FIT1047 - Week 9

Networks: Network and Transport layers

MONASH University

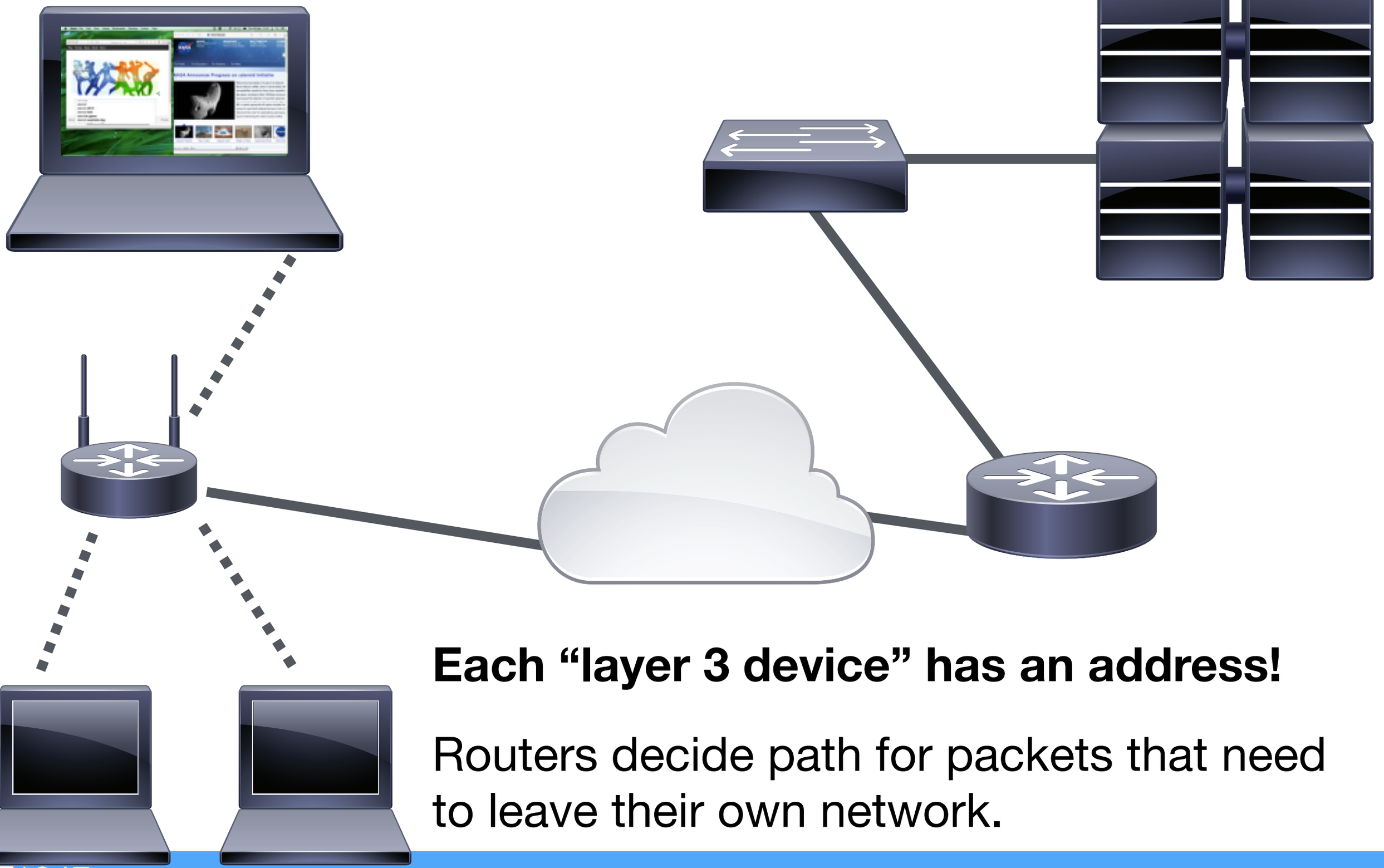
Goals for this week

- See how **routers connect different networks**
- Understand how the transport layer makes sure messages **arrive correctly** and at the **right process**
- Study the **structure of the Internet**

The Network Layer:

Adresses

Addressing devices



Each “layer 3 device” has an address!

Routers decide path for packets that need to leave their own network.

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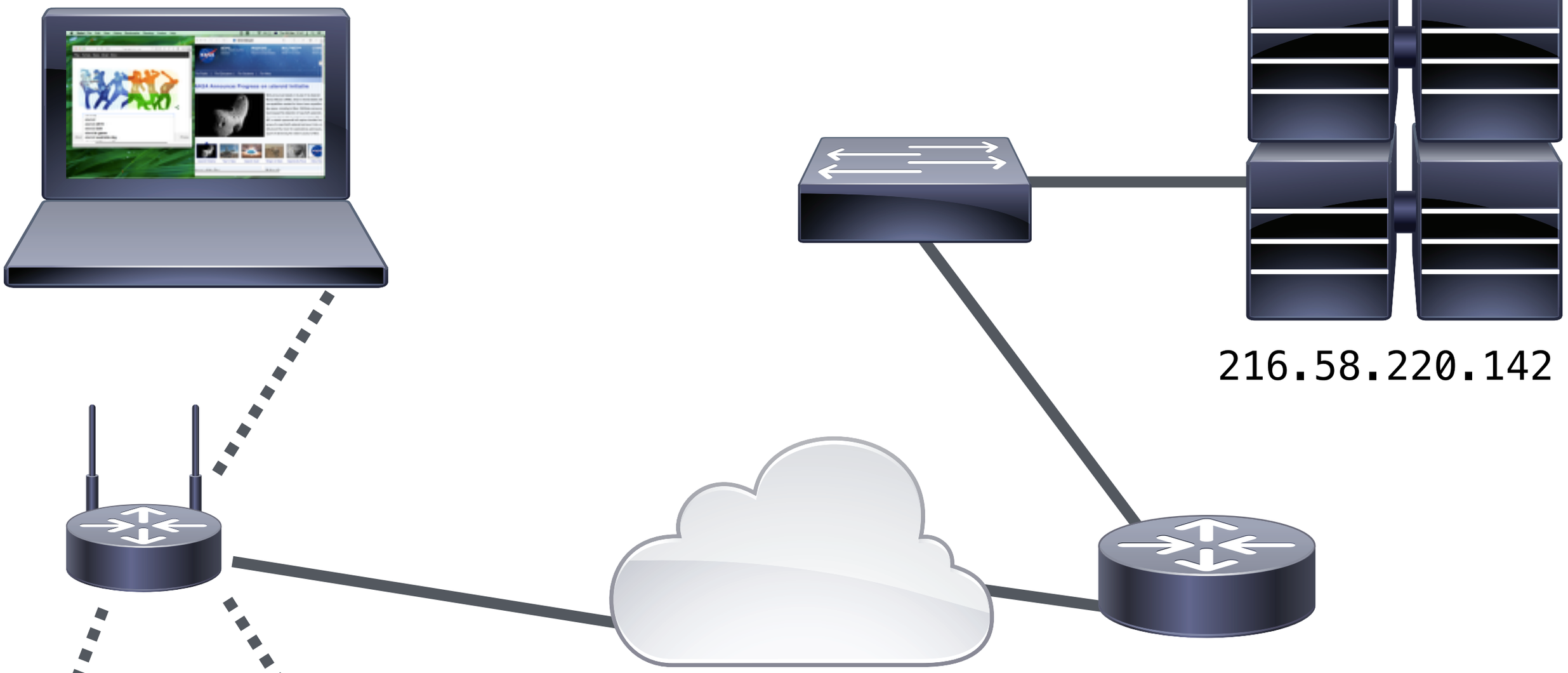

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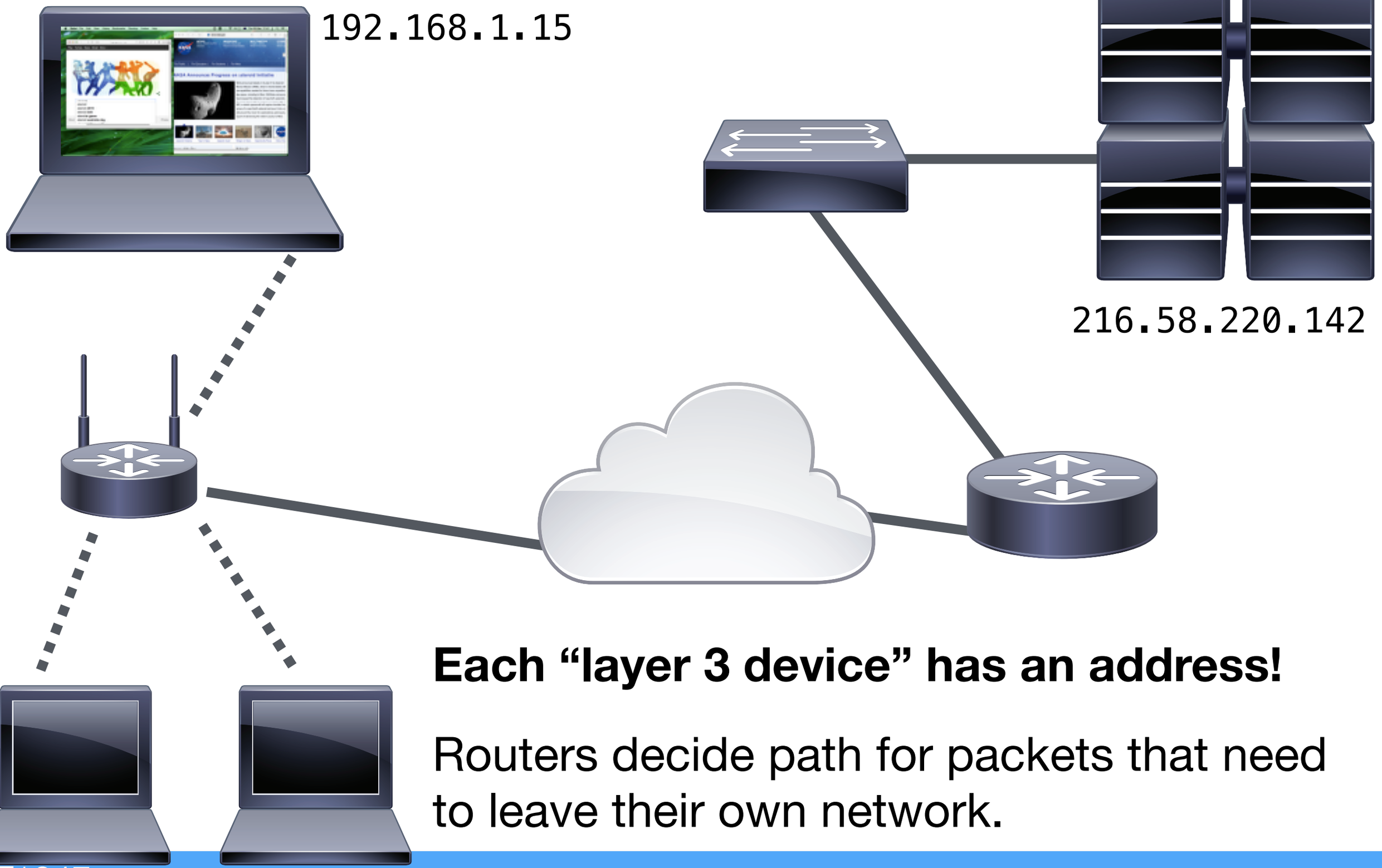

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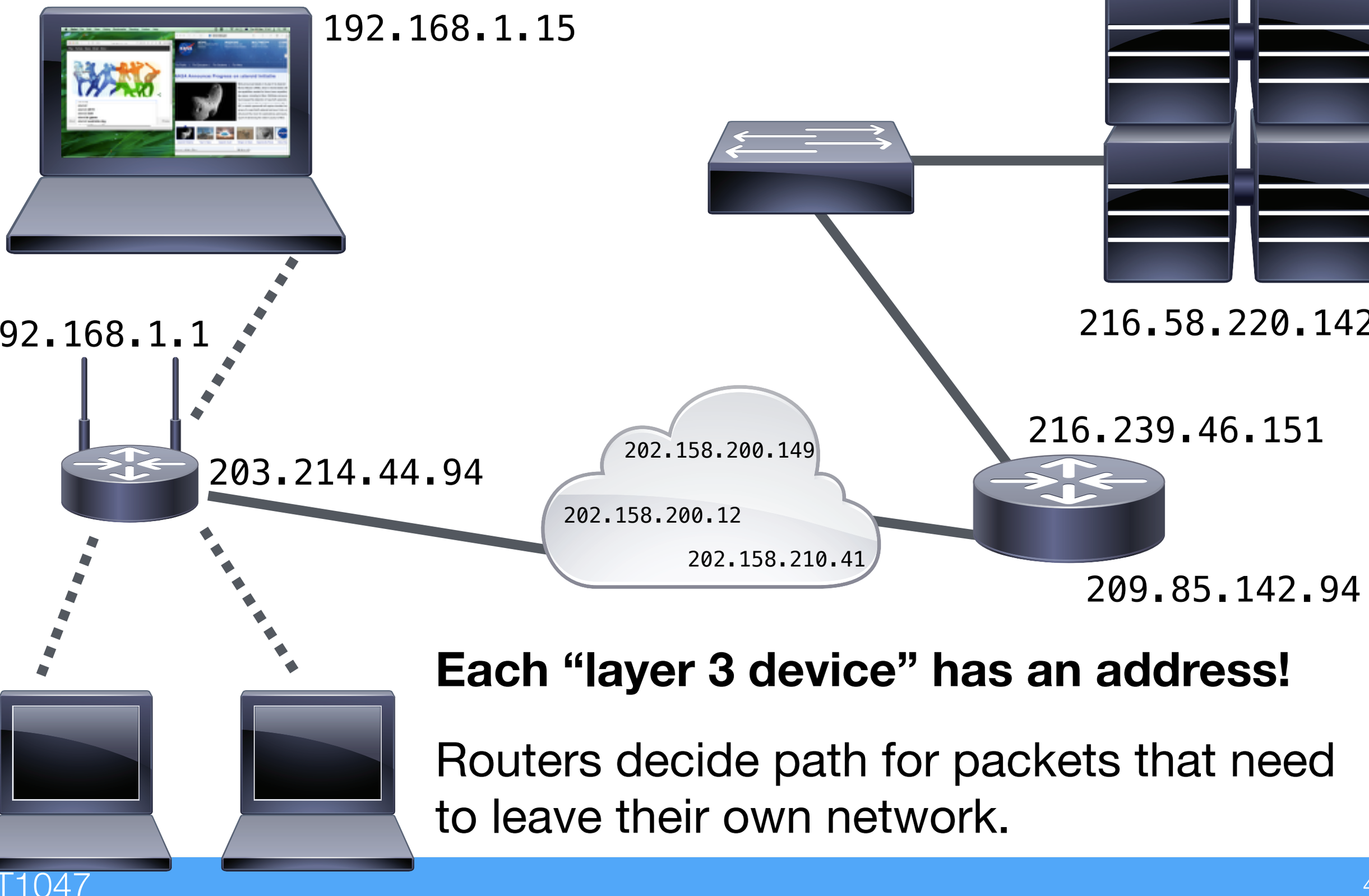

