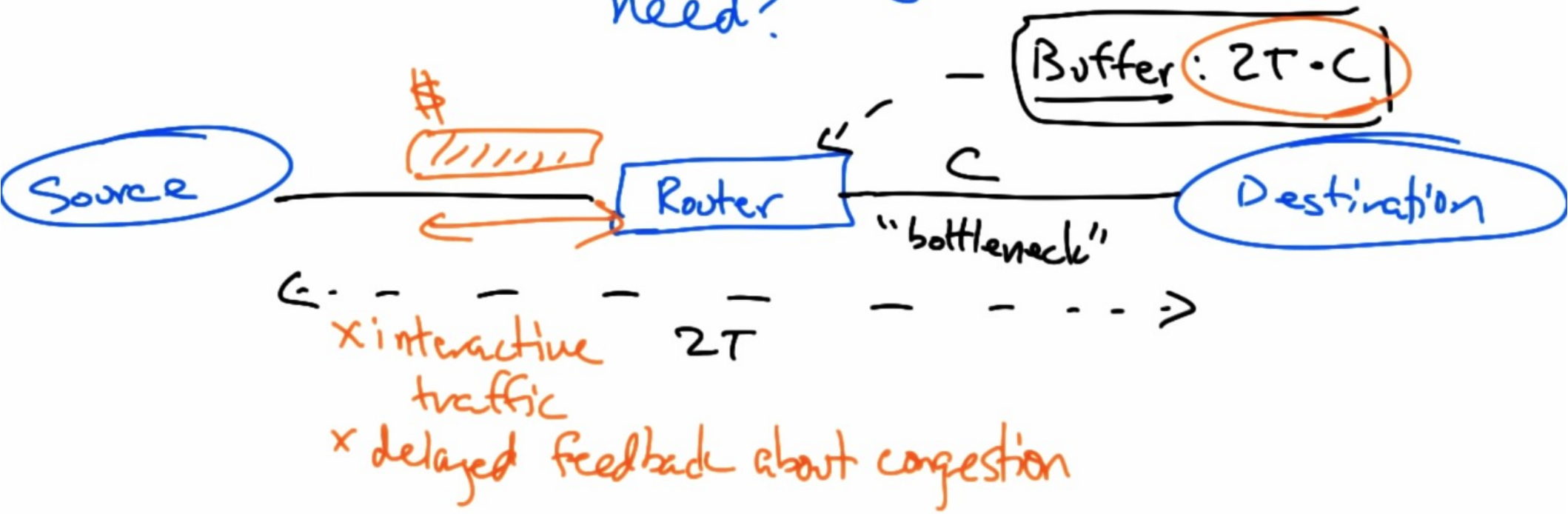
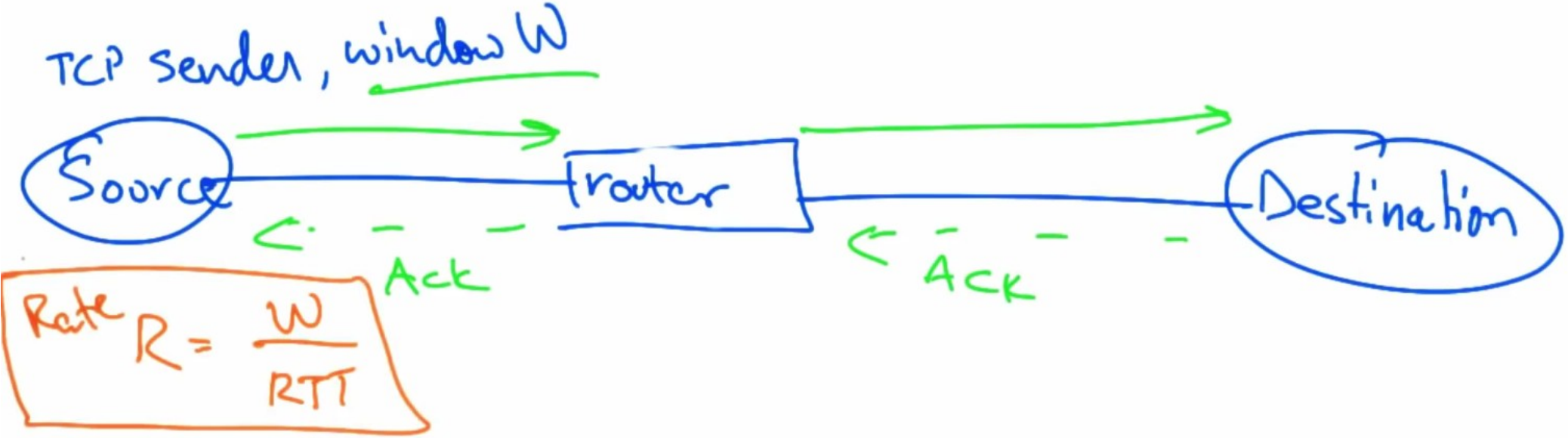