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IP version 4 addresses

32 bit addresses

- Written using “dotted decimal” notation
- Example: 130.194.66.43

```
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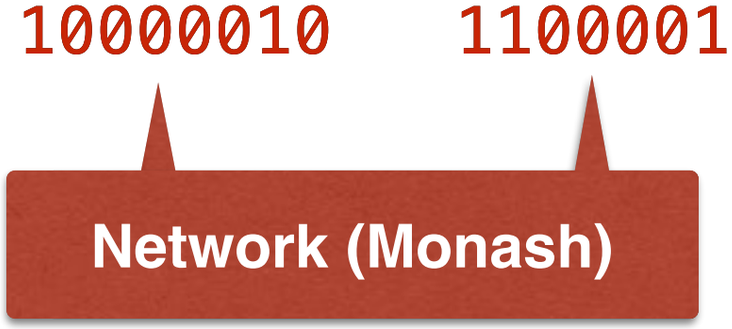

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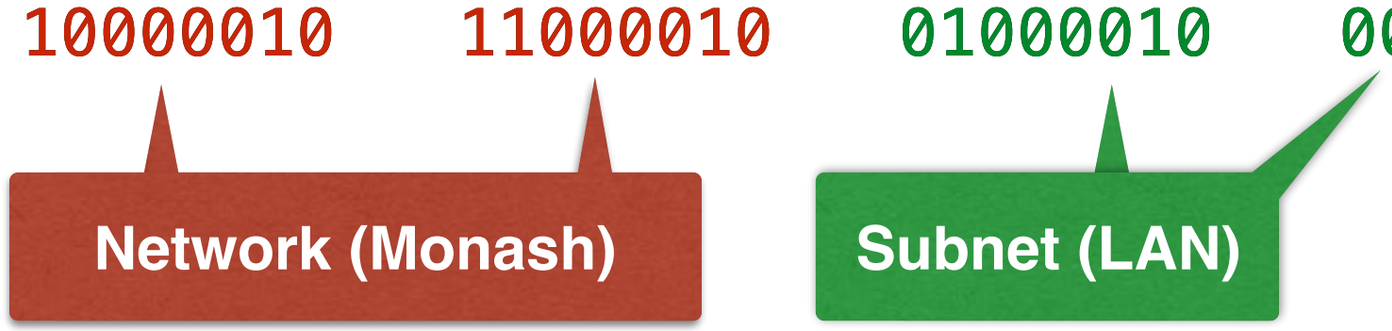

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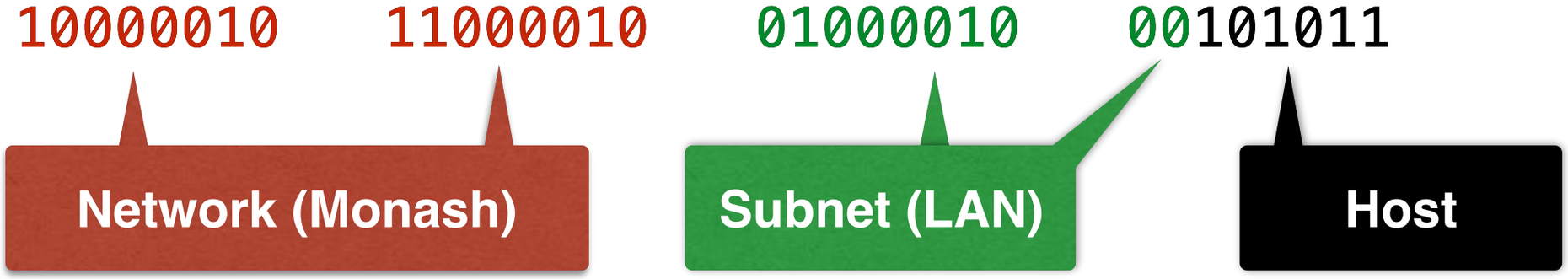

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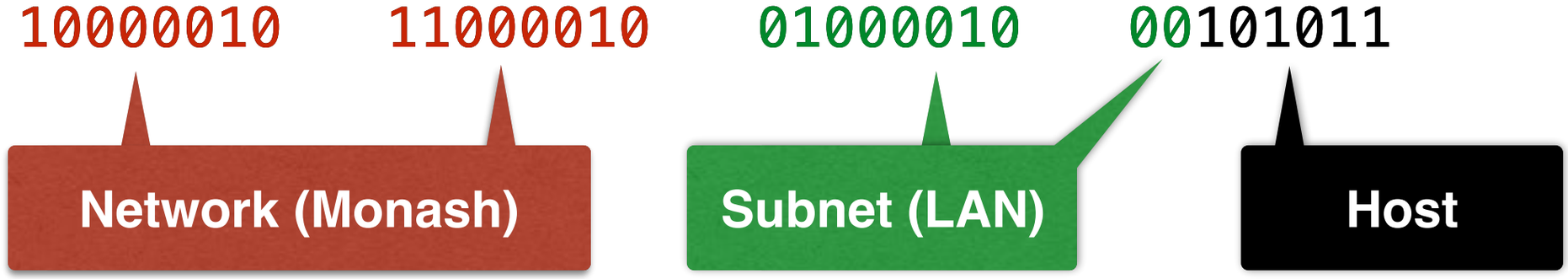

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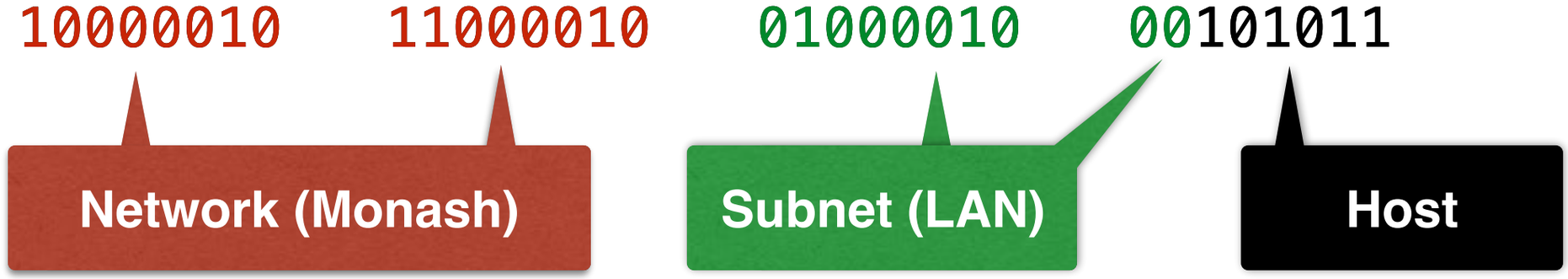

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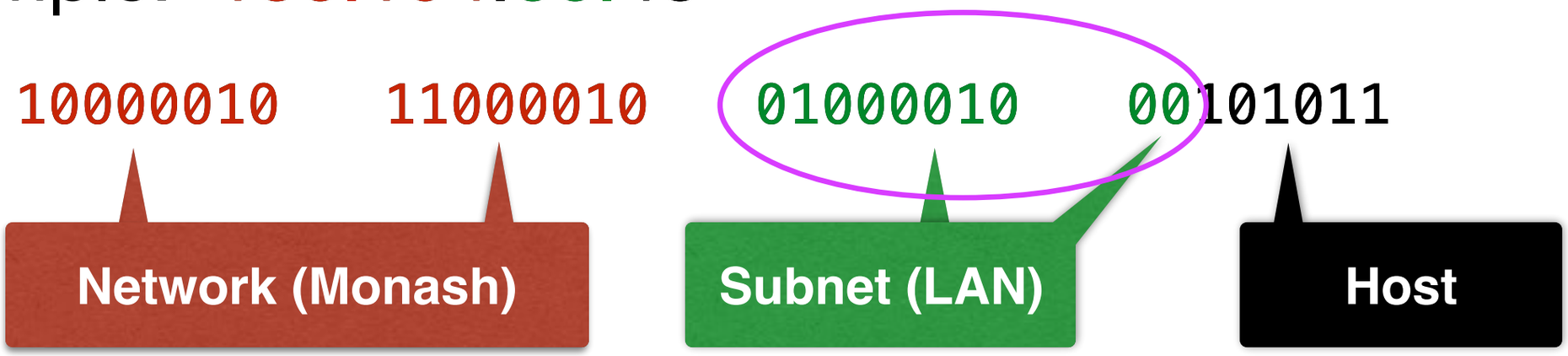

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no. of bits in network + subnet

Network Classes

Subnet masks often expressed using dotted notation

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Previously used hierarchy:

- Class A: /8 (e.g. IBM, MIT, AT&T, Apple, …)
- Class B: /16 (e.g. Monash 130.194.0.0/16)
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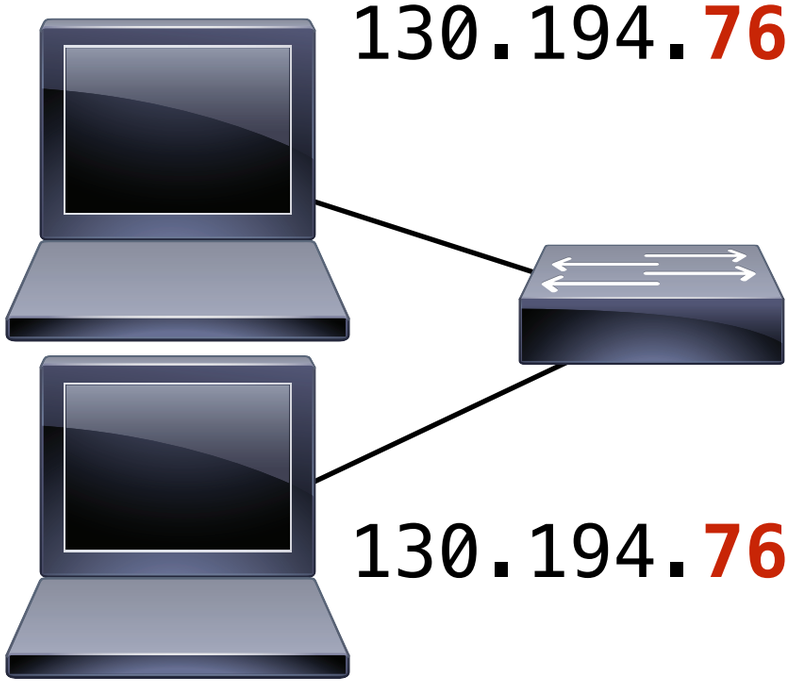
Now: classless

- e.g. /22, which can also be written as 255.255.252.0

Subnets



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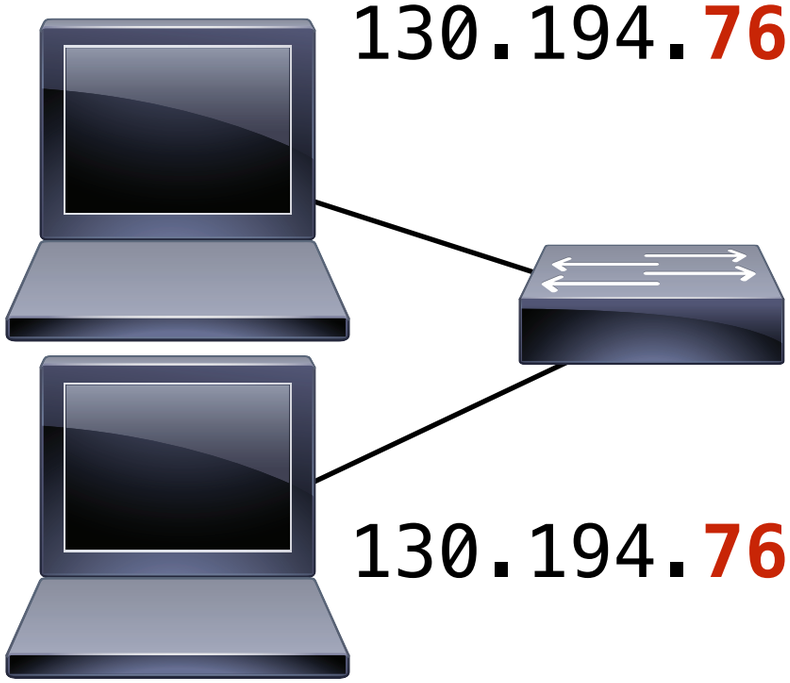

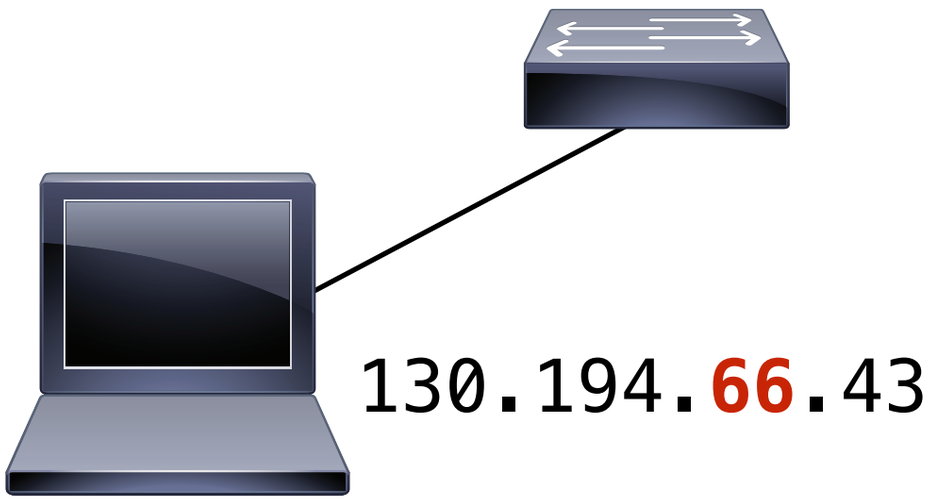

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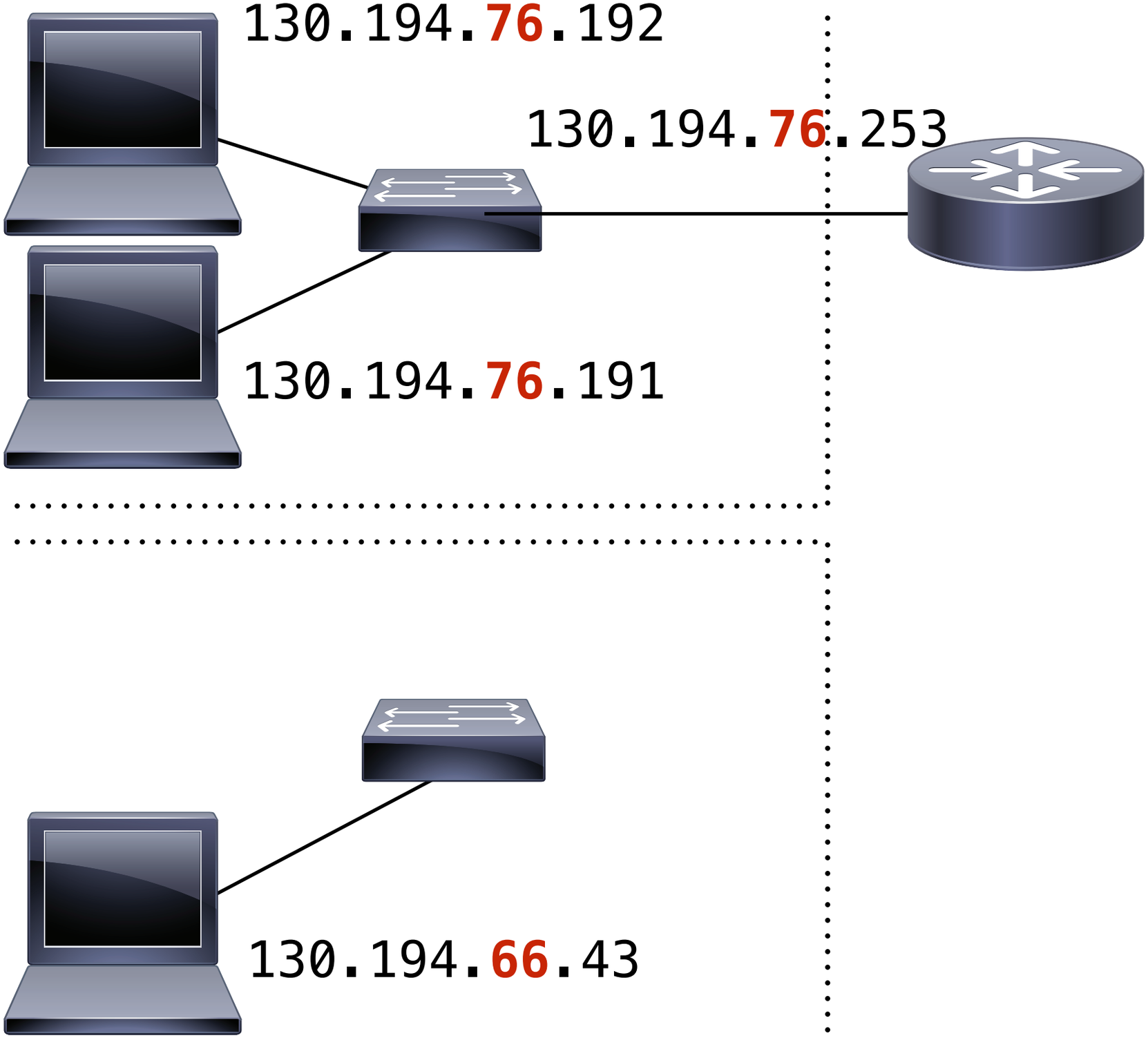

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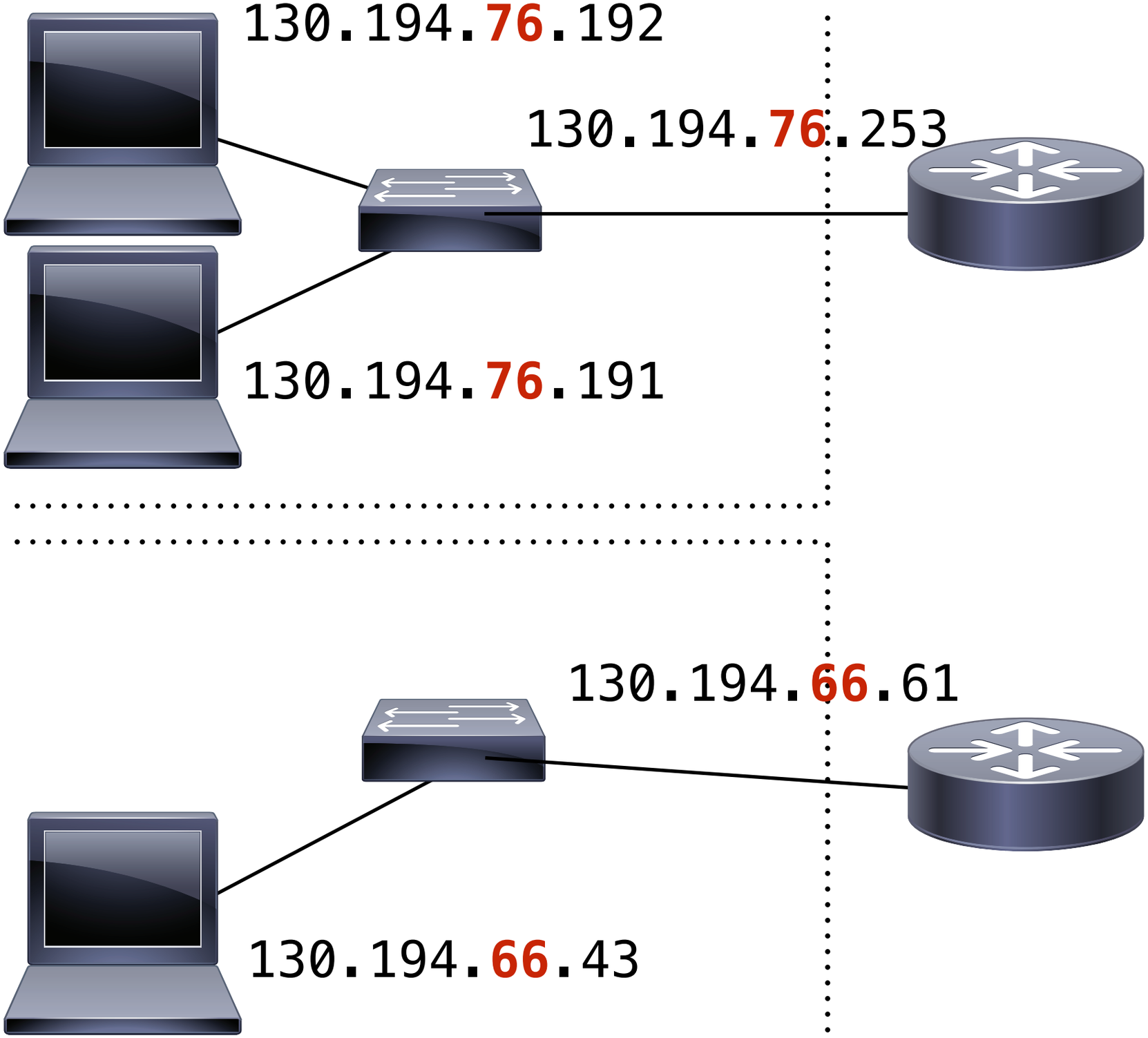
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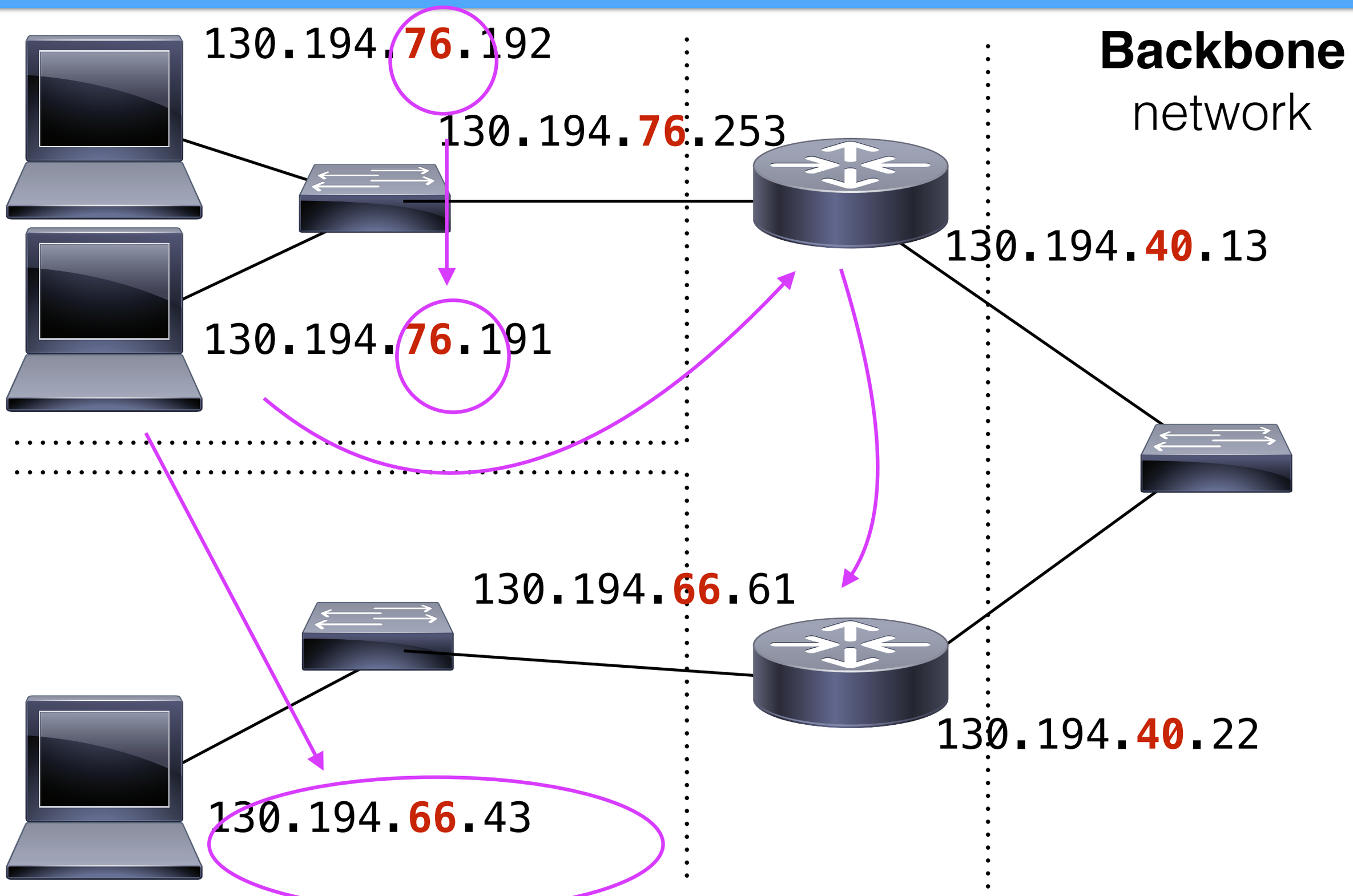
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Backbone
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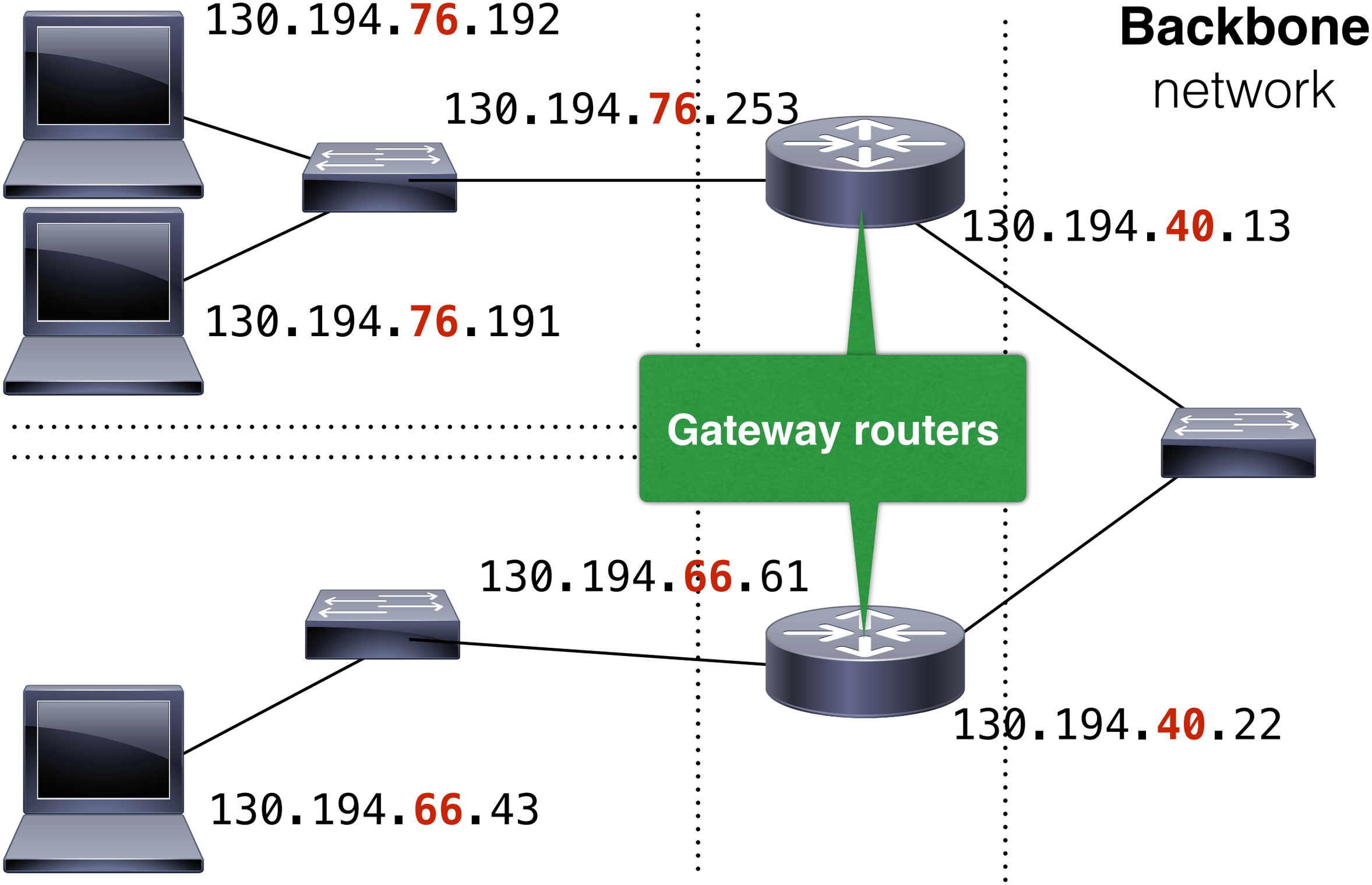
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IP version 6

IPv4 addresses: 32 bits

- In theory 4,294,467,295 addresses
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IPv6

- "new" version of the IP protocol (from 1998…)
- 128 bits per address
- so that's four times more, right?

IP version 6

$2^{128}=$

IP version 6

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340,282,366,920,938,463,463,374,607,431,768,211,456

(340 undecillion)

IPv6 addresses

IP version 6

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A bit excessive?

- At least 7 addresses for every atom of every person on earth
- 665,570,793,348,866,943,898,599 addresses per square meter of the surface of the earth

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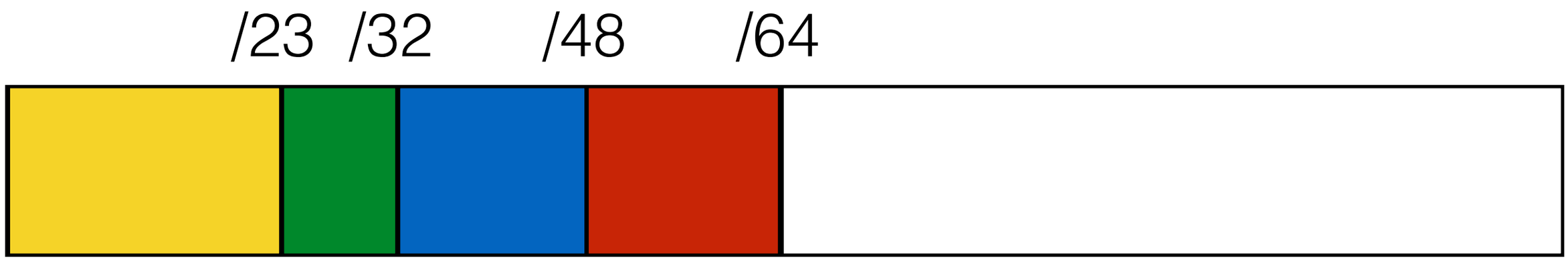
Required!

- The huge space is used to create **hierarchies**
- This makes it easy to assign whole subnets

IP version 6 address space

Typical allocation:



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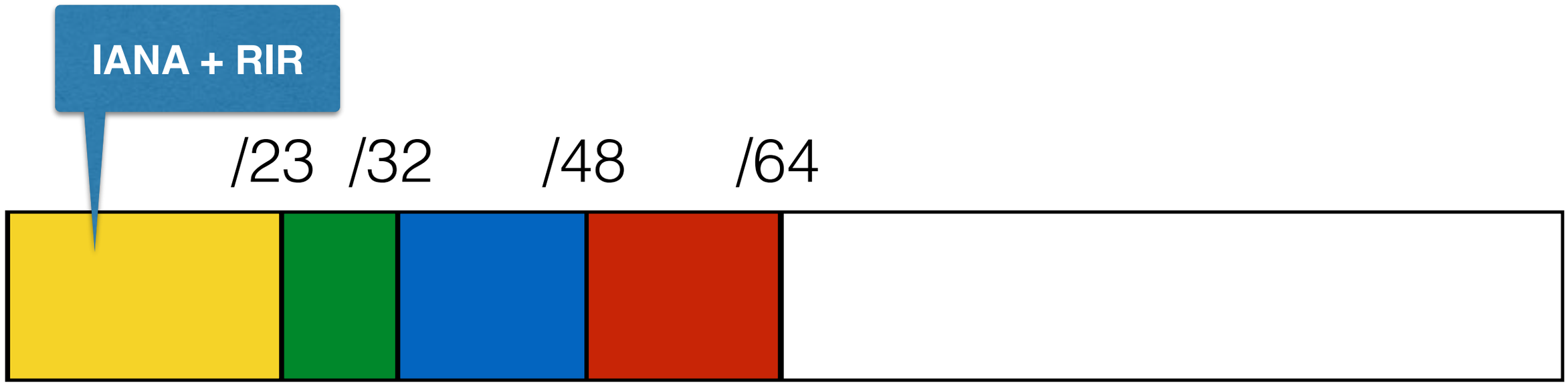

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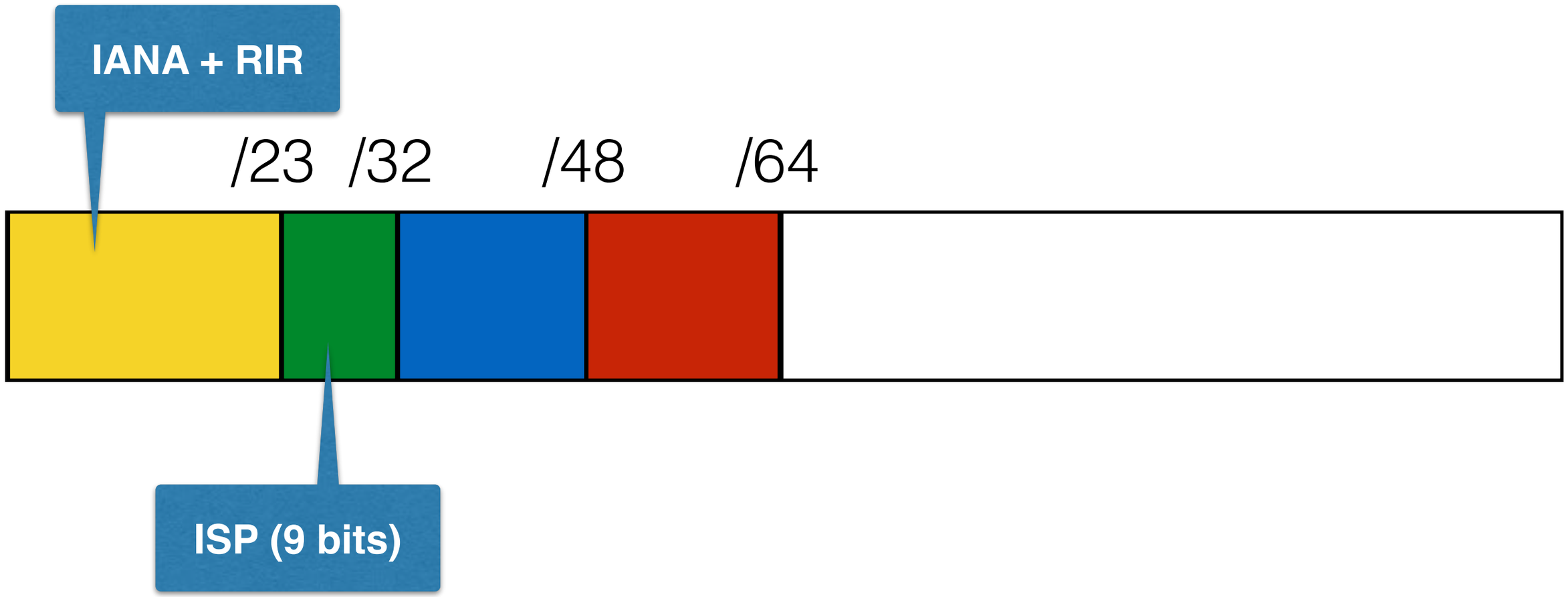

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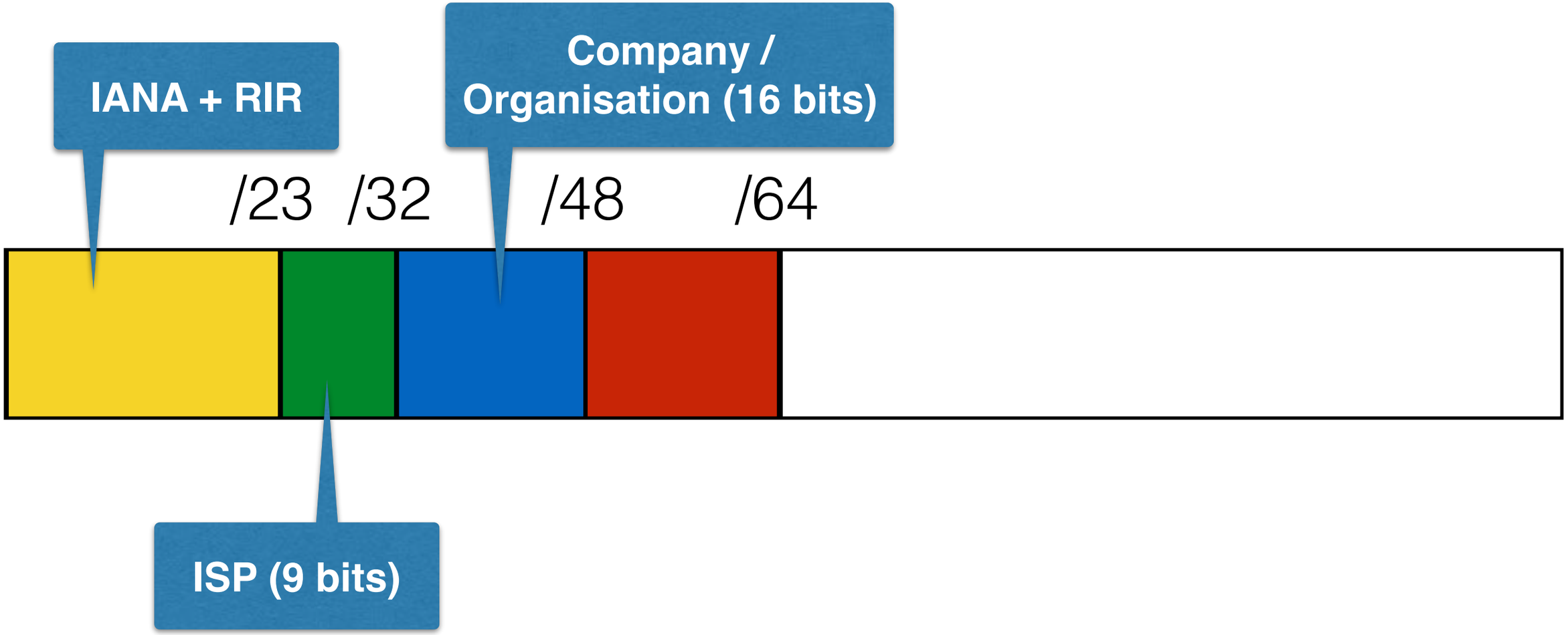