Buffer Sizing for a TCP Sender

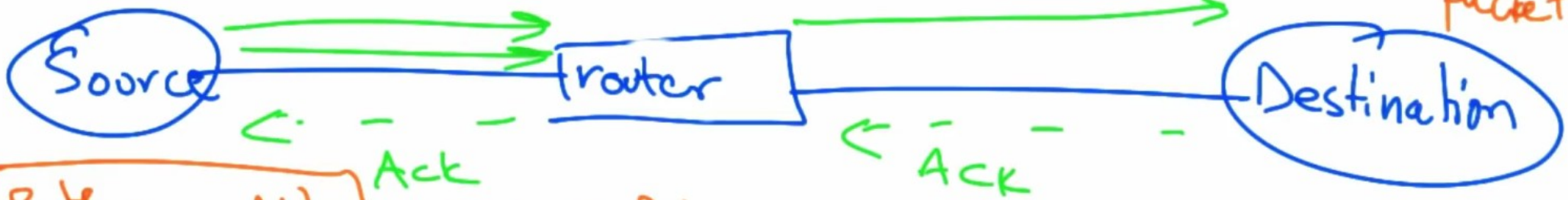


Buffer Sizing for a TCP Sender

TCP sender, window W

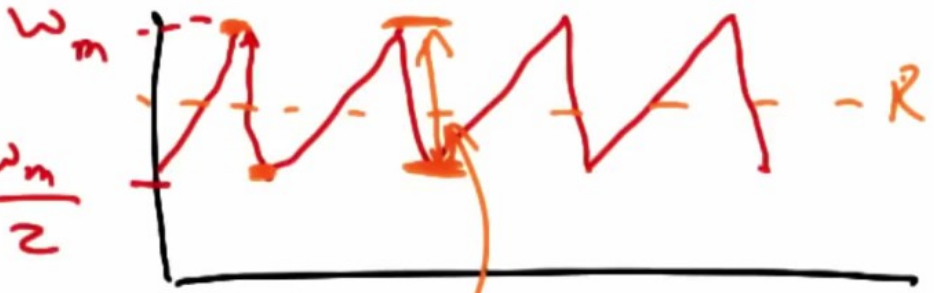
TCP: AIMD

W ACKs → Send W+1 packets



Rate $R = \frac{W}{RTT}$

RTT: T, B/C

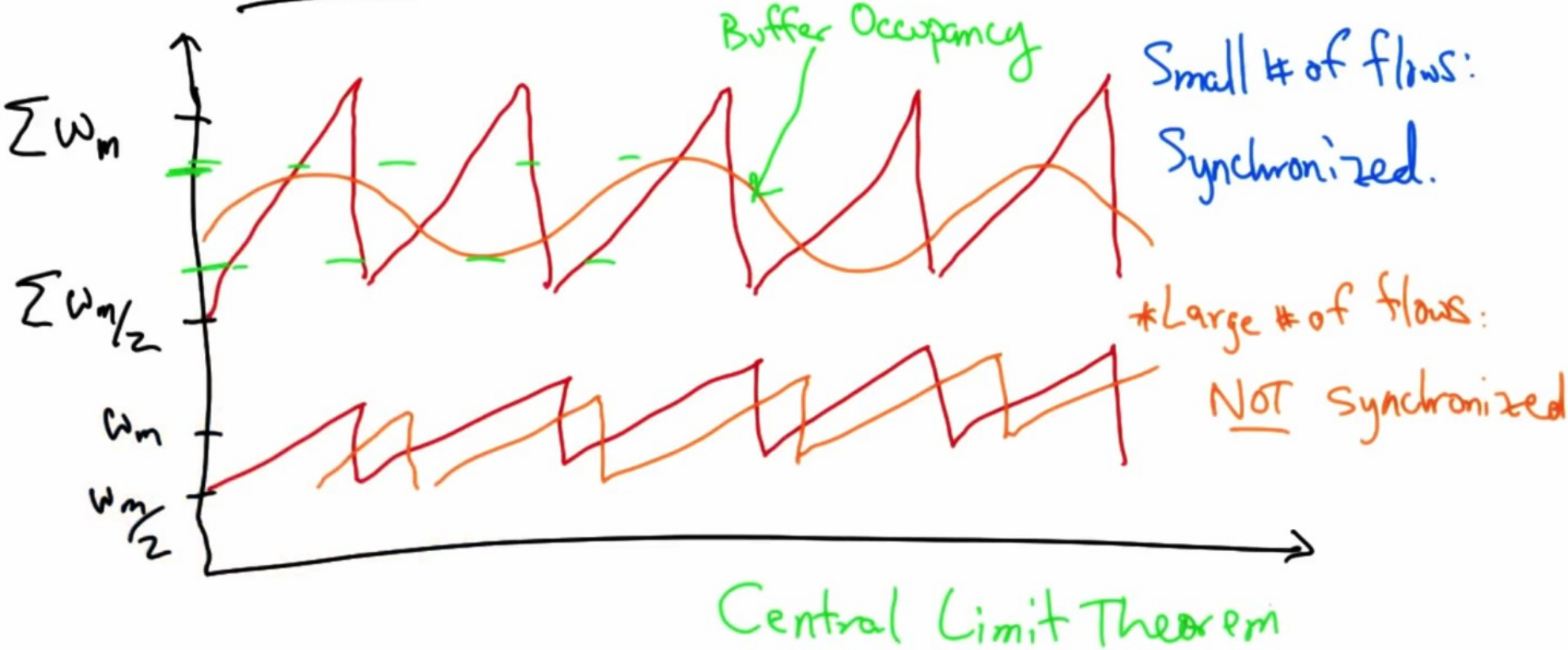


$$\frac{W_{old}}{2T + B/C} = \frac{W_{old}/2}{2T}$$

$$\frac{W_{old}}{RTT_{old}} = \frac{W_{new}}{RTT_{new}}$$

$$B = 2T \cdot C$$

If TCP flows Are Synchronized



Central Limit Theorem (CLT)

More variables ⇒ narrower Gaussian

(congestion windows of flows)

(fluctuation of sum of all of the congestion windows)

$1/\sqrt{n}$

$2T \cdot C \longrightarrow \frac{2T \cdot C}{\sqrt{n}}$