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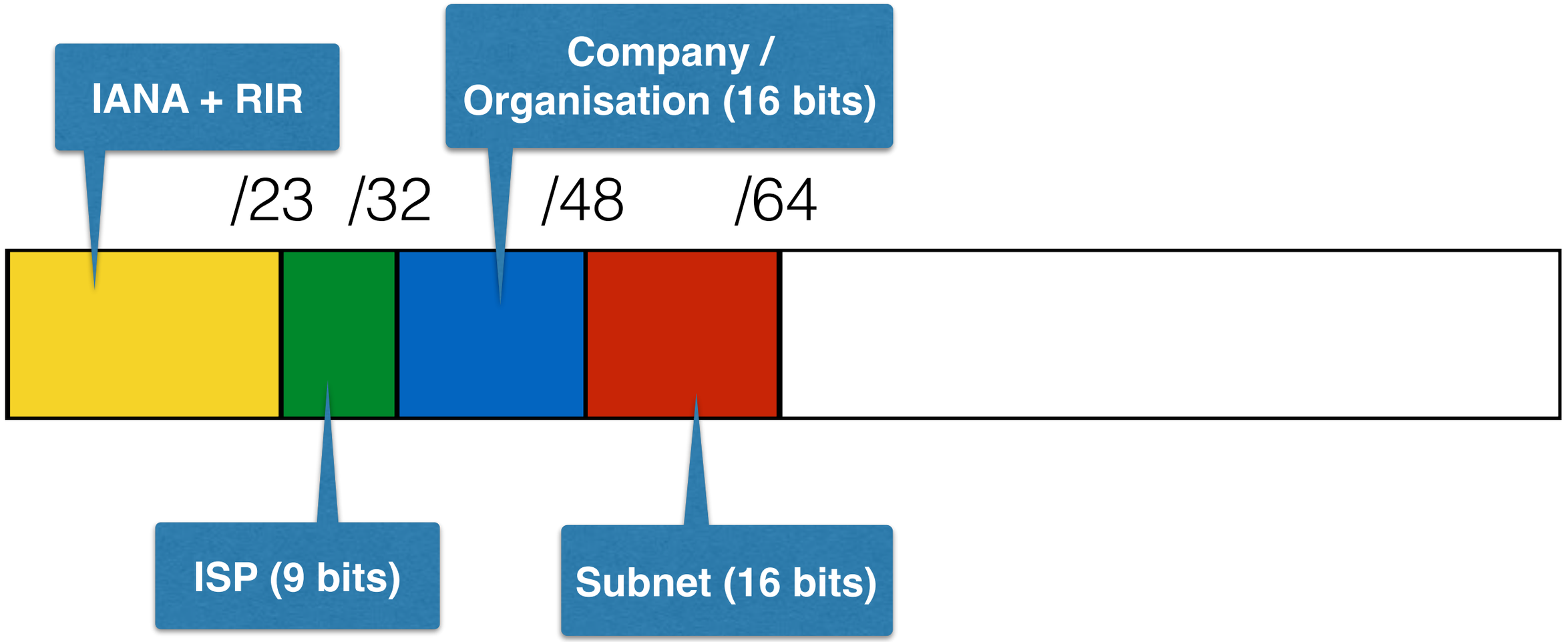

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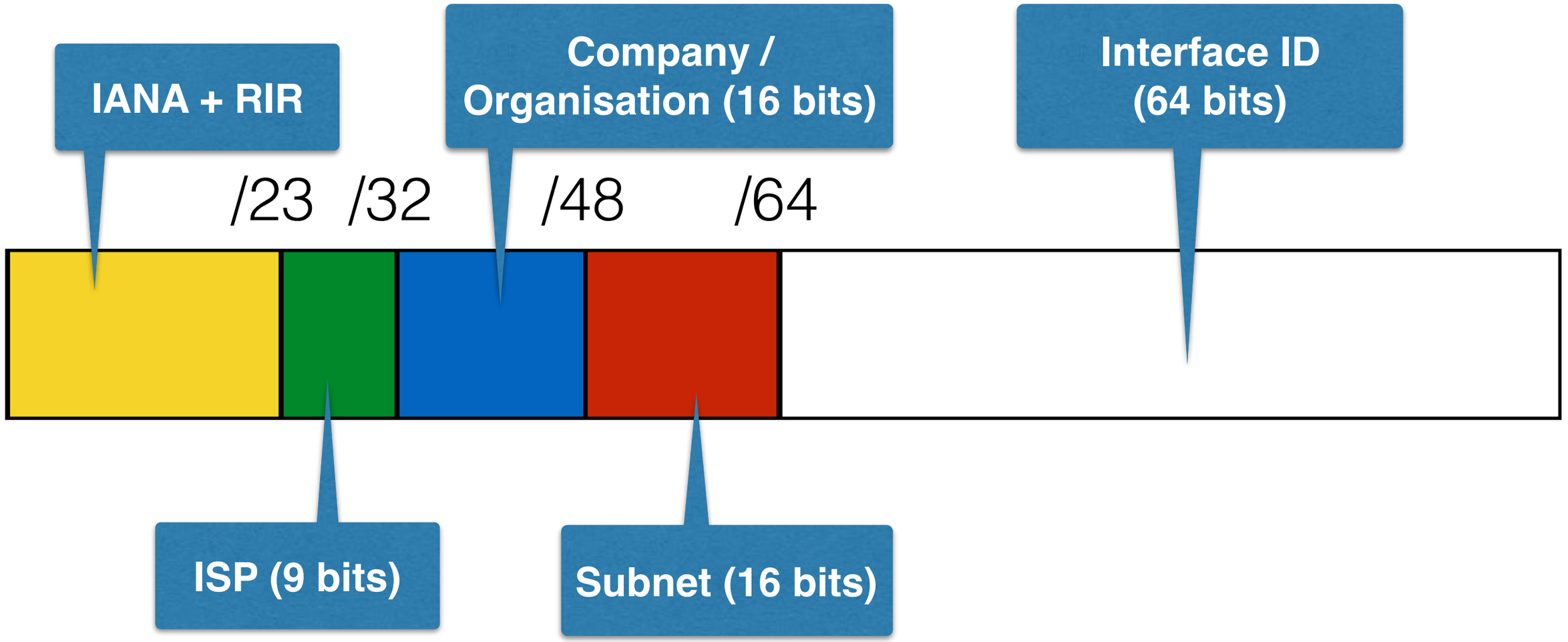

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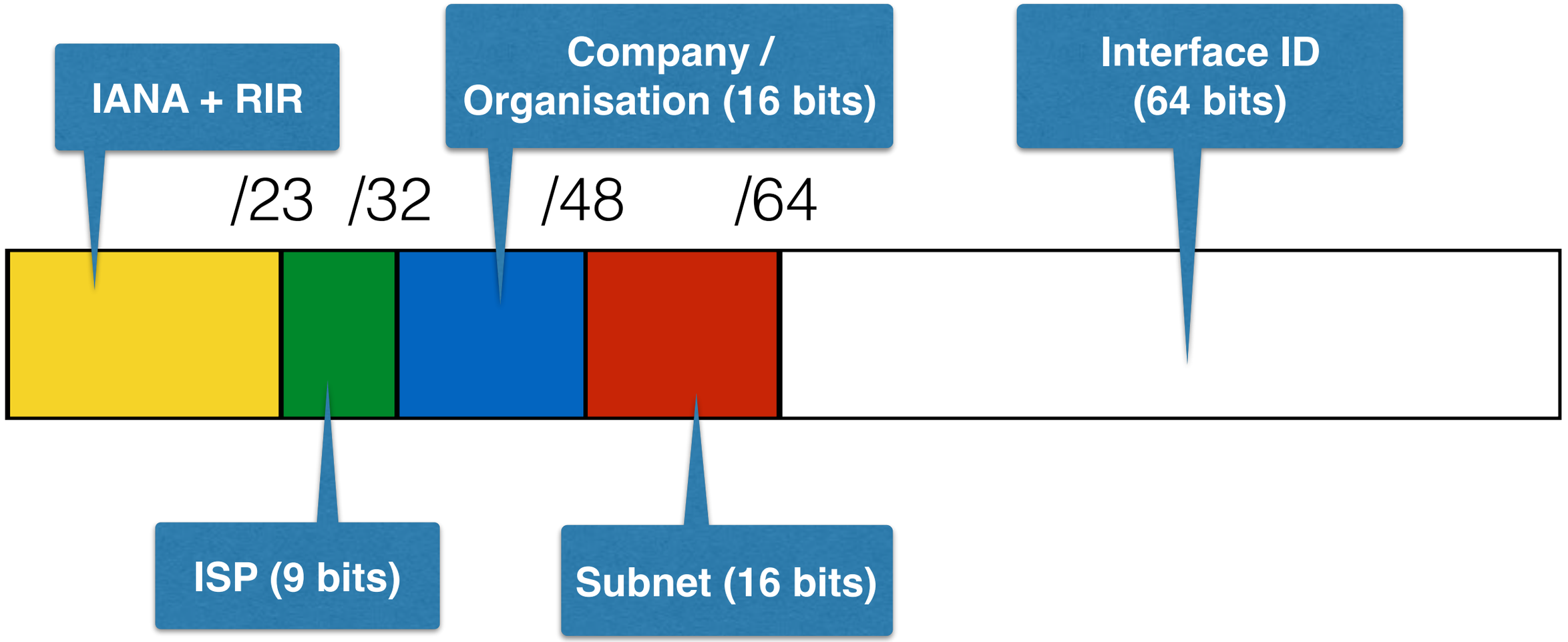

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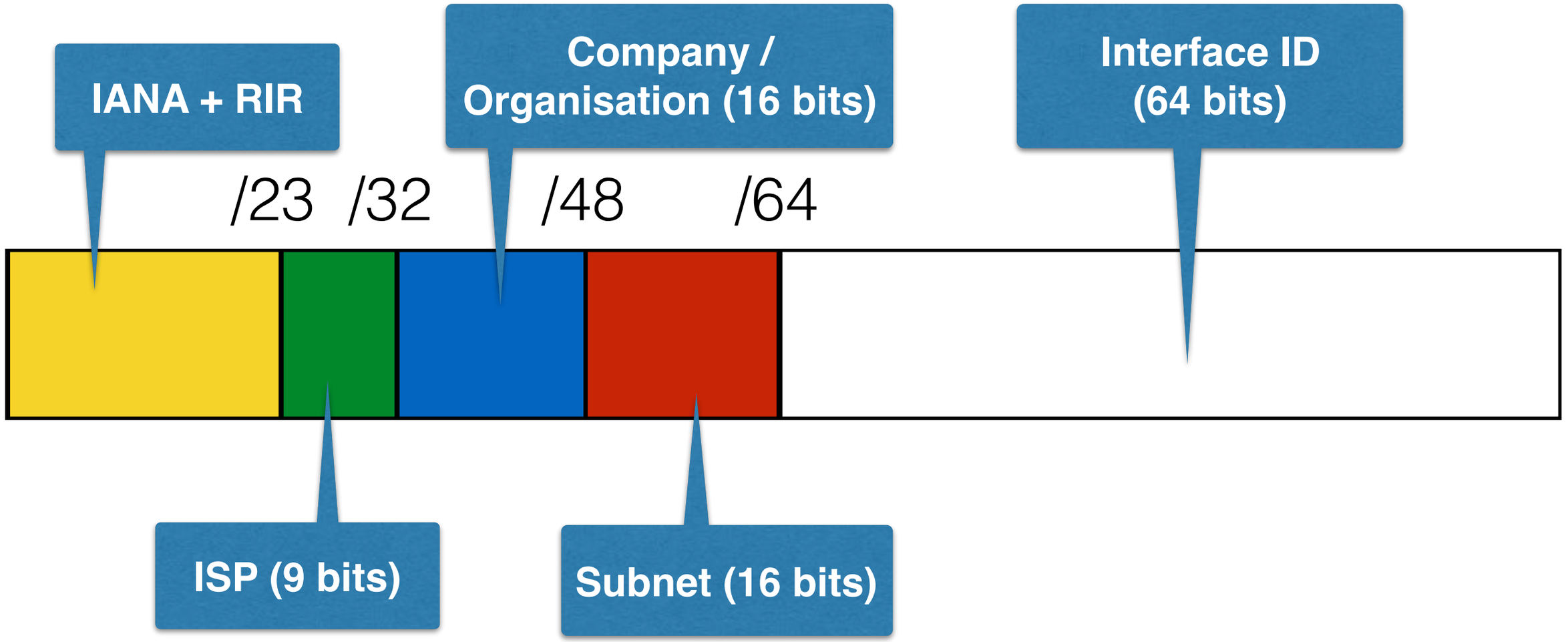

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Every company can run more than 65,000 different LANs

IPv6 transition

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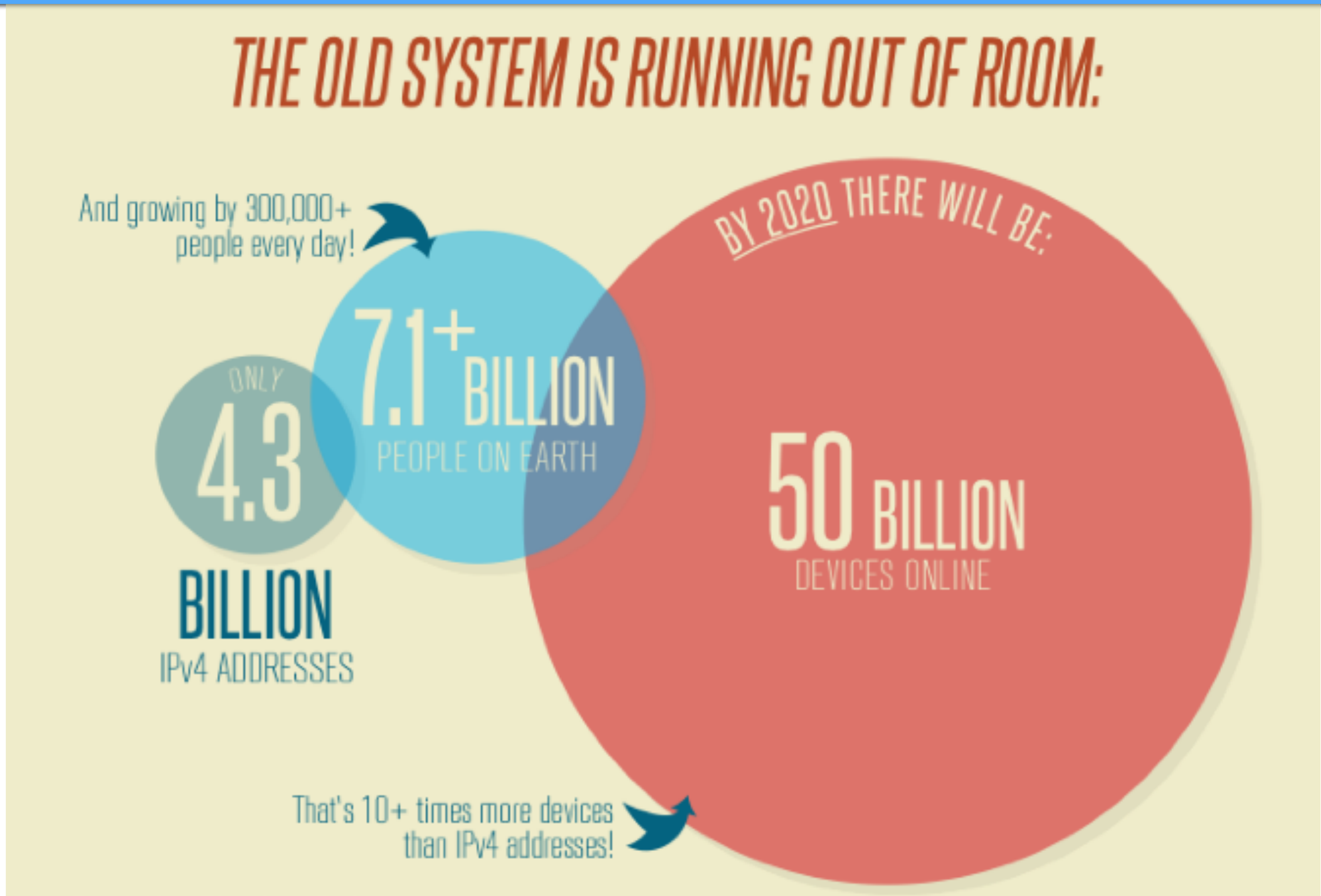
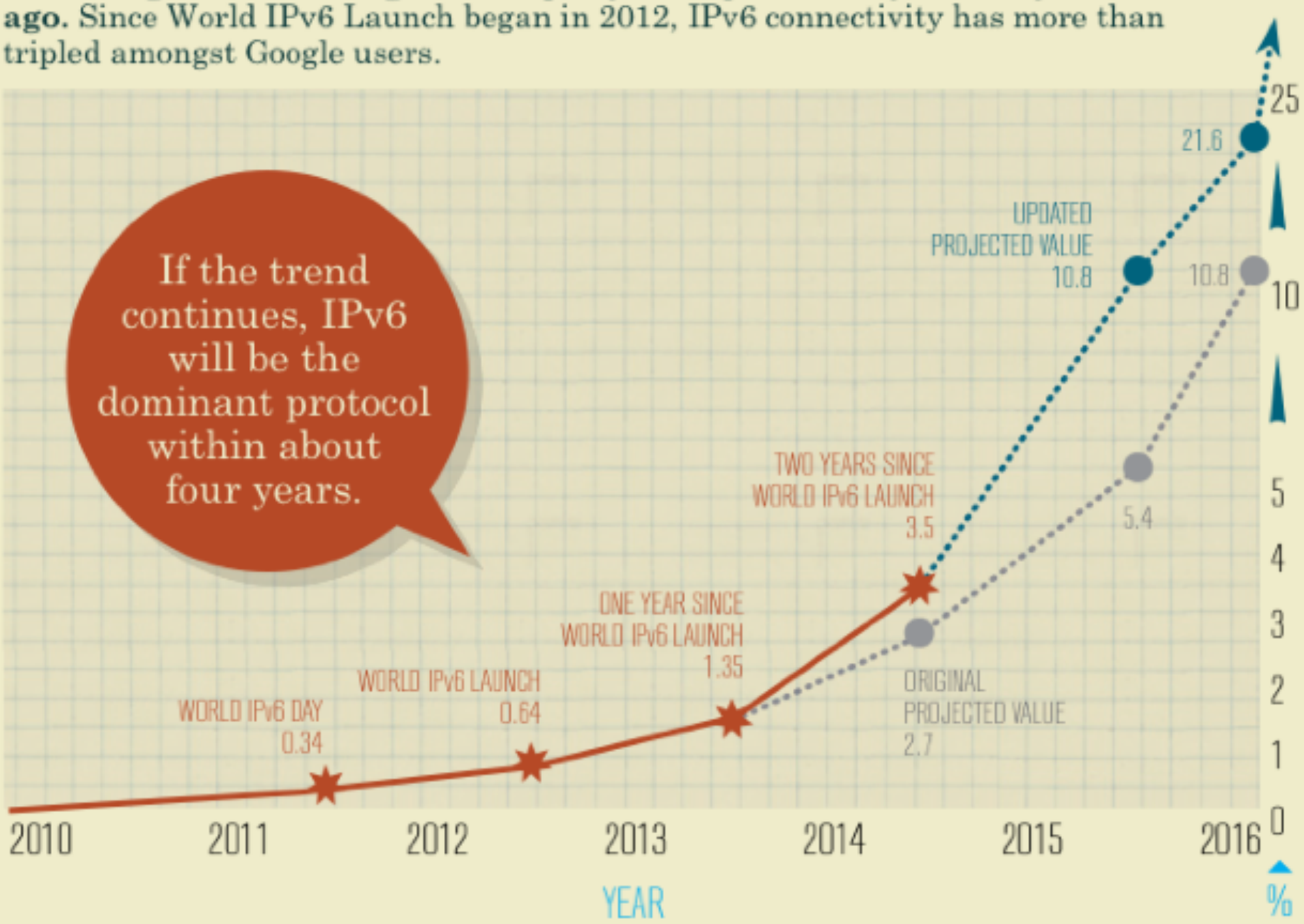


IPv6 transition

IPv6 MOMENTUM

IPv6 usage is increasing more rapidly than predicted just two years ago. Since World IPv6 Launch began in 2012, IPv6 connectivity has more than tripled amongst Google users.



Address resolution

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This is known as address resolution.

Address resolution: Application Layer

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- Application layer protocol for address resolution
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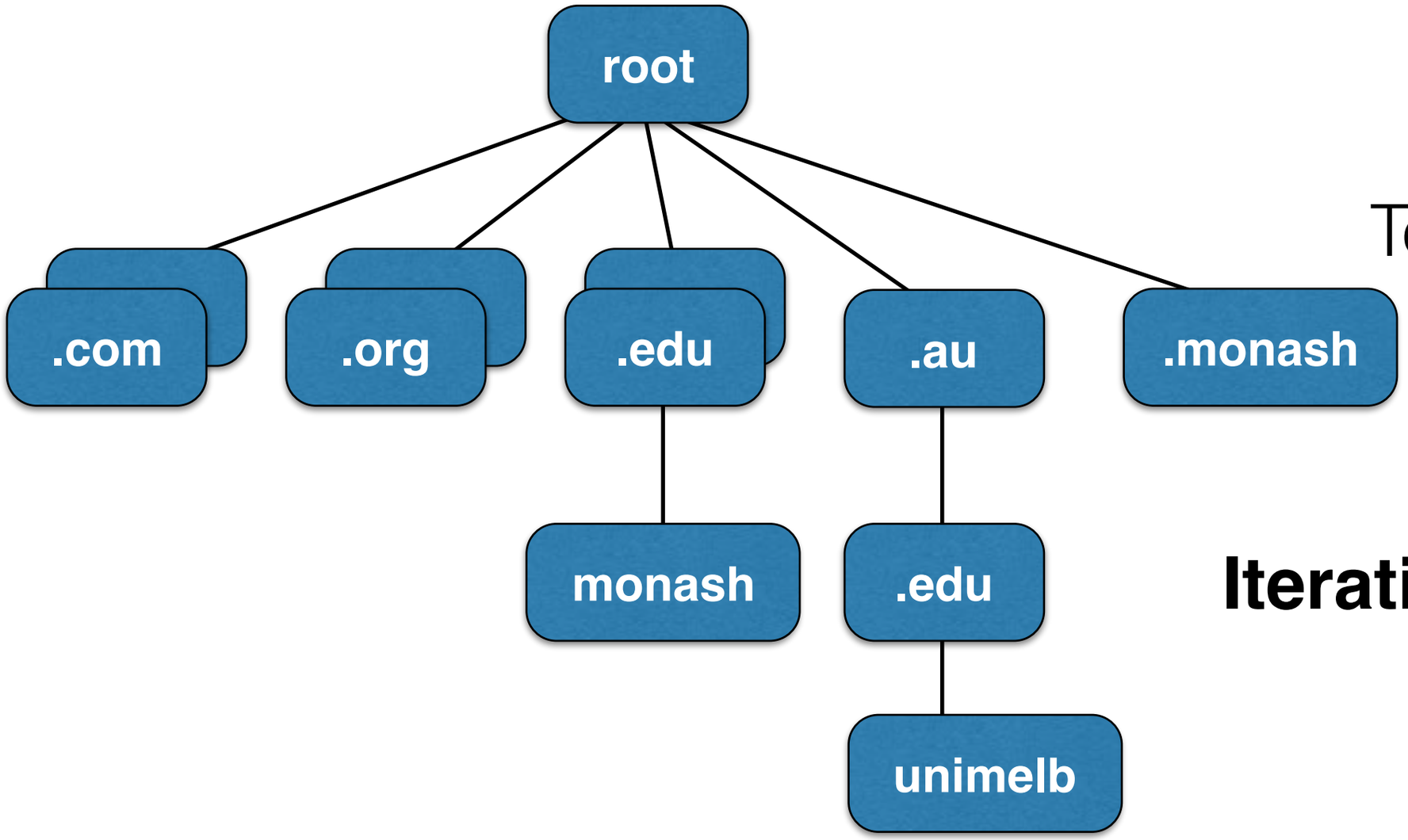
DNS Servers

- Implement a **distributed database** of names
- Are organised in a **hierarchy** reflecting the **structure** of the domain names

DNS

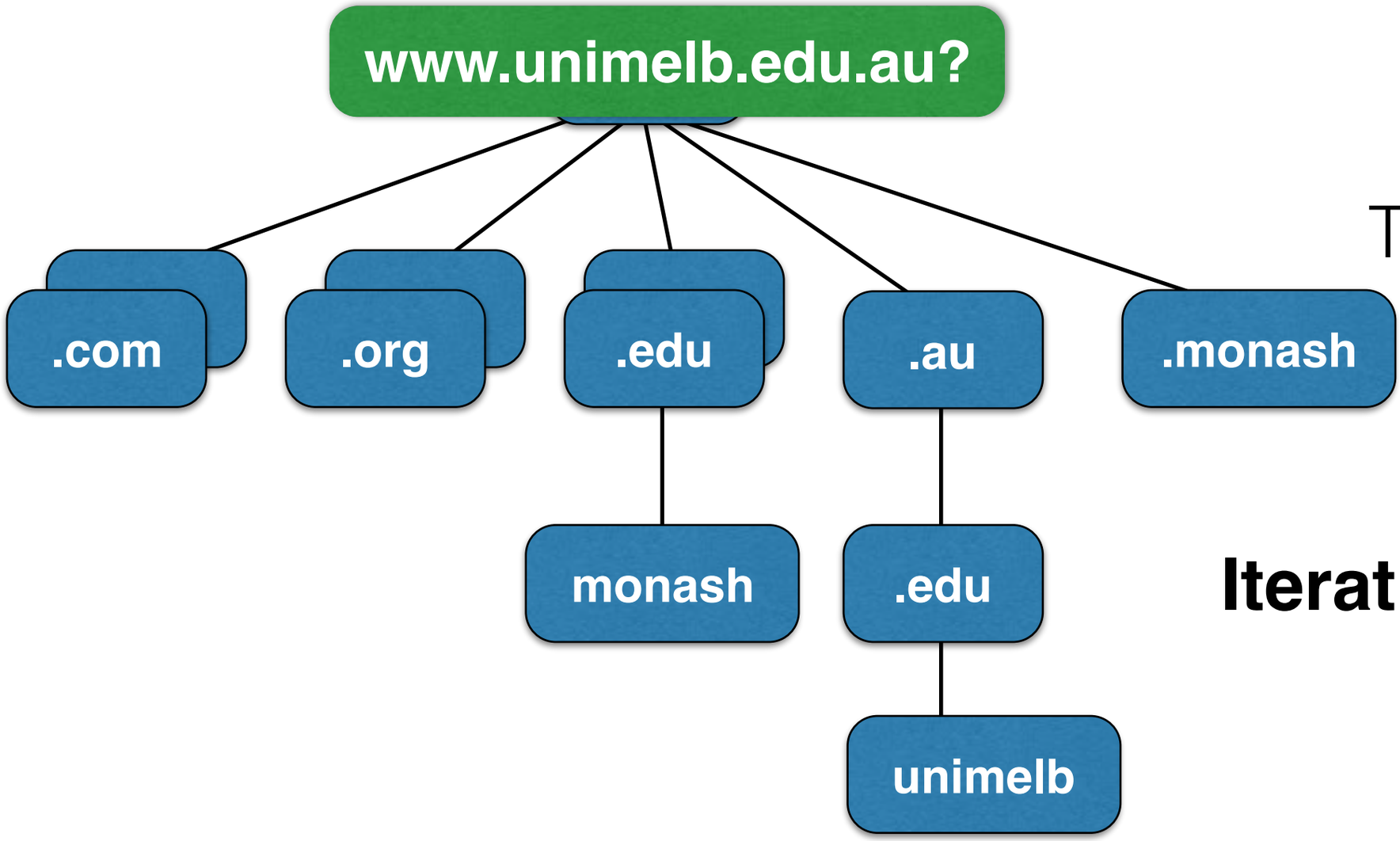


Root Zone

Top-Level Domain (TLD)

Iterative DNS lookup

DNS



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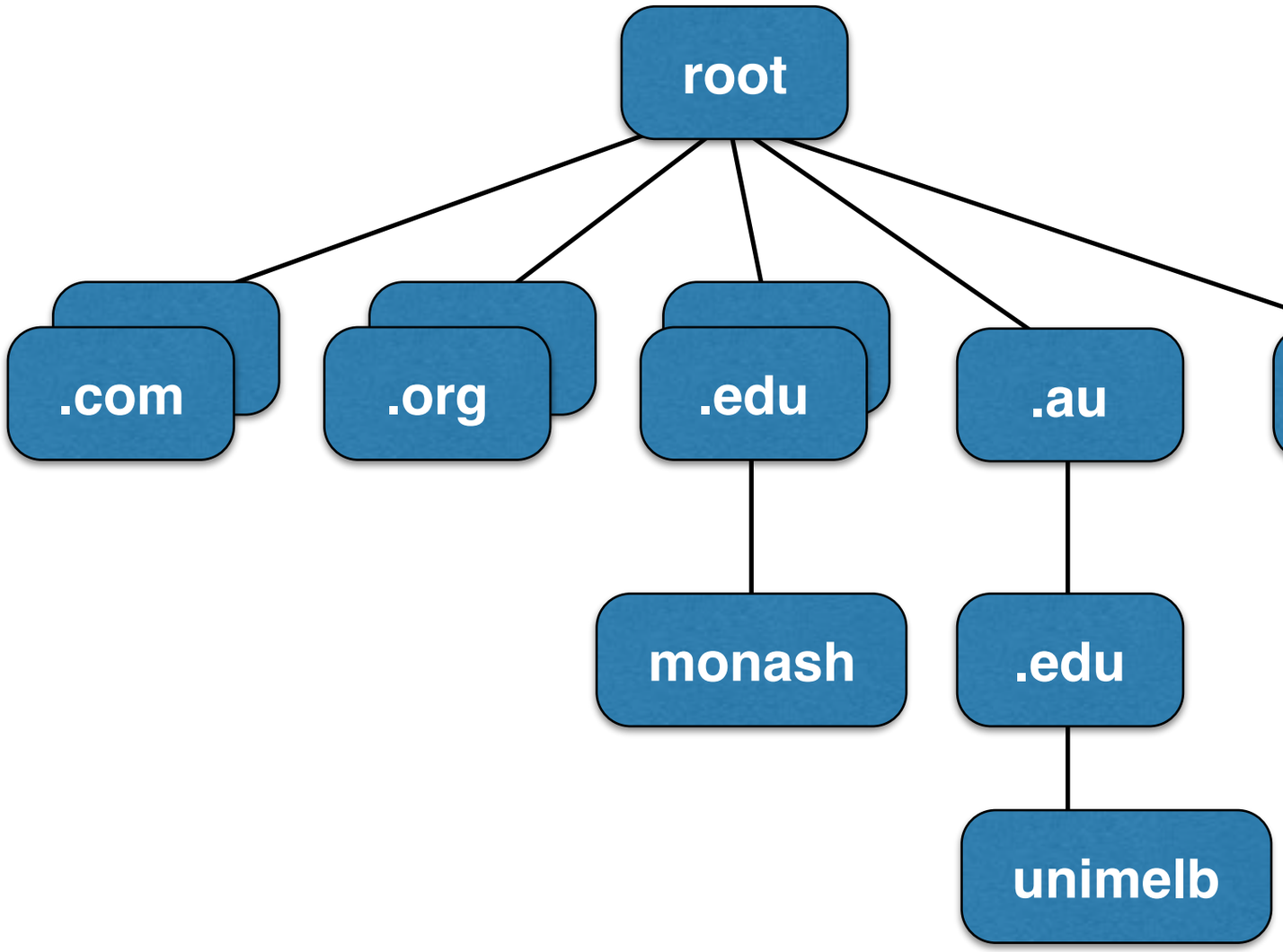

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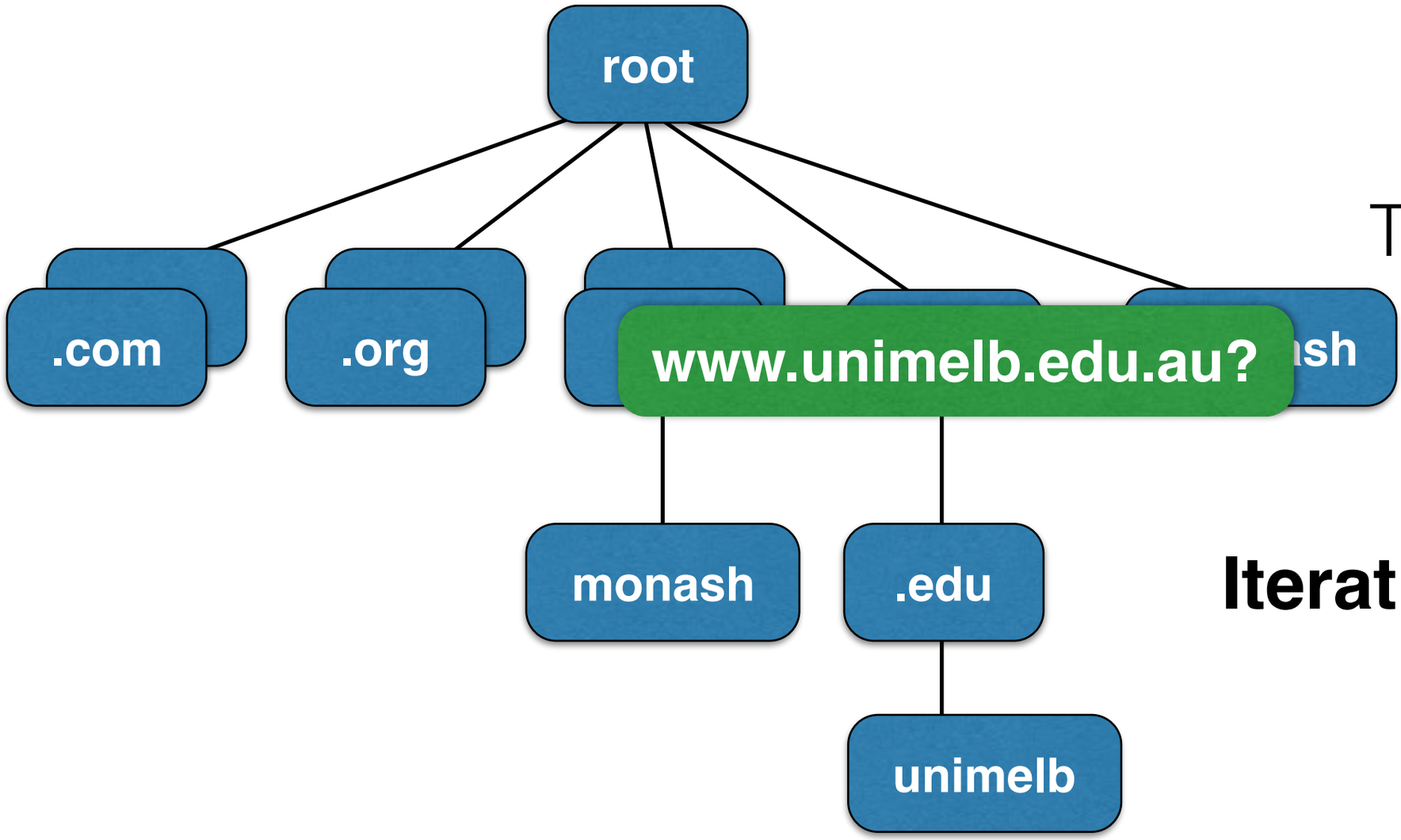

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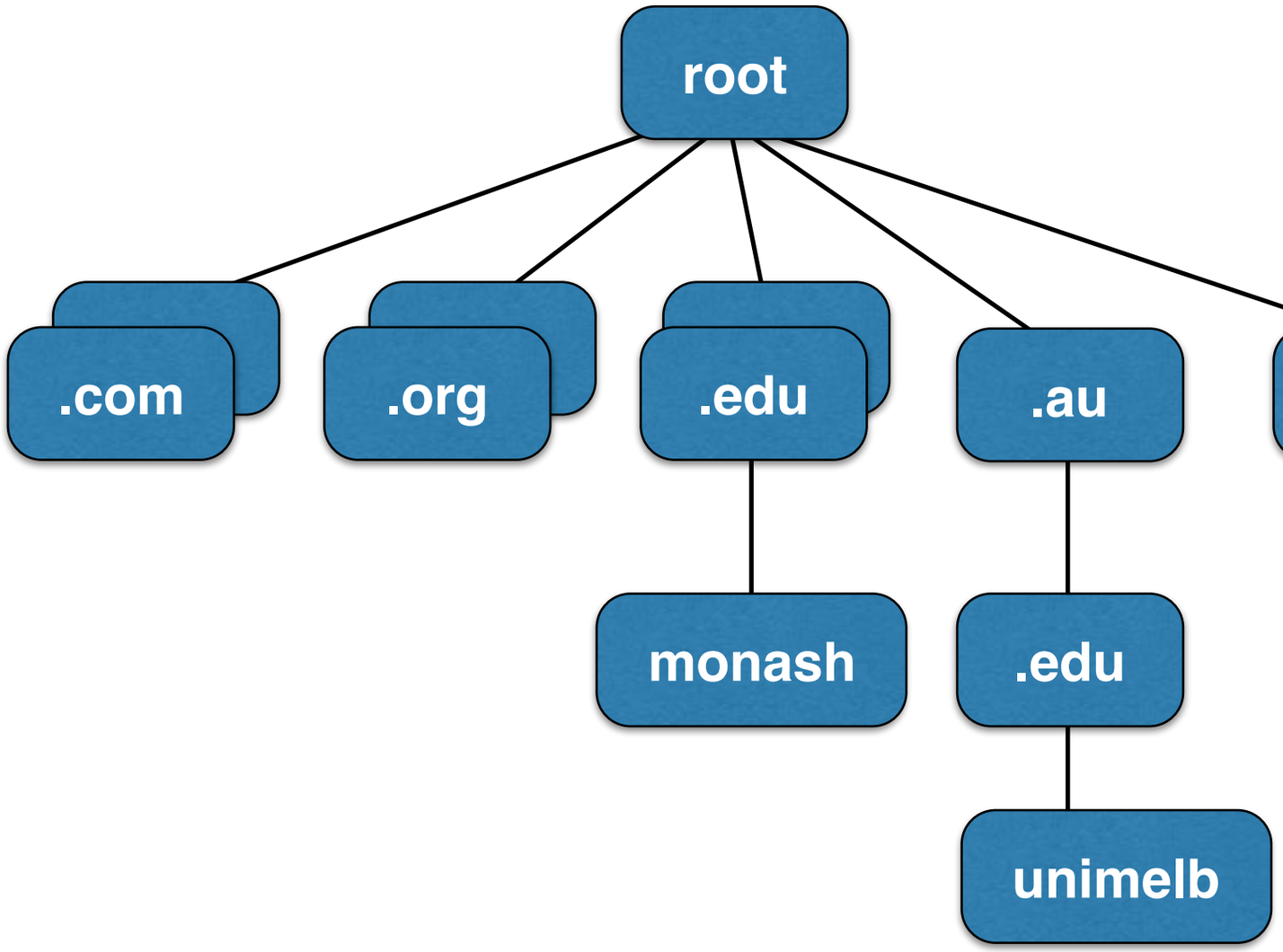

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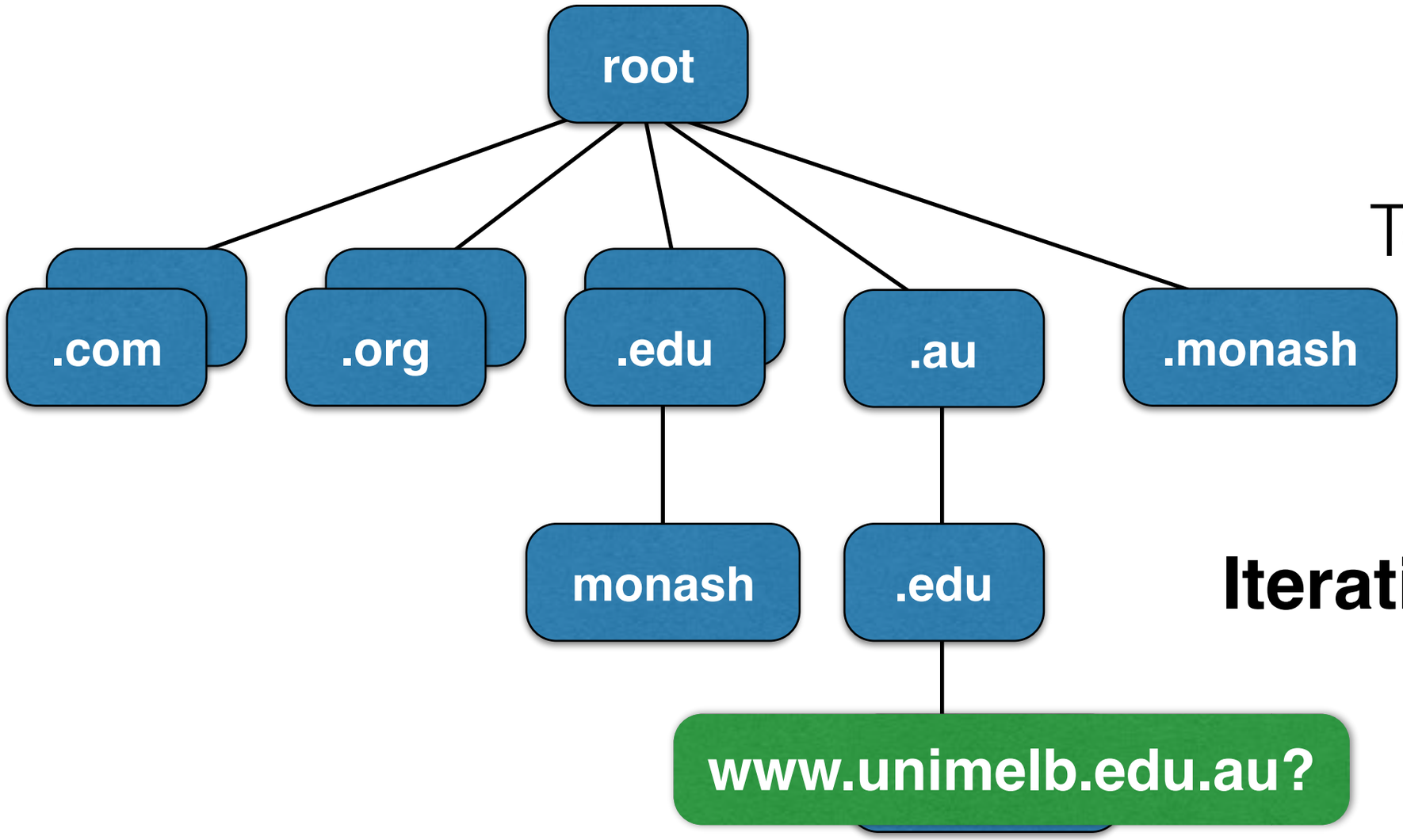

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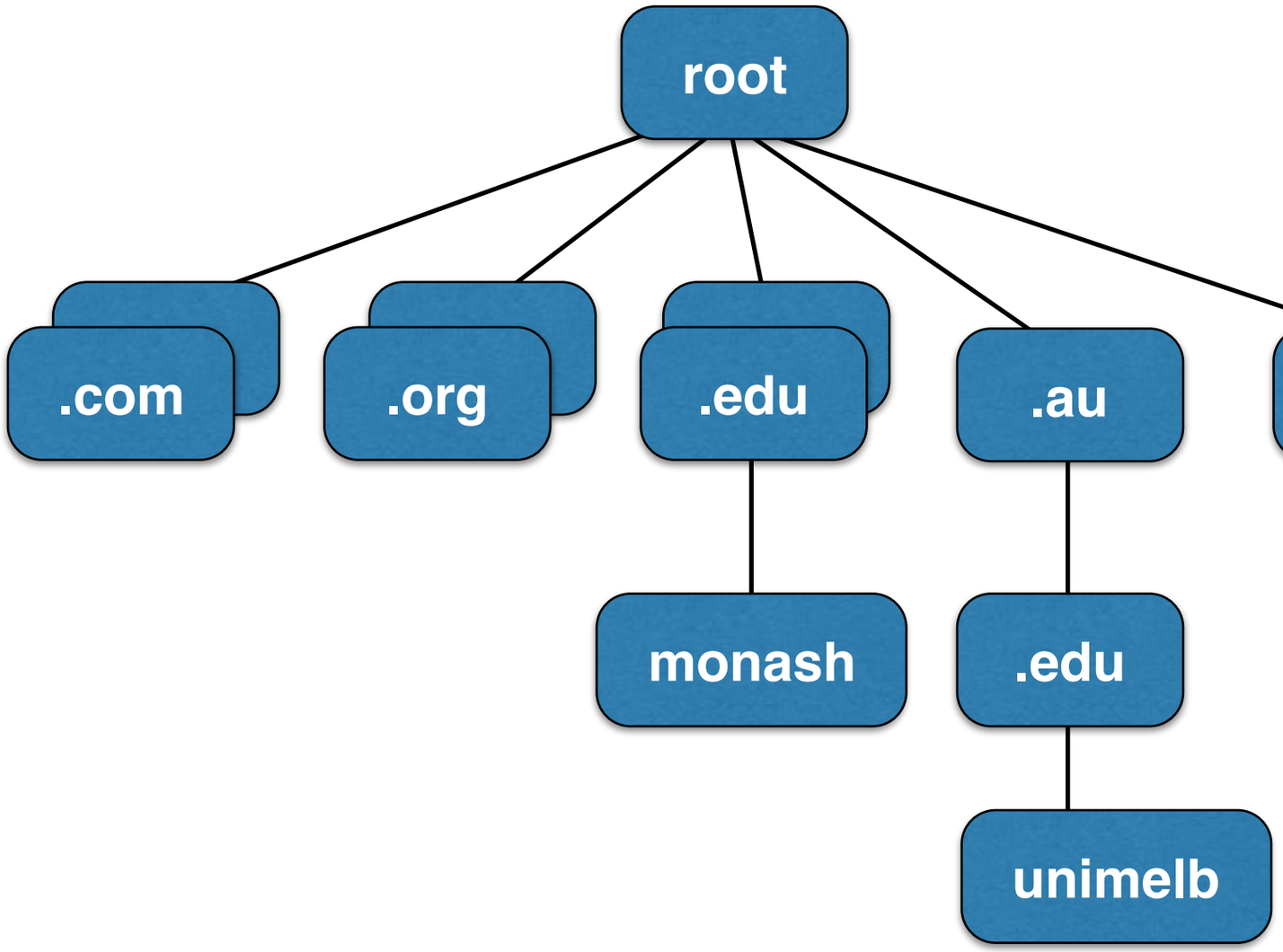

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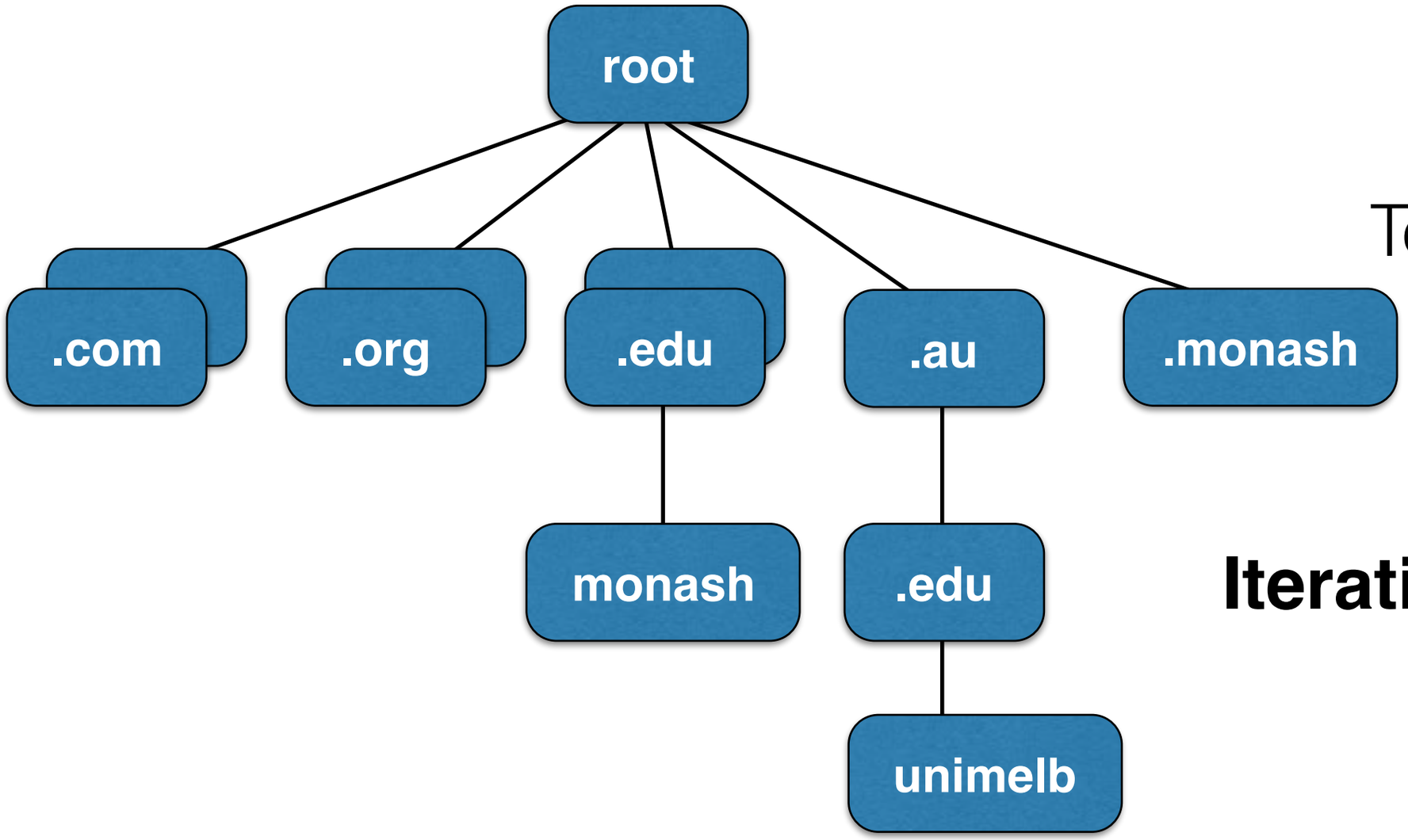

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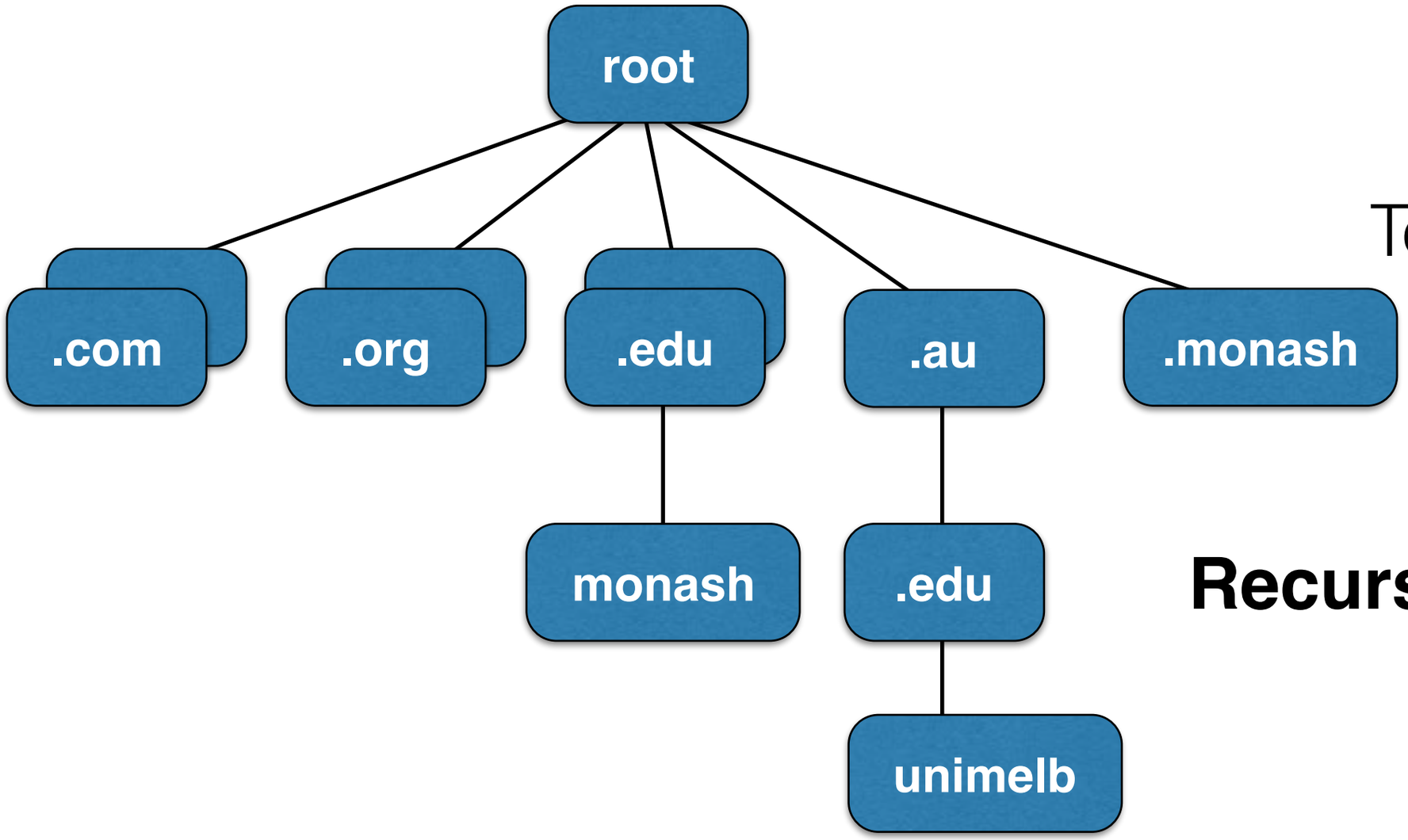

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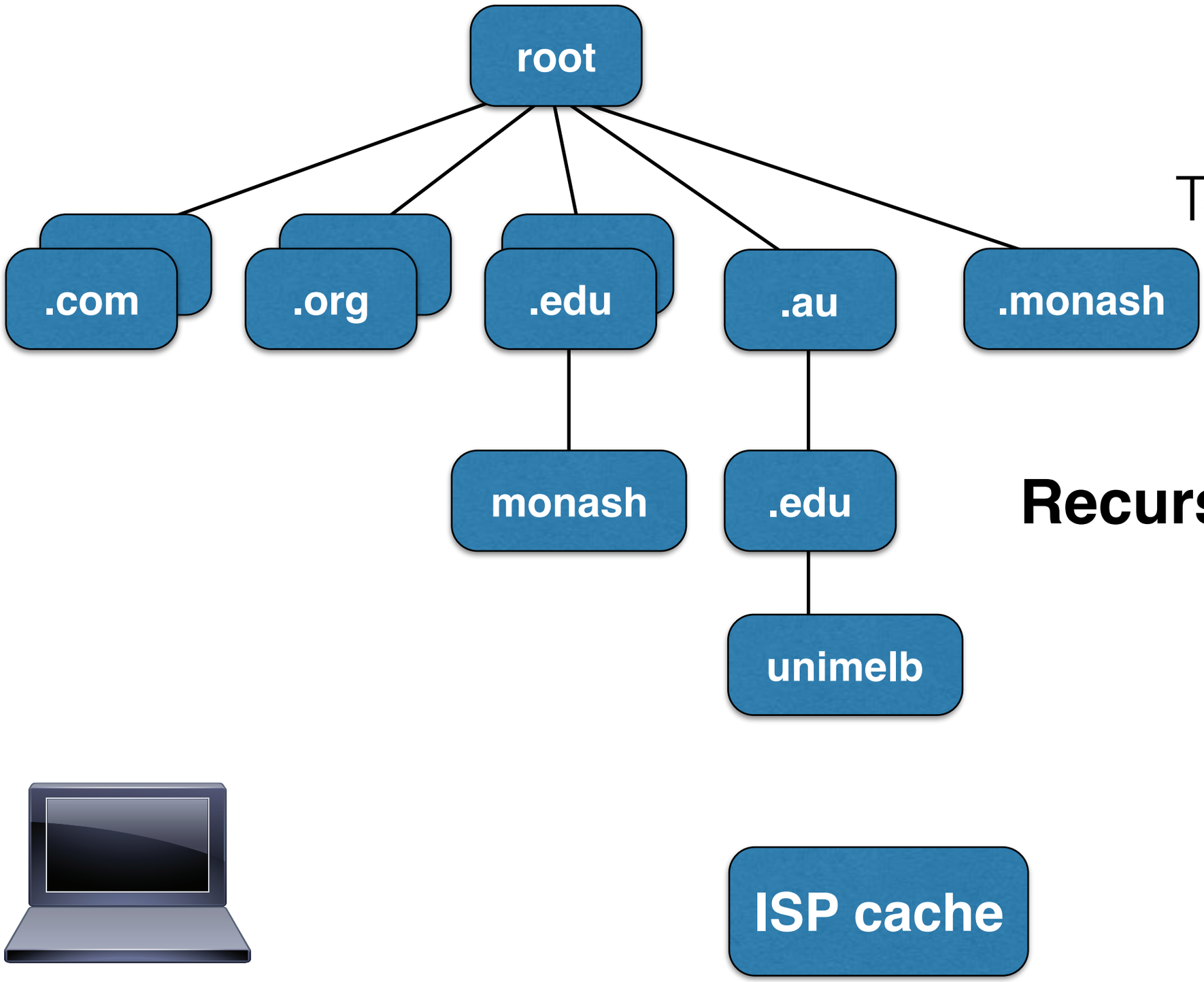
Recursive DNS lookup

DNS



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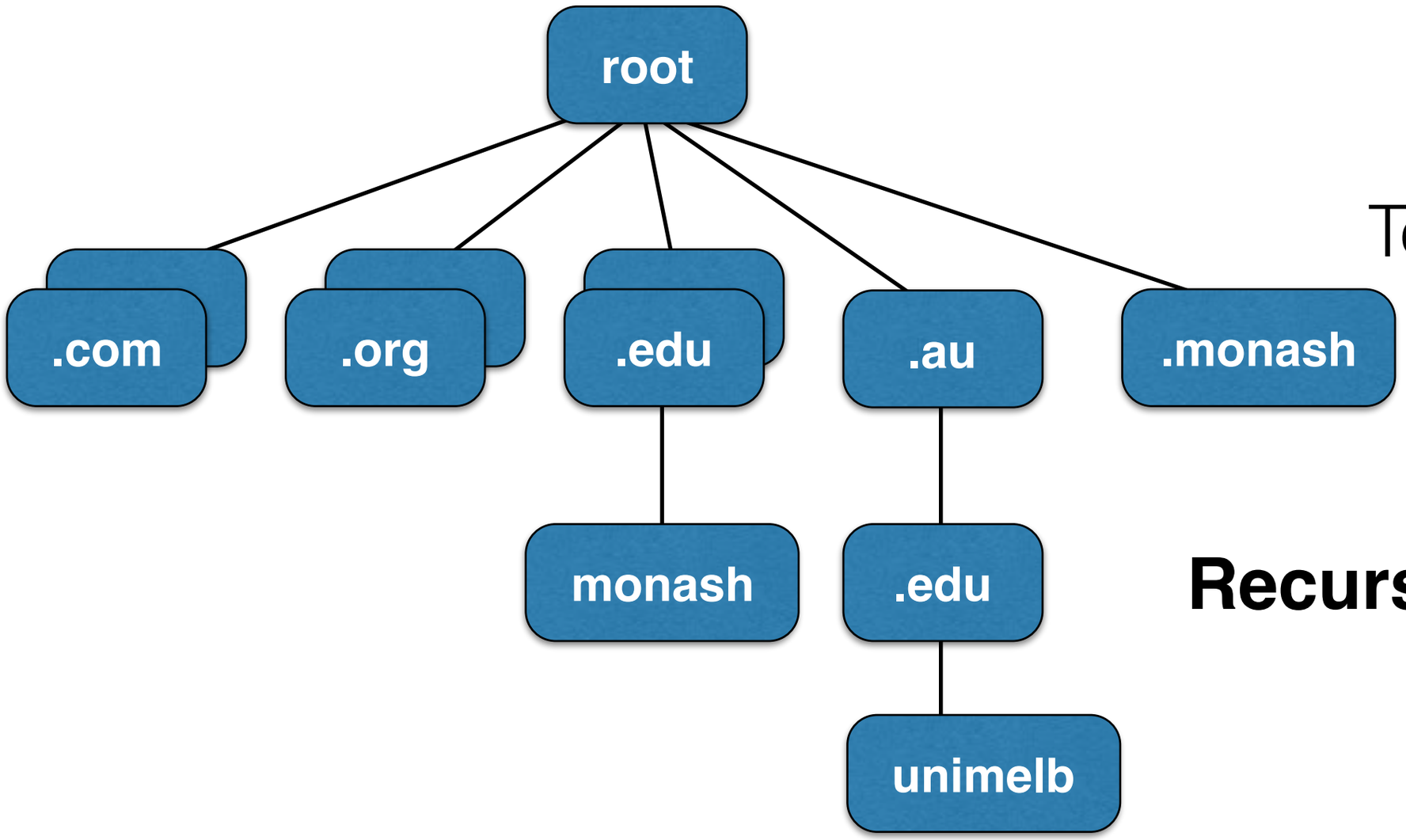
Recursive DNS lookup

ISP cache

DNS



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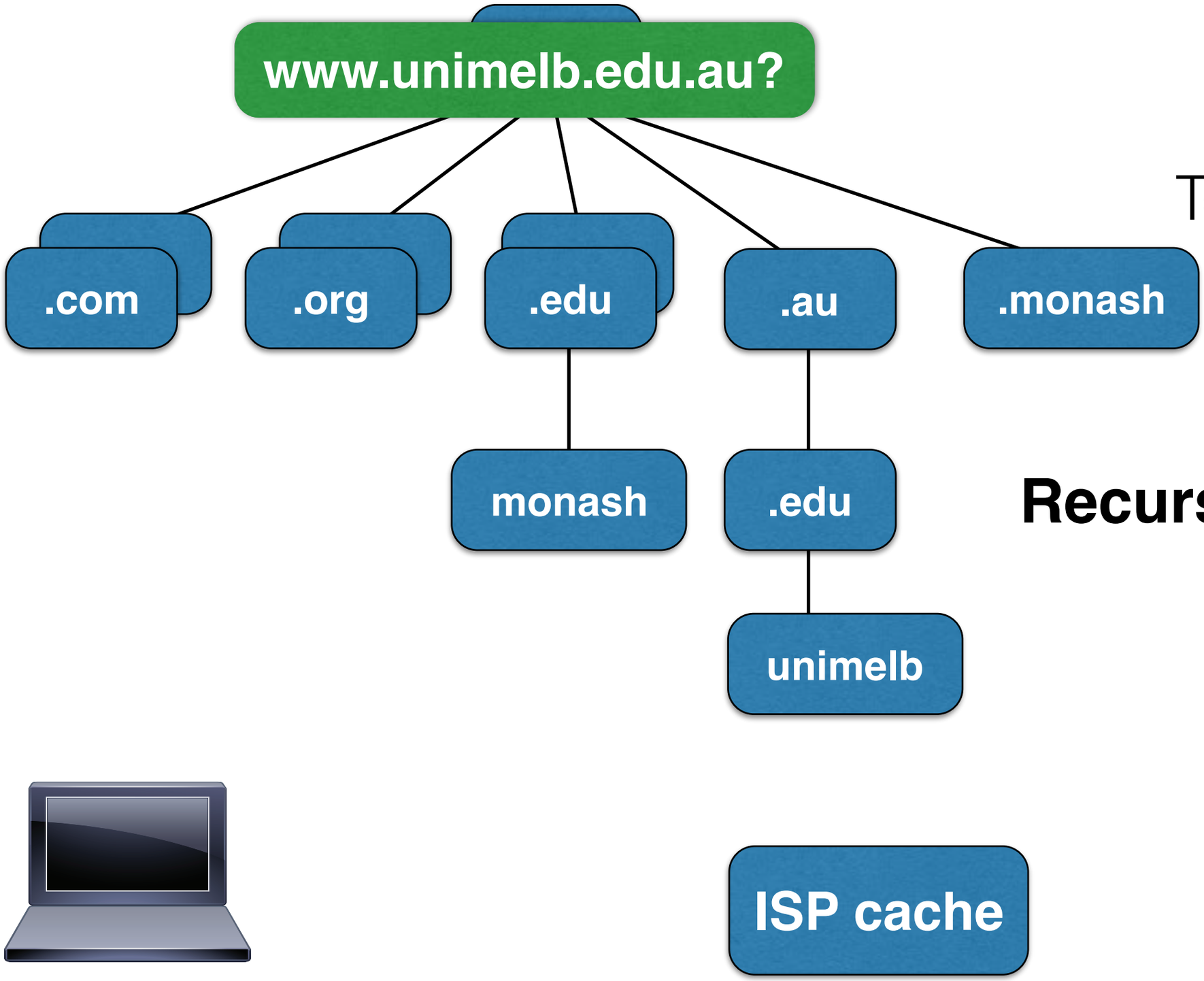
Recursive DNS lookup

www.unimelb.edu.au?

DNS

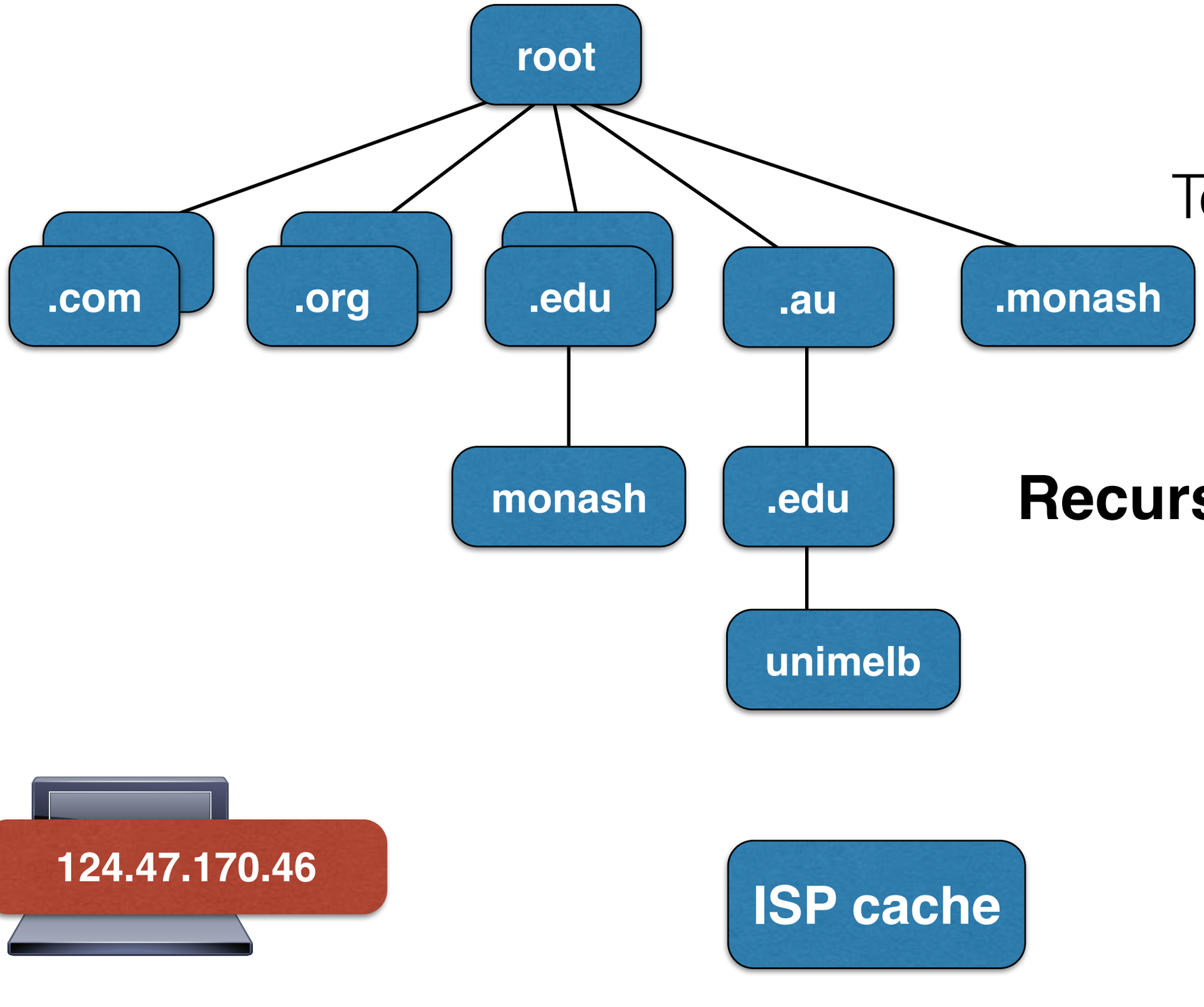


Root Zone

Top-Level Domain (TLD)

Recursive DNS lookup

DNS



Root Zone

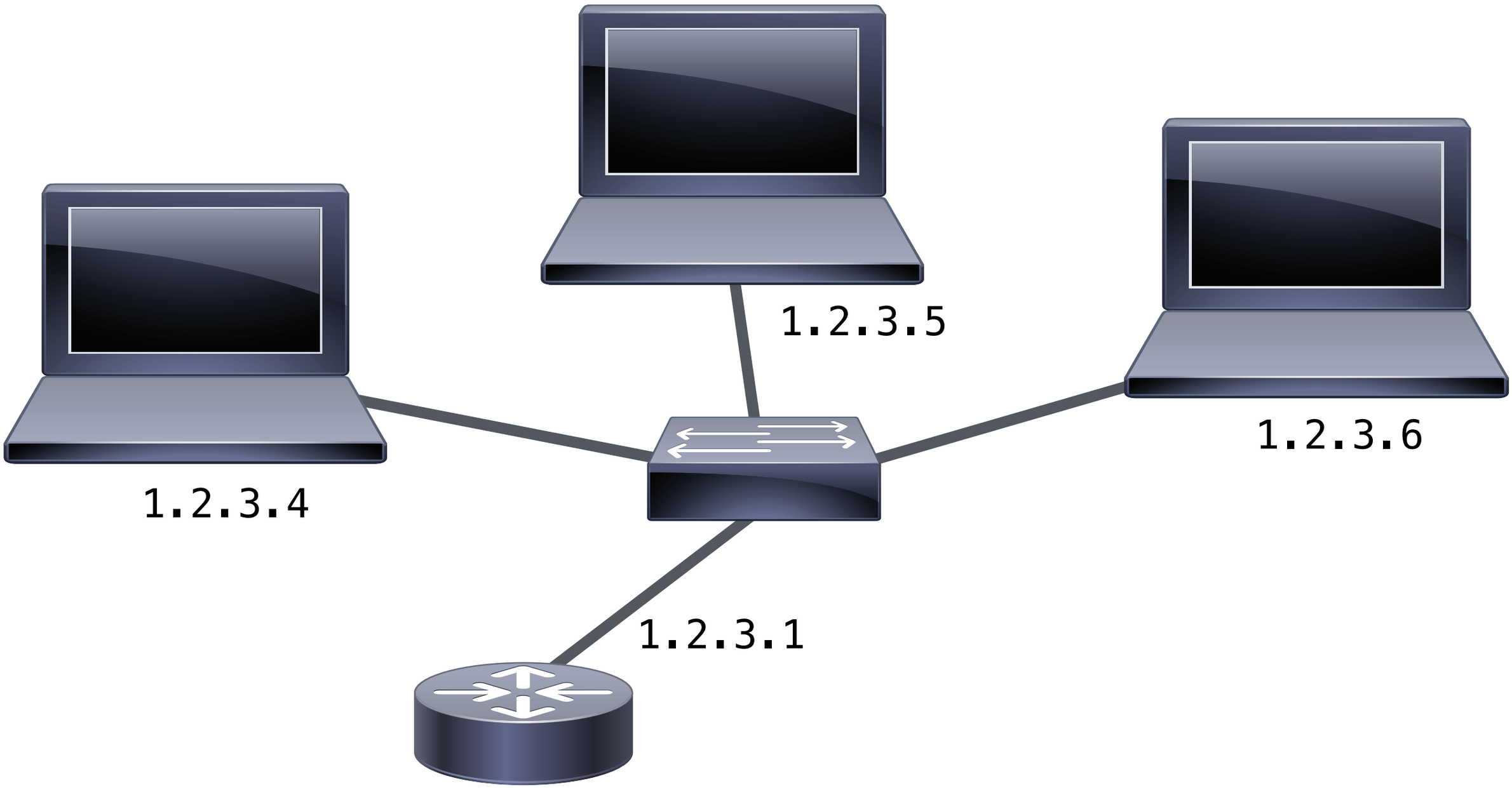
Top-Level Domain (TLD)

Recursive DNS lookup

ISP cache

Address resolution: Data Link Layer

How to find the MAC address for an IP address:



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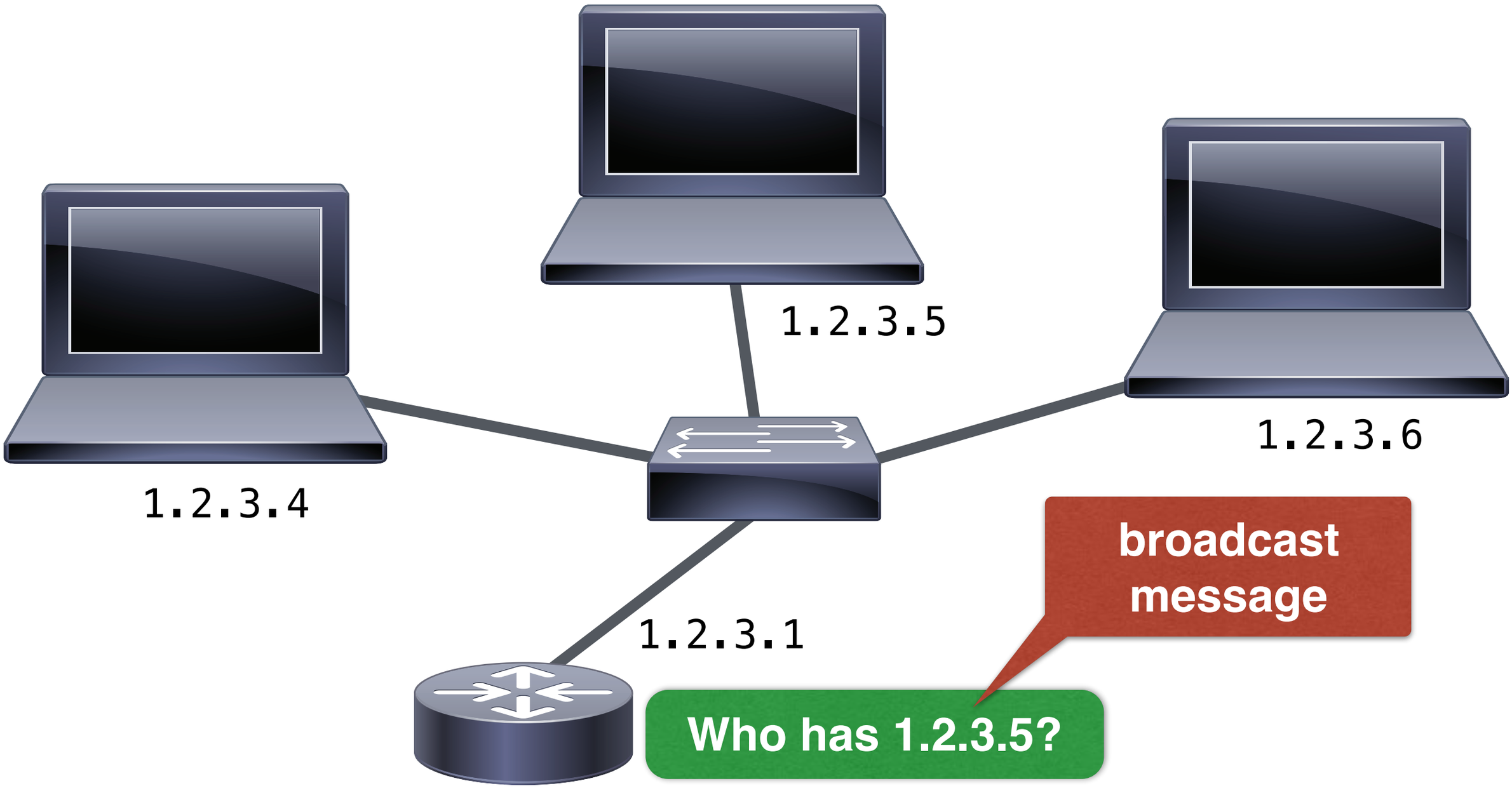

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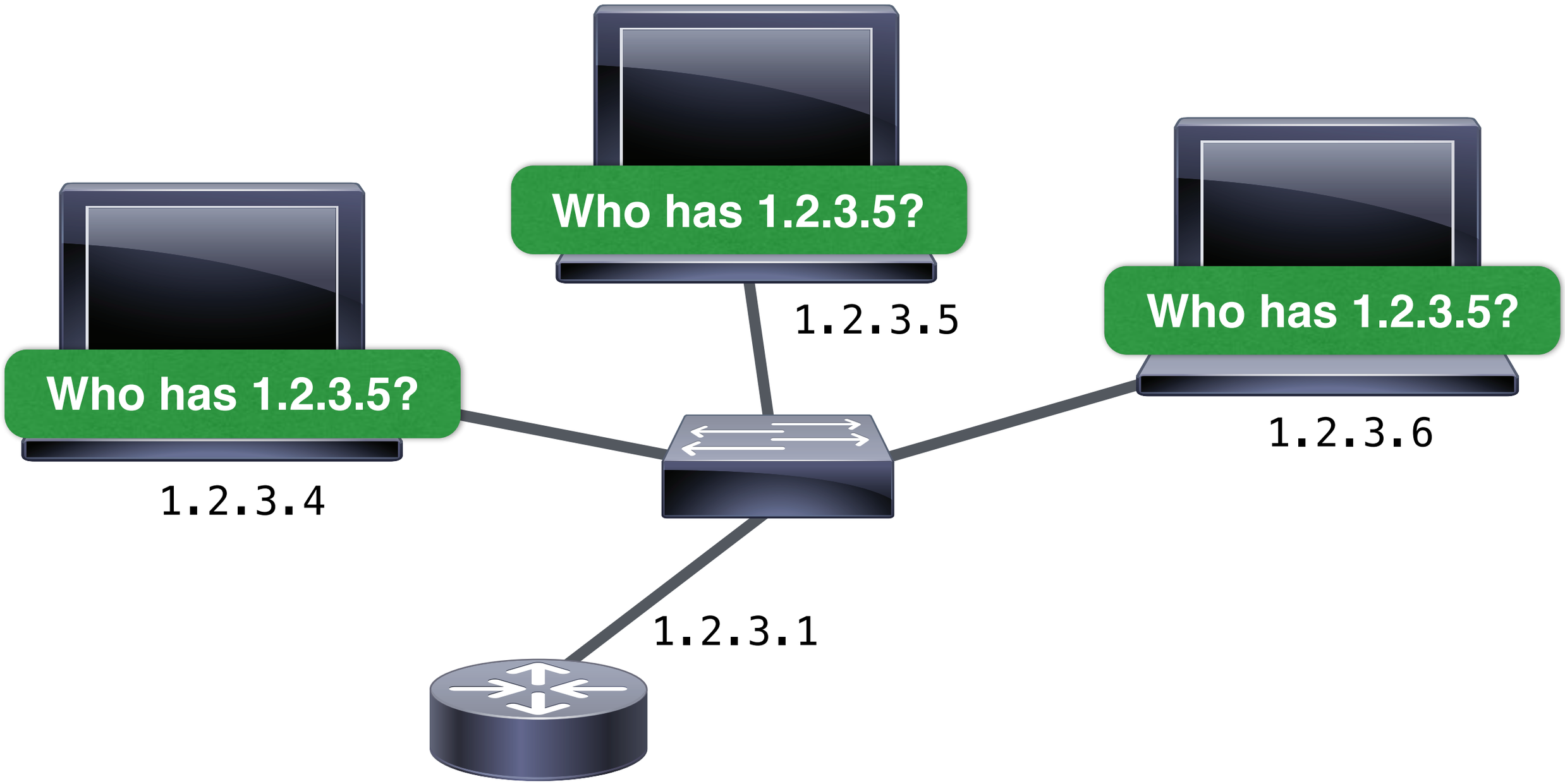

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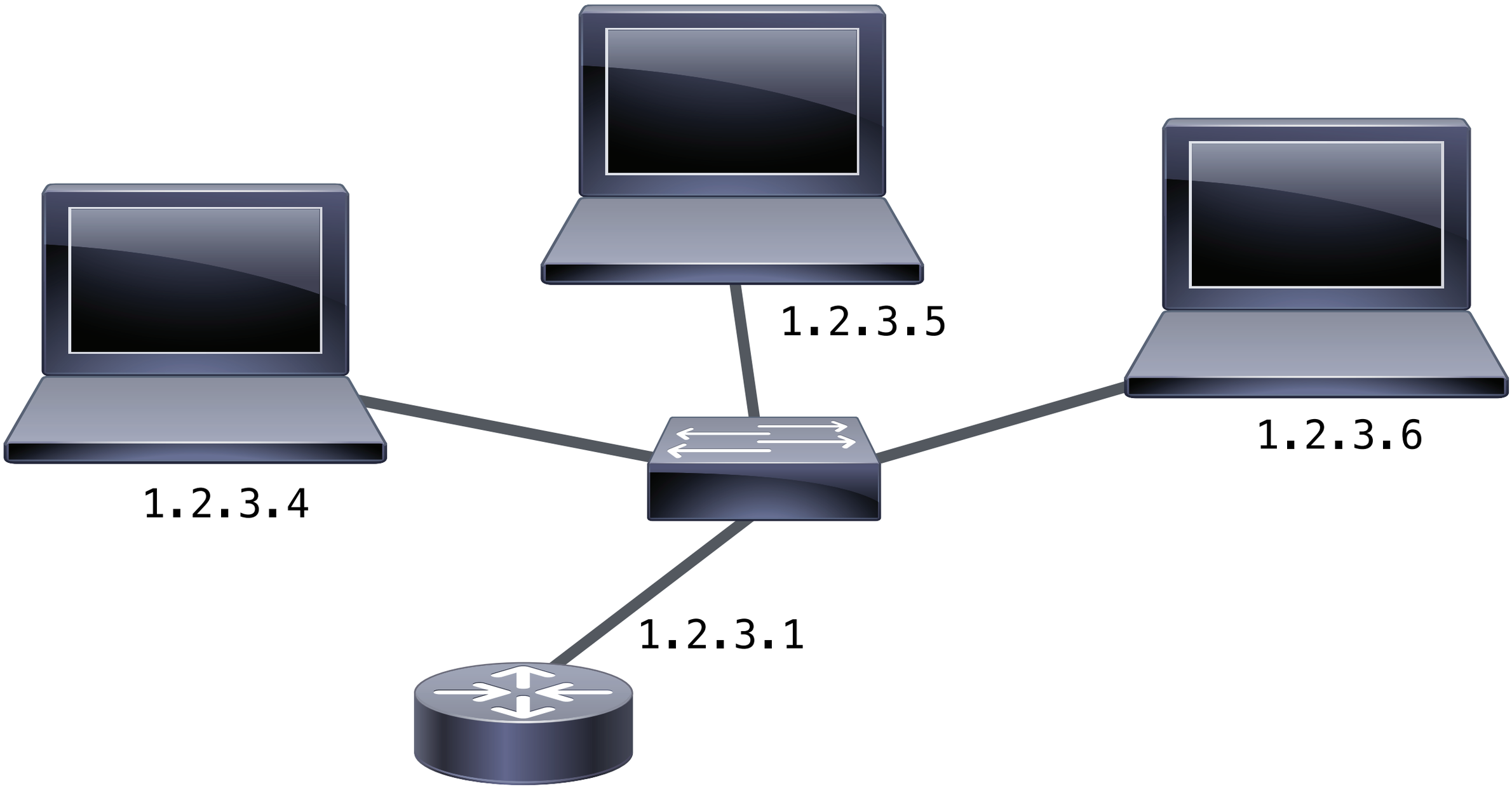

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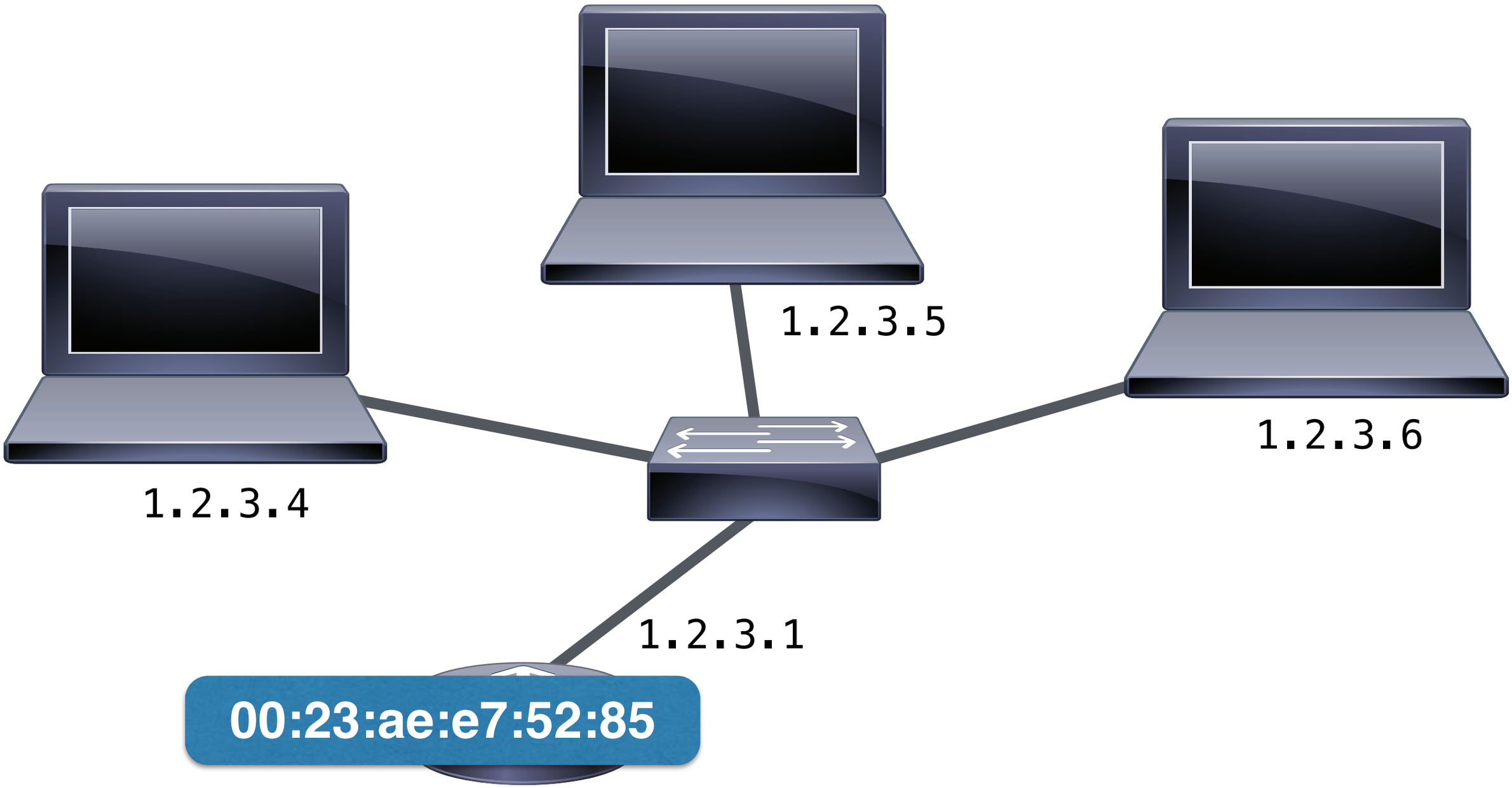

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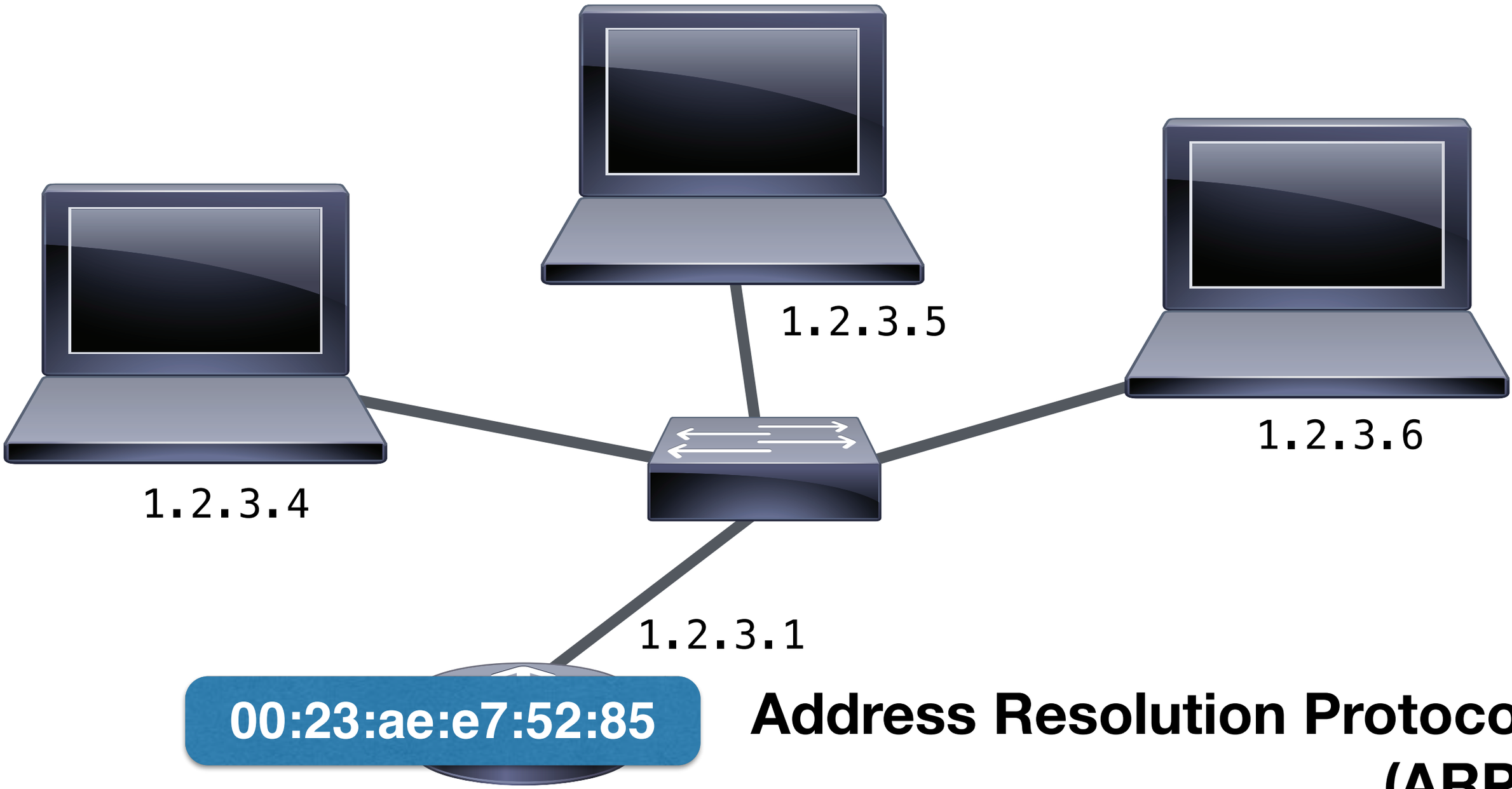

Address Resolution Protocol (ARP)

The Network Layer:

Routing

Routers

Routers connect networks

- Internet is a network of networks!
- Most important piece of Internet infrastructure

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A router is a layer 3 device

- one IP address per **interface**, i.e. typically per subnet it is connected to
- Clients send packets to routers **if destination is outside their own subnet**
- Routers use IP address to determine **where the packet is sent next**

Routing tables

Routing tables

For each incoming packet, the router

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- looks at the packet's **destination IP address**

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  to which other router should I send a packet for this destination, or can I deliver it directly?

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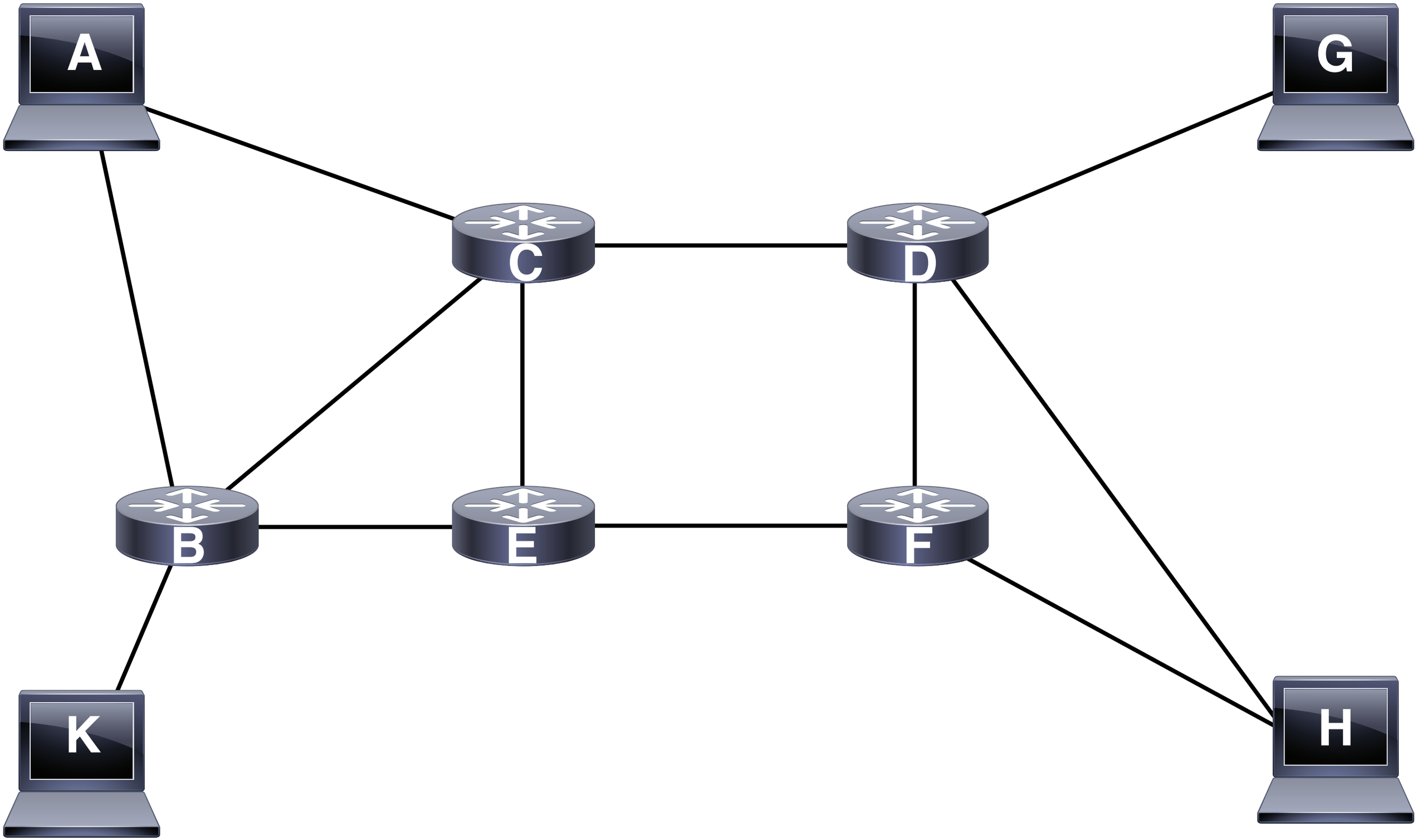
- if destination not in table: send to **default gateway**

Routing tables

For each incoming packet, the router

- looks at the packet's **destination IP address**
- consults the **routing table:**
  to which other router should I send a packet for this destination, or can I deliver it directly?
- if destination not in table: send to **default gateway**
- if no default gateway configured: **packet can't be routed**

Routing example



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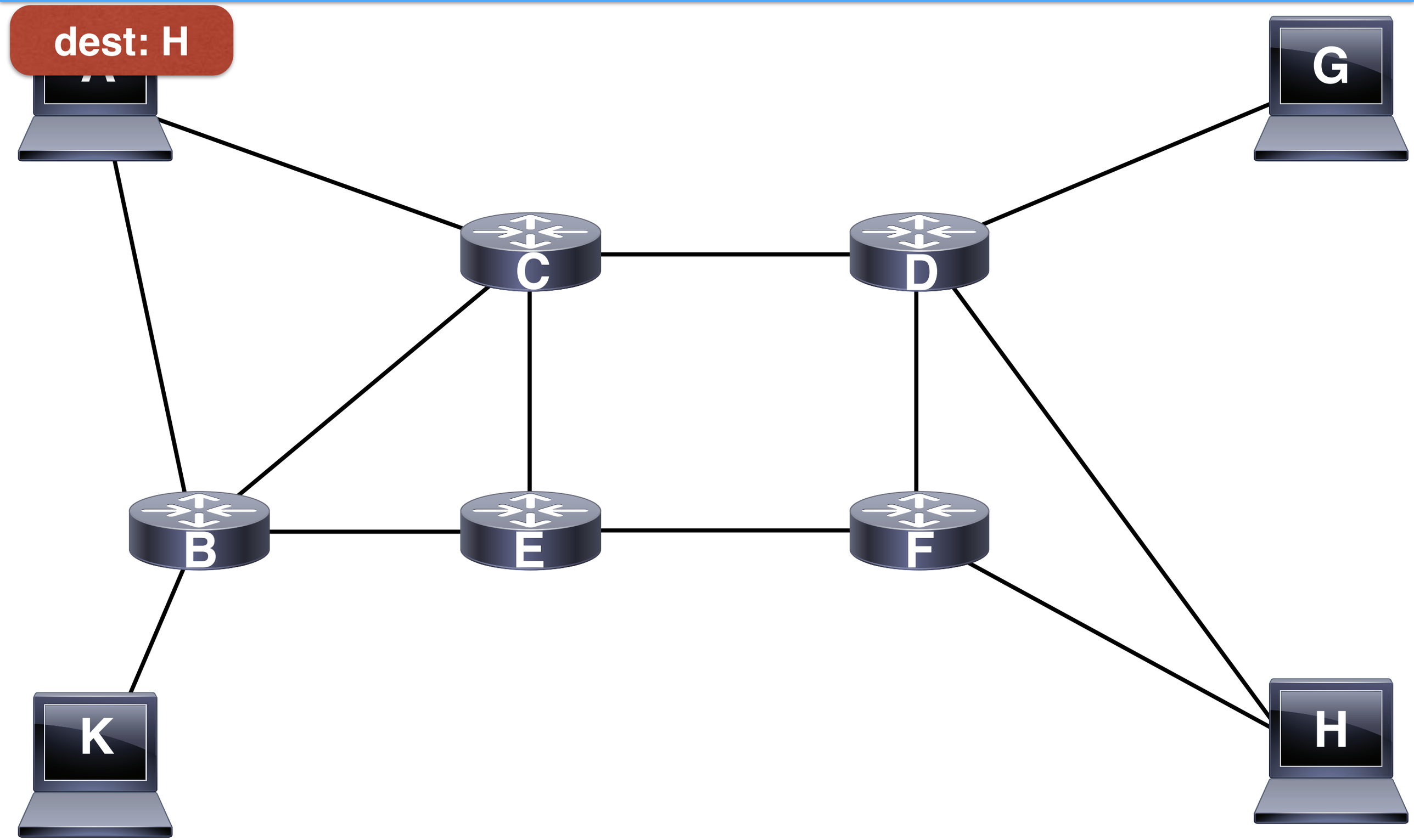
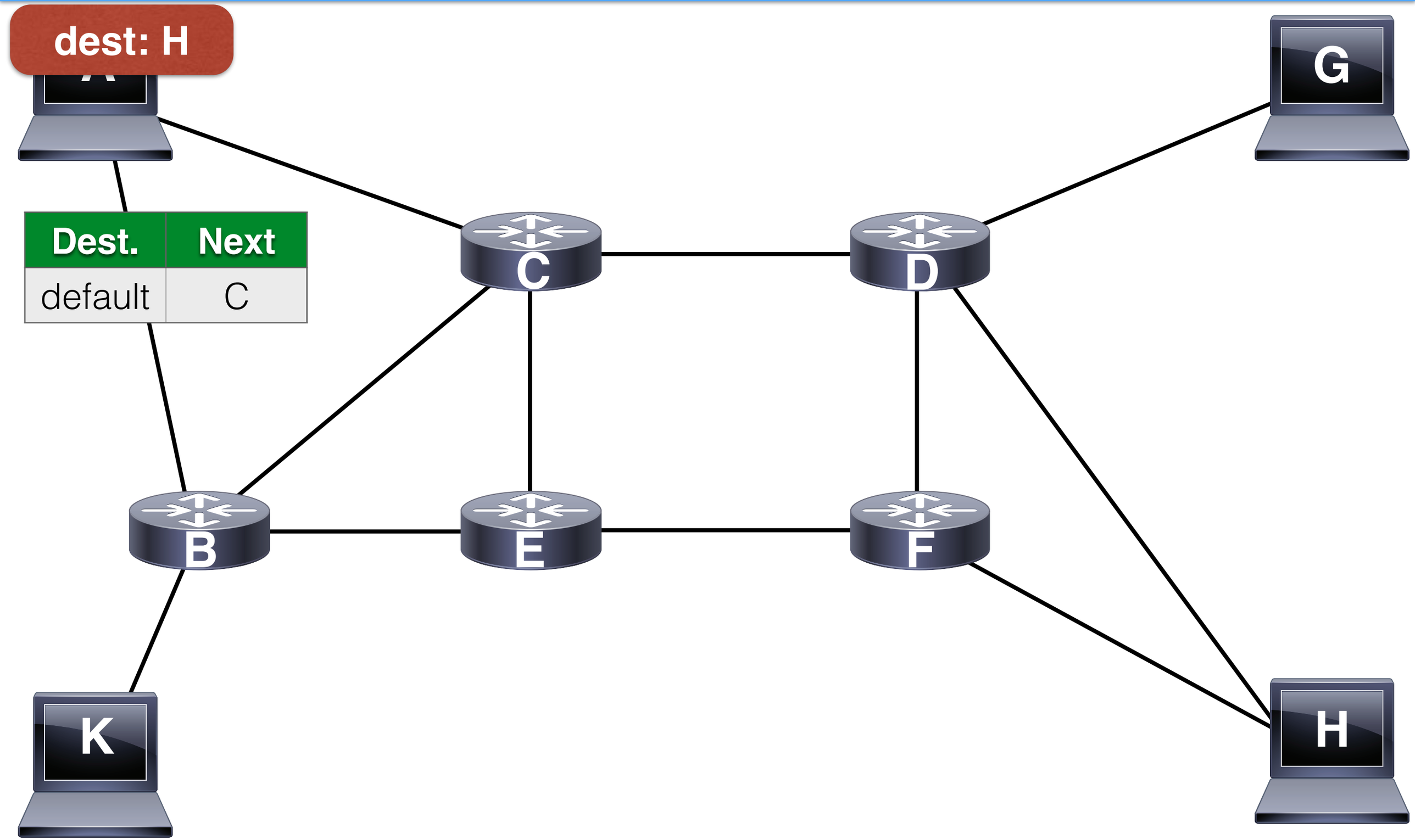


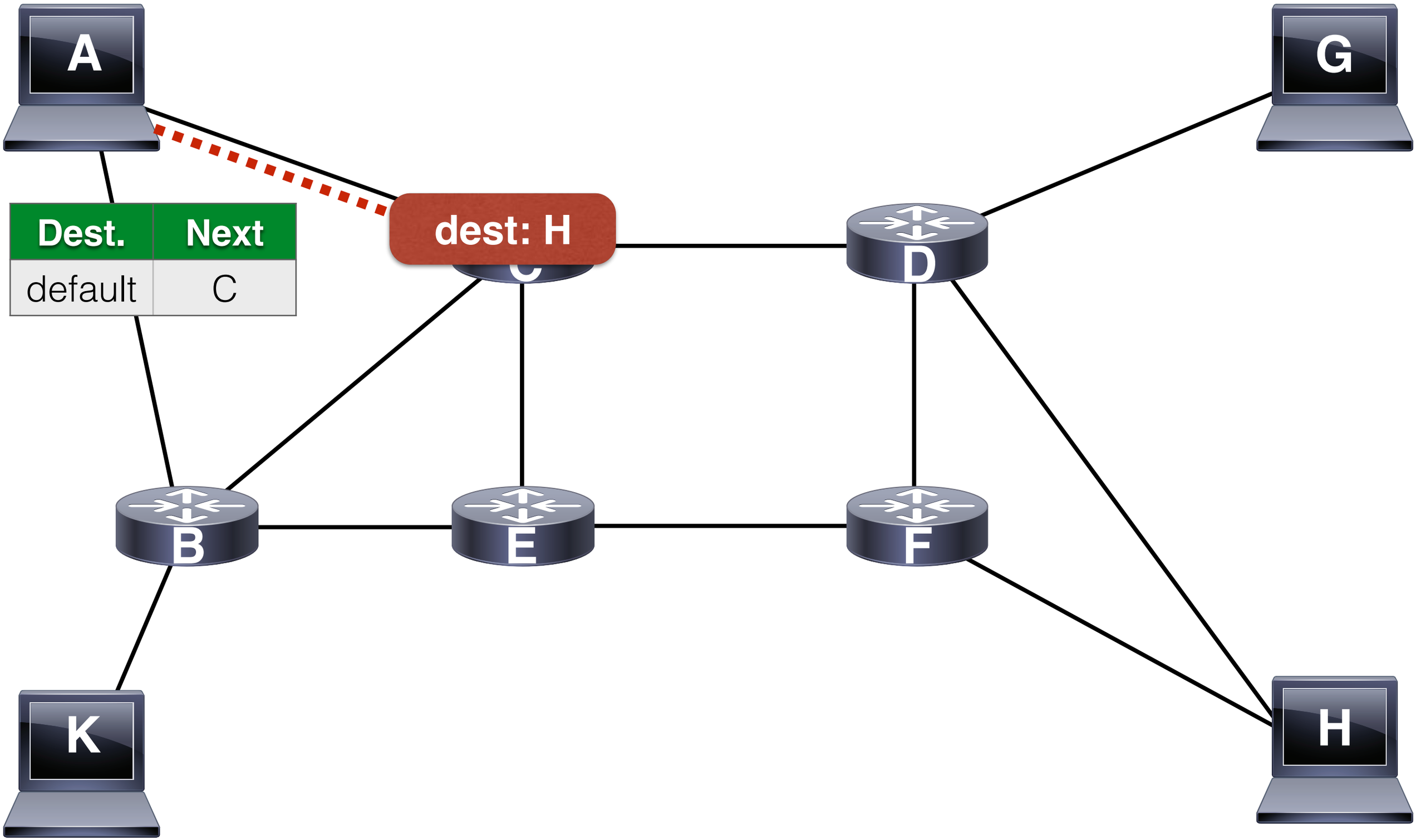
Routing example

dest: H

Dest.	Next
default	C



Routing example



Dest.	Next
default	C

Routing example

Dest.	Next
A	A
G	D
H	E
K	E

Dest.	Next
default	C

dest: H

A

G

C

D

B

E

F

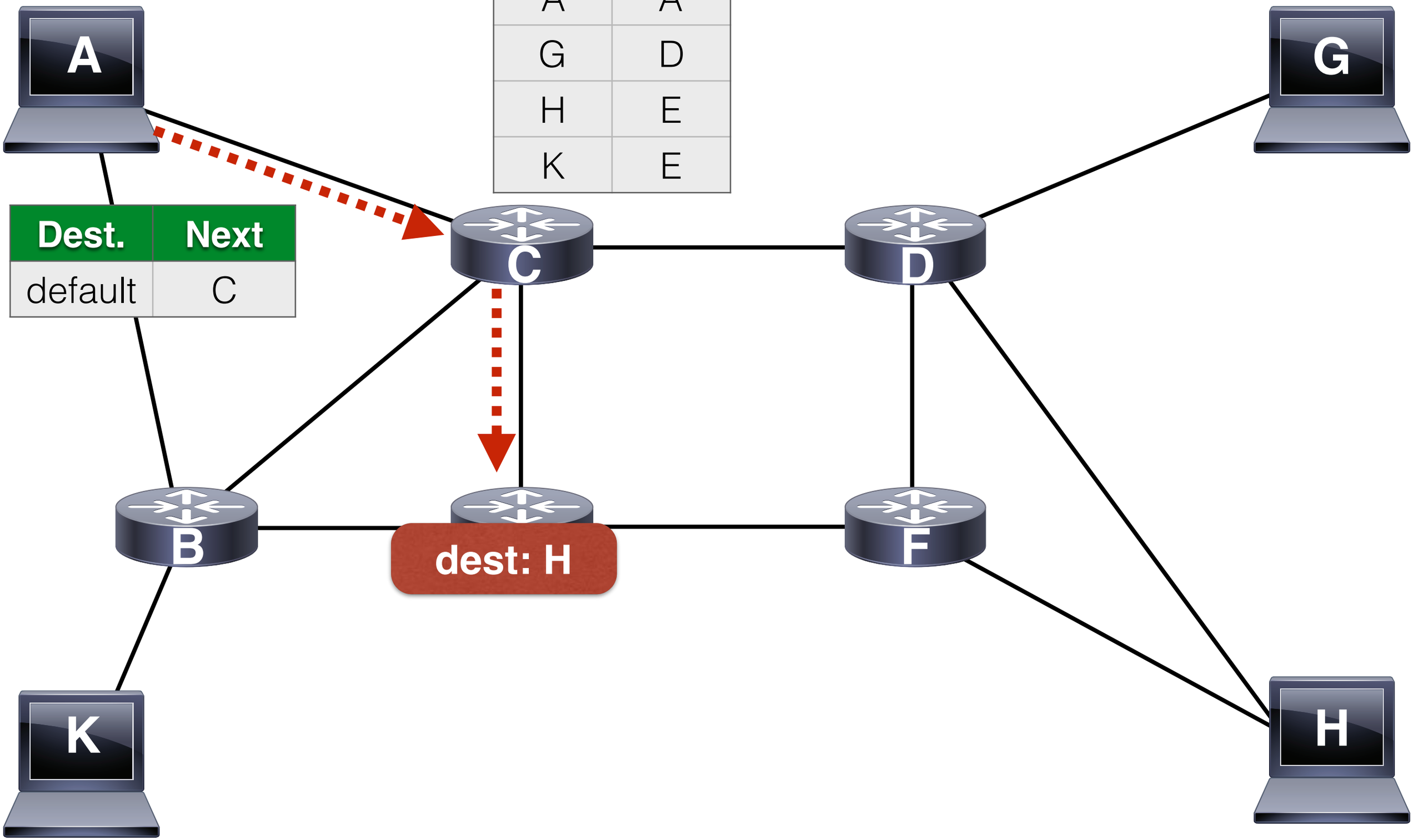
K

H

Routing example

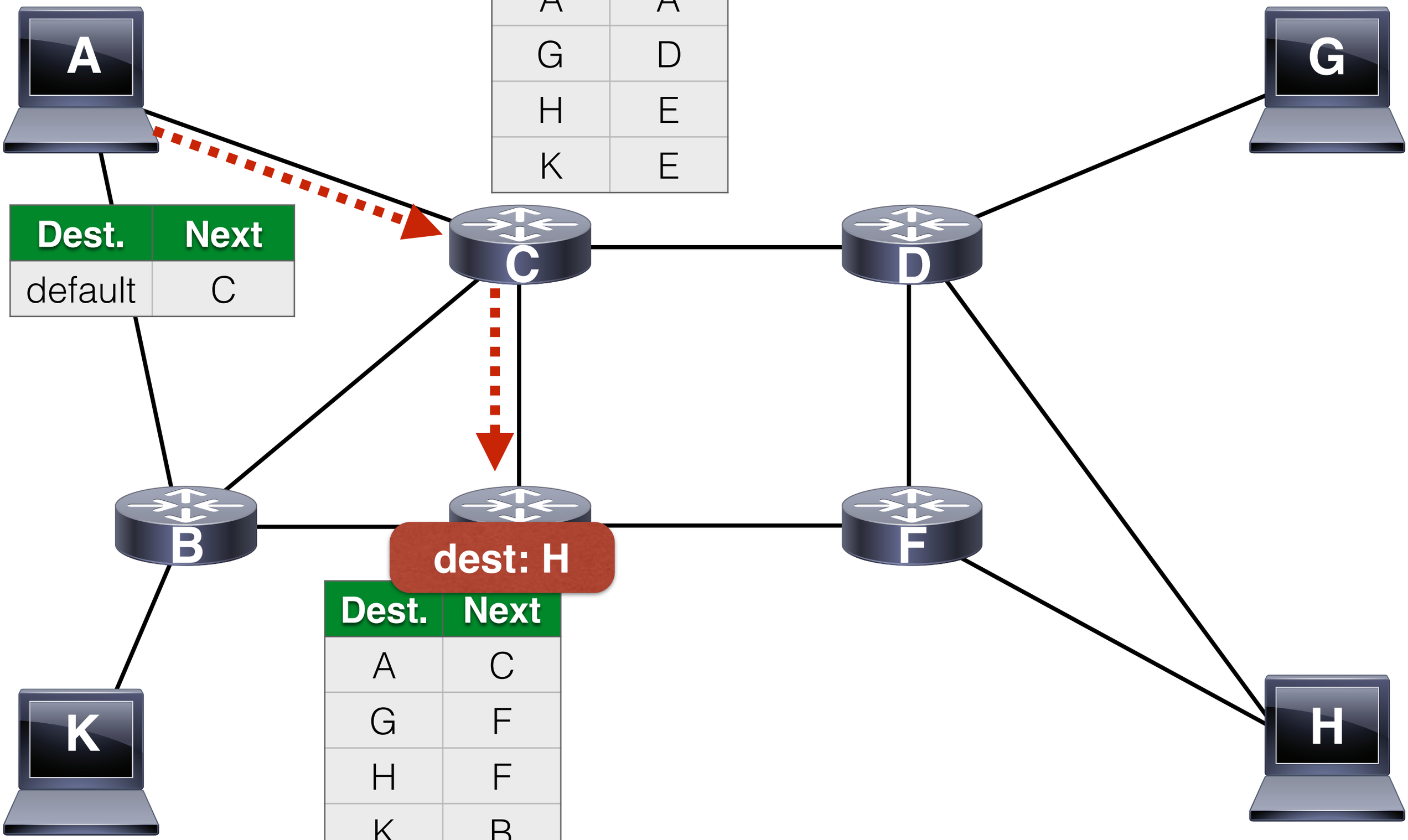
Dest.	Next
A	A
G	D
H	E
K	E

Dest.	Next
default	C



Routing example

Dest.	Next
A	A
G	D
H	E
K	E



Dest.	Next
default	C

Dest.	Next
A	C
G	F
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K	B

Routing example

Dest.	Next
A	A
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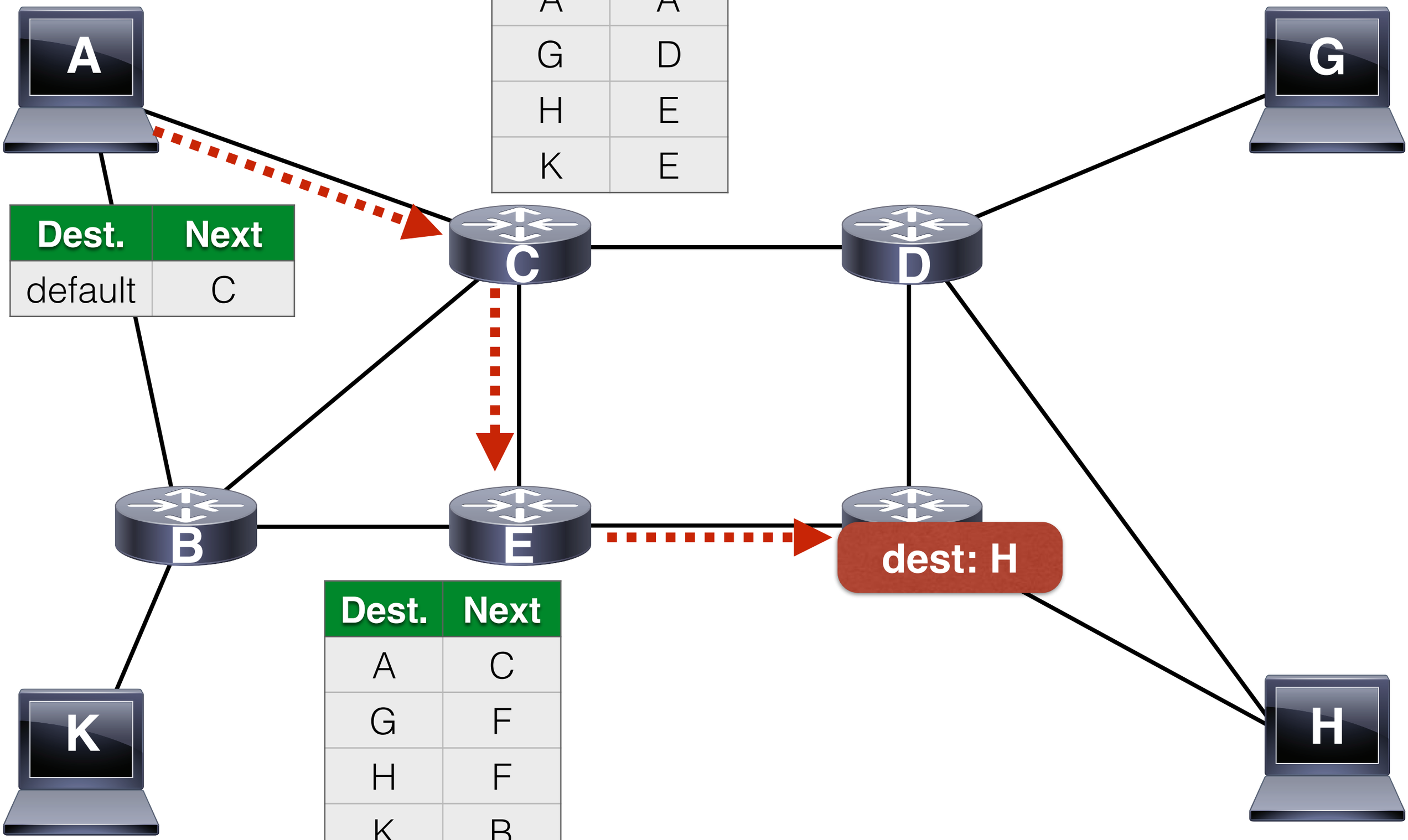
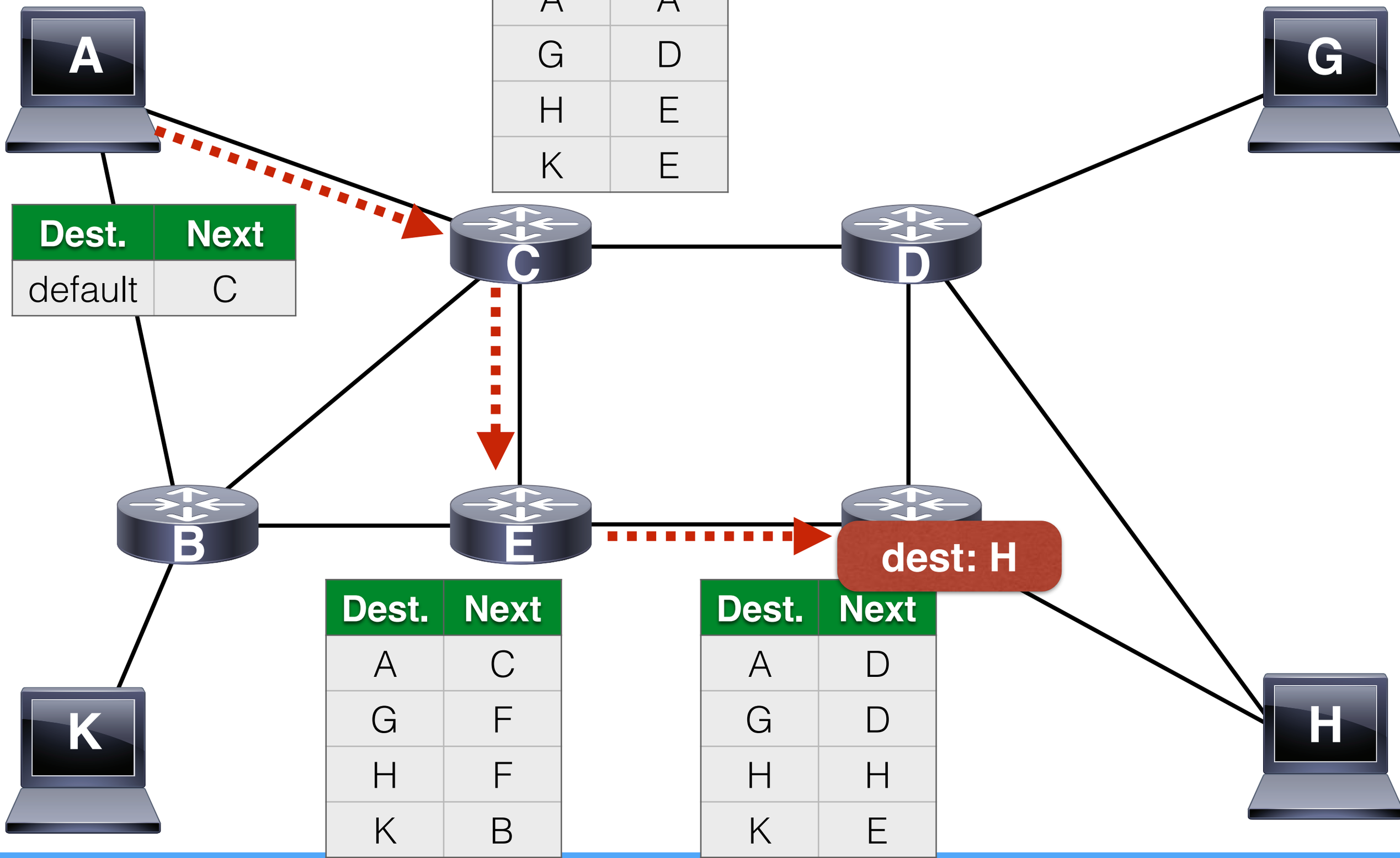


Dest.	Next
default	C

Dest.	Next
A	C
G	F
H	F
K	B

Routing example



Dest.	Next
A	A
G	D
H	E
K	E

Dest.	Next
default	C

Dest.	Next
A	C
G	F
H	F
K	B

Dest.	Next
A	D
G	D
H	H
K	E

Routing example

Dest.	Next
A	A
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H	E
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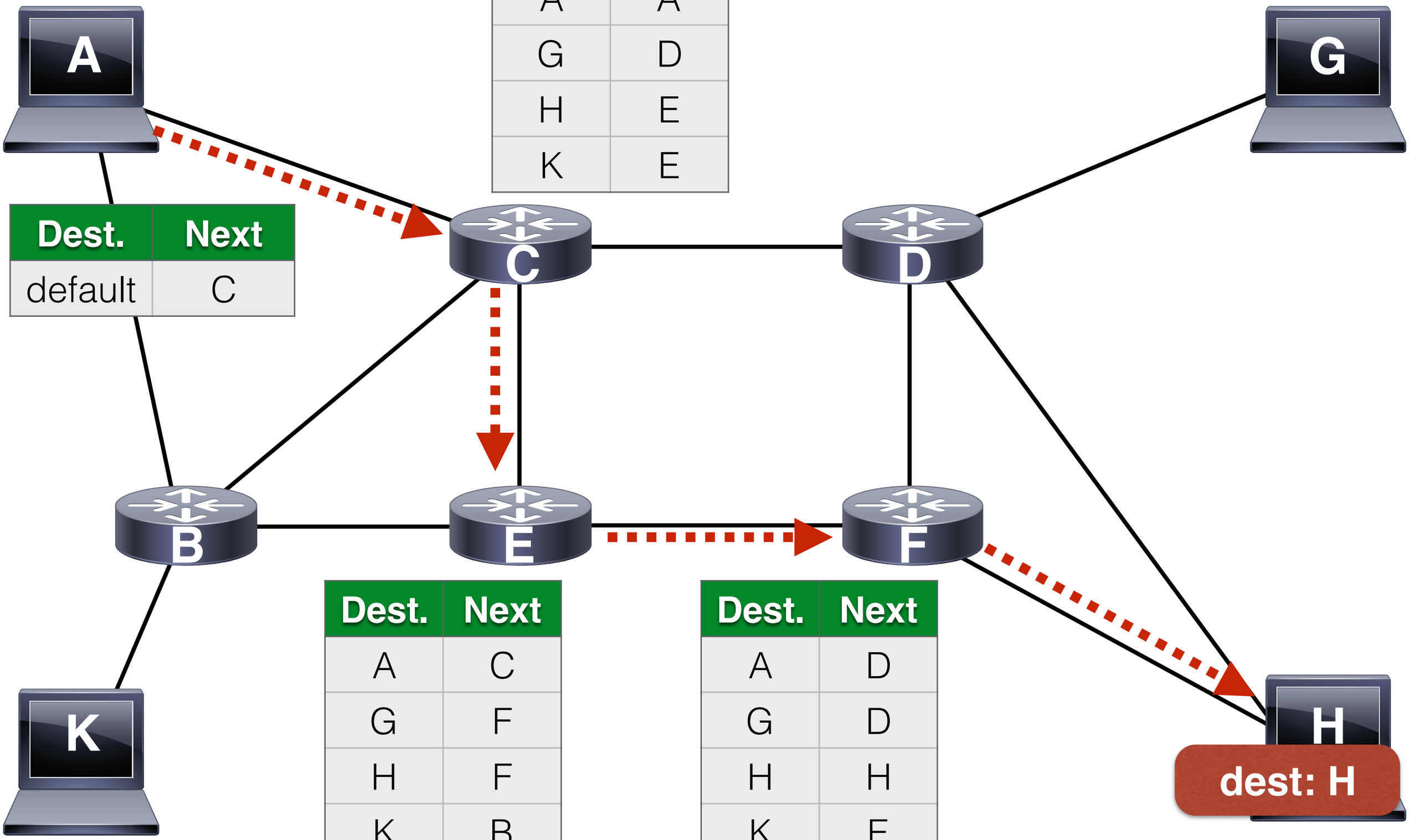

Dest.	Next
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Dest.	Next
A	C
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Dest.	Next
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Routing example

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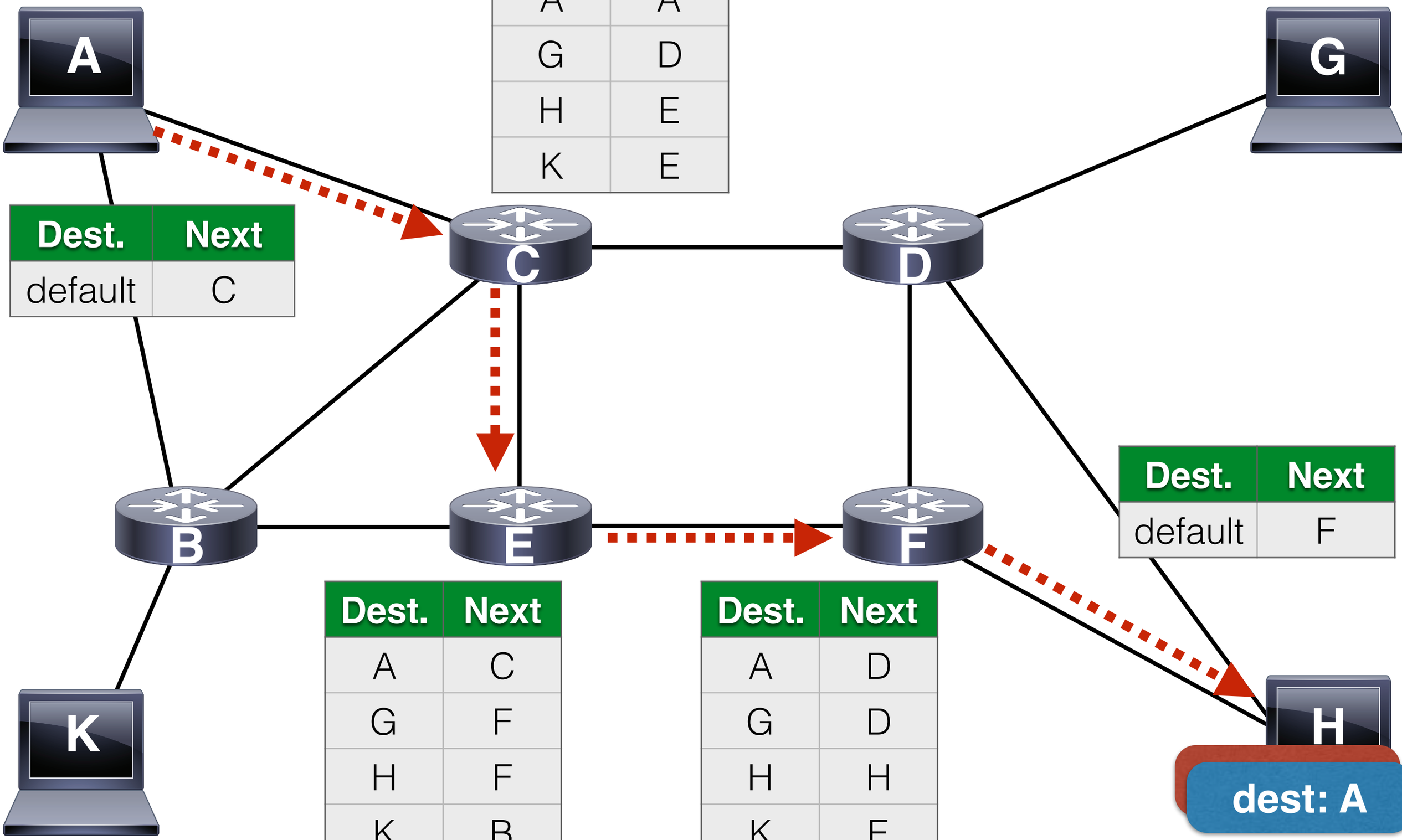

Dest.	Next
default	C

Dest.	Next
A	C
G	F
H	F
K	B

Dest.	Next
A	D
G	D
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K	E

Dest.	Next
default	F

Routing example

Dest.	Next
A	A
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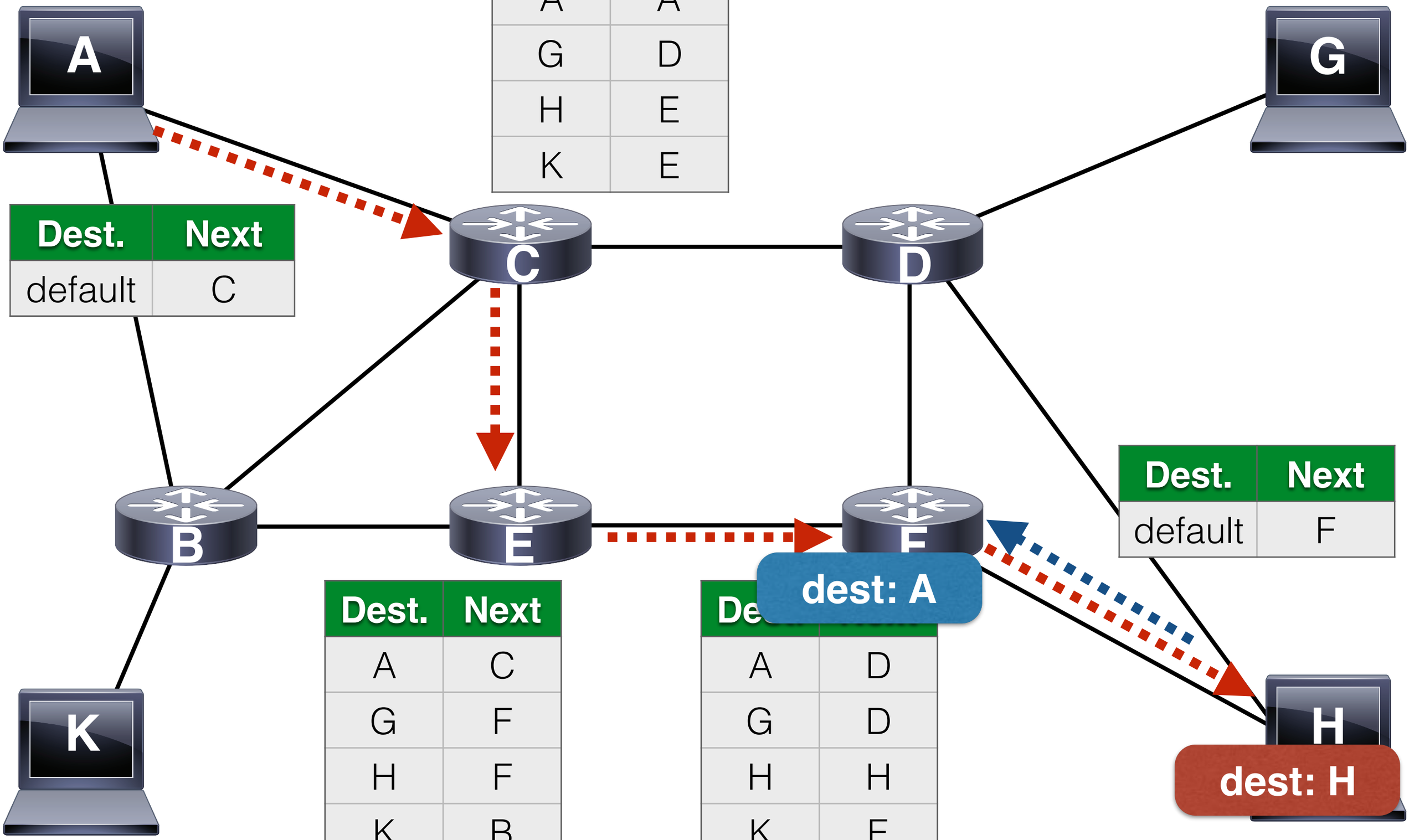

Dest.	Next
default	C

Dest.	Next
A	C
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Dest.	Next
A	D
G	D
H	H
K	E

Dest.	Next
default	F

Routing example

Dest.	Next
A	A
G	D
H	E
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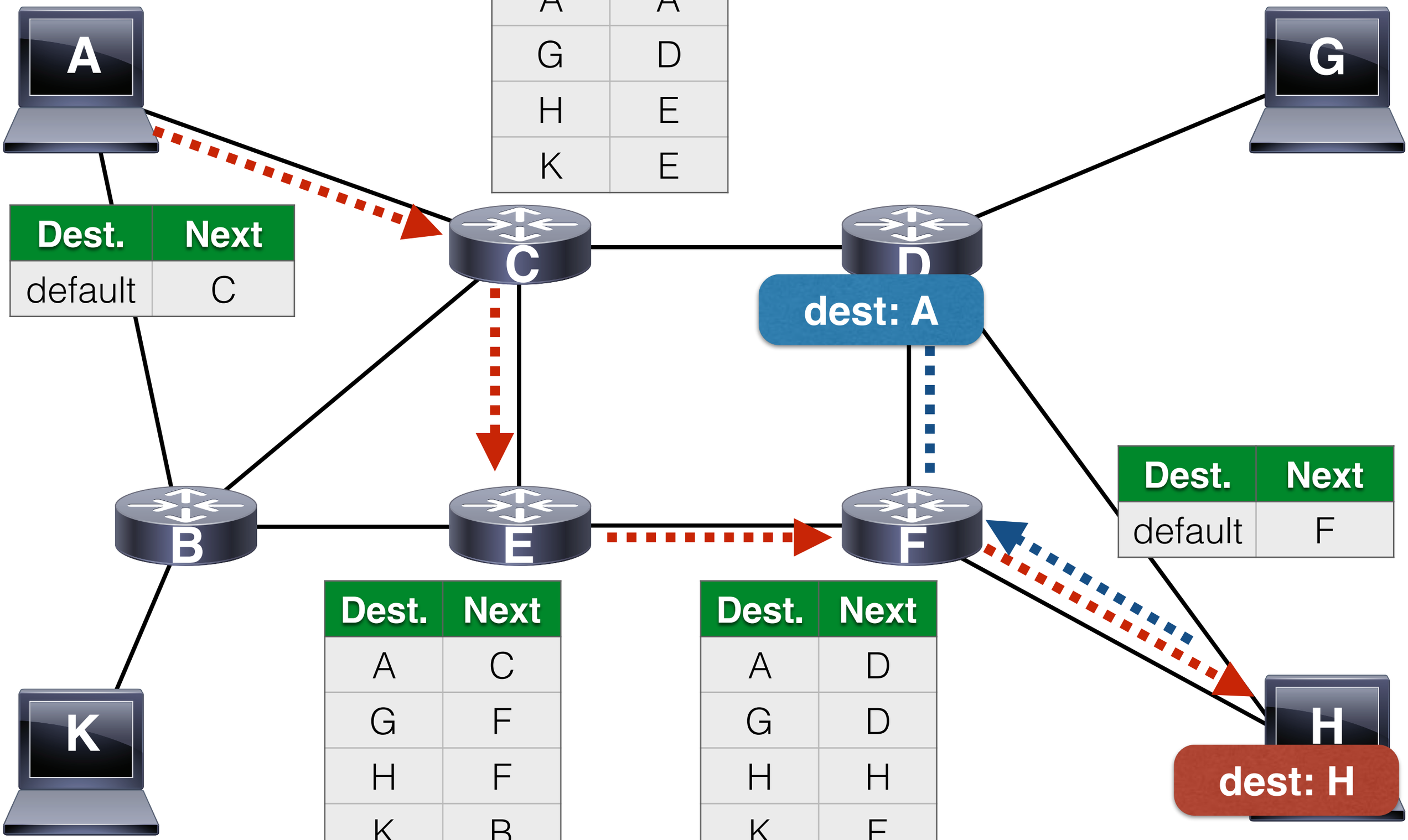

Dest.	Next
default	C

Dest.	Next
default	F

Dest.	Next
A	C
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Dest.	Next
A	D
G	D
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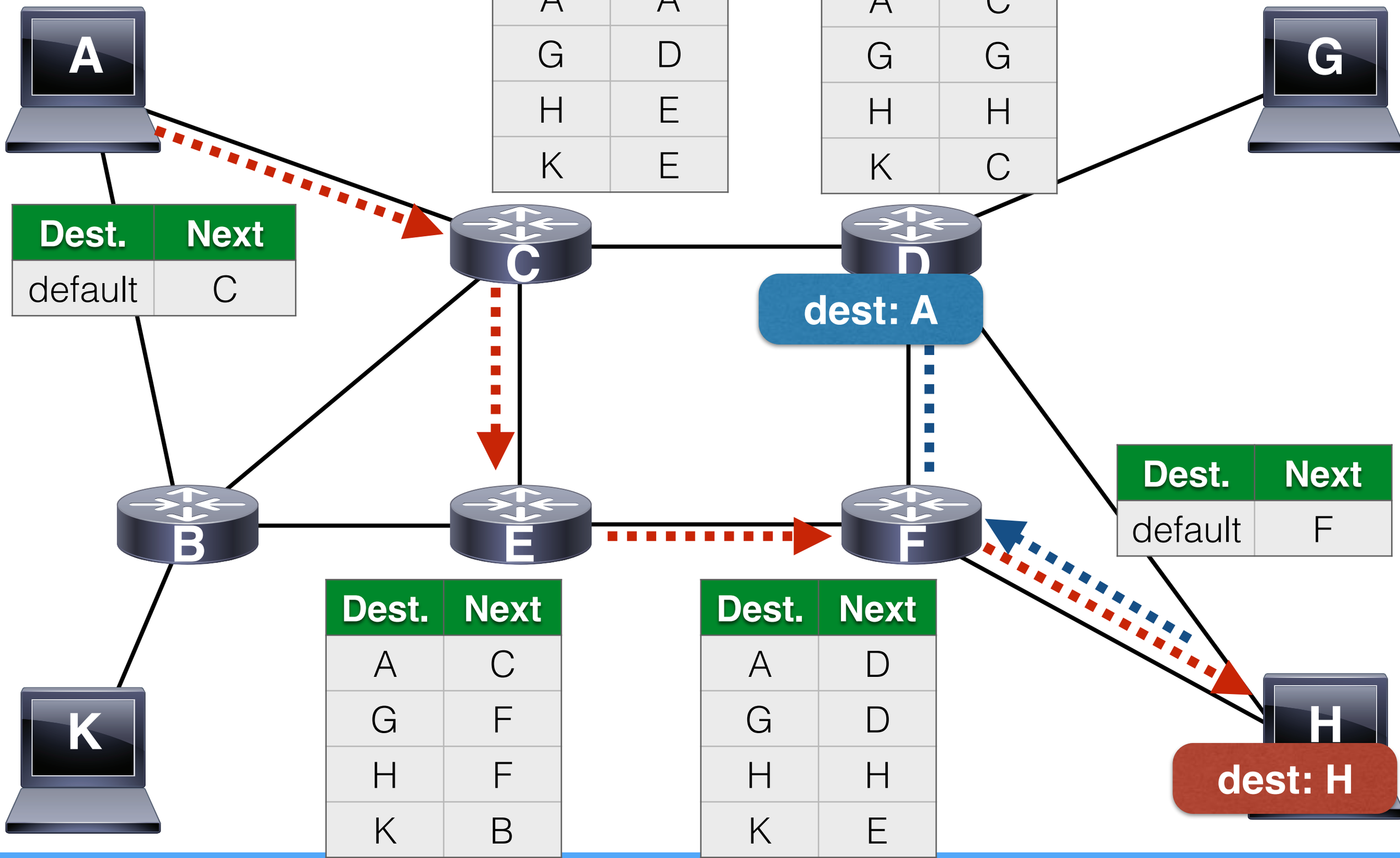
K	E

Routing example



Dest.	Next
default	C

Dest.	Next
A	A
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H	E
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Dest.	Next
A	C
G	G
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K	C

Dest.	Next
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Dest.	Next
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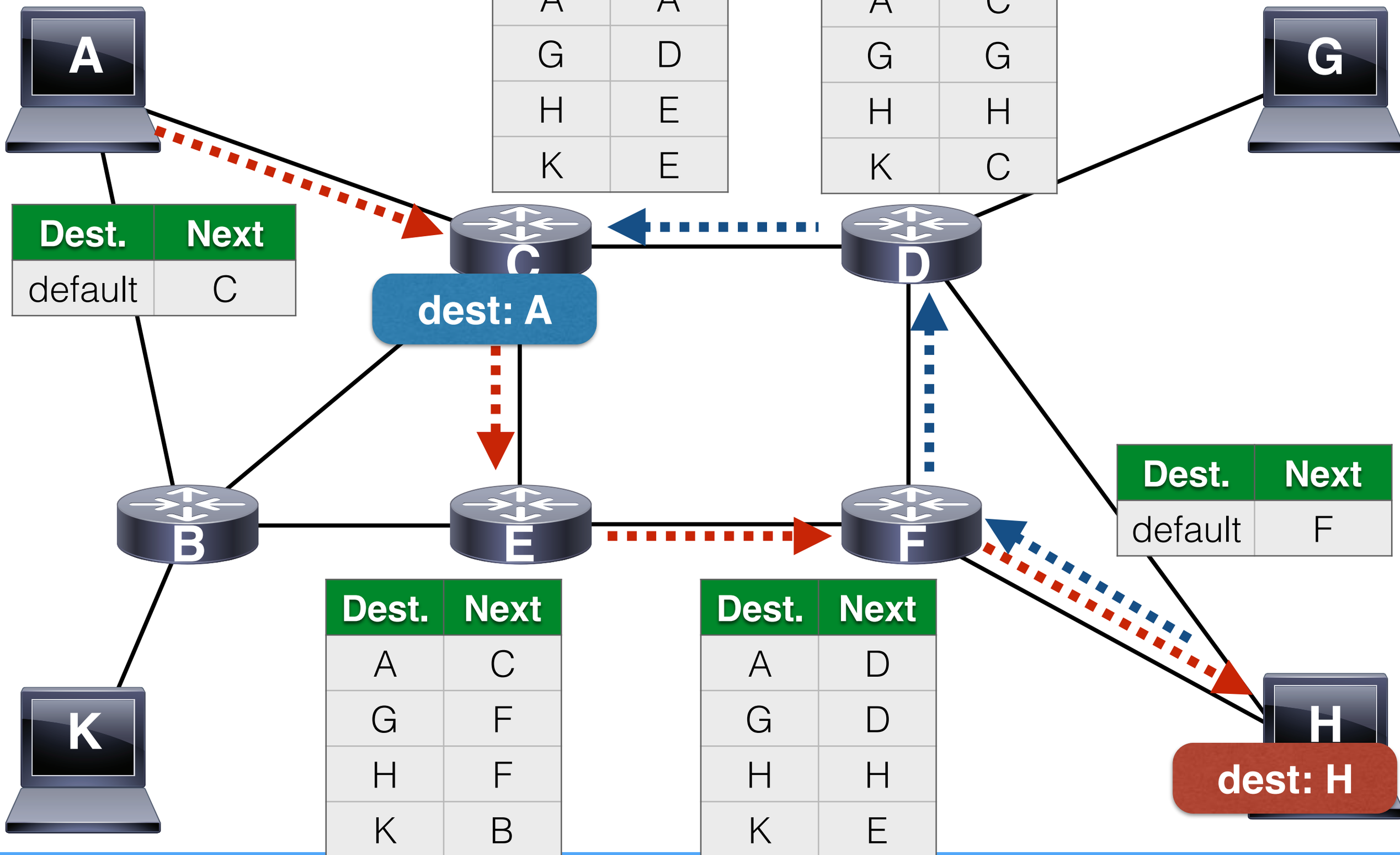
K	E

Dest.	Next
default	F

Routing example



Dest.	Next
A	A
G	D
H	E
K	E

Dest.	Next
A	C
G	G
H	H
K	C

Dest.	Next
default	C

Dest.	Next
A	C
G	F
H	F
K	B

Dest.	Next
A	D
G	D
H	H
K	E

Dest.	Next
default	F

Routing example

dest: A

Dest.	Next
A	A
G	D
H	E
K	E

Dest.	Next
A	C
G	G
H	H
K	C

Dest.	Next
default	C

Dest.	Next
default	F

Dest.	Next
A	C
G	F
H	F
K	B

Dest.	Next
A	D
G	D
H	H
K	E

dest: H

Types of routing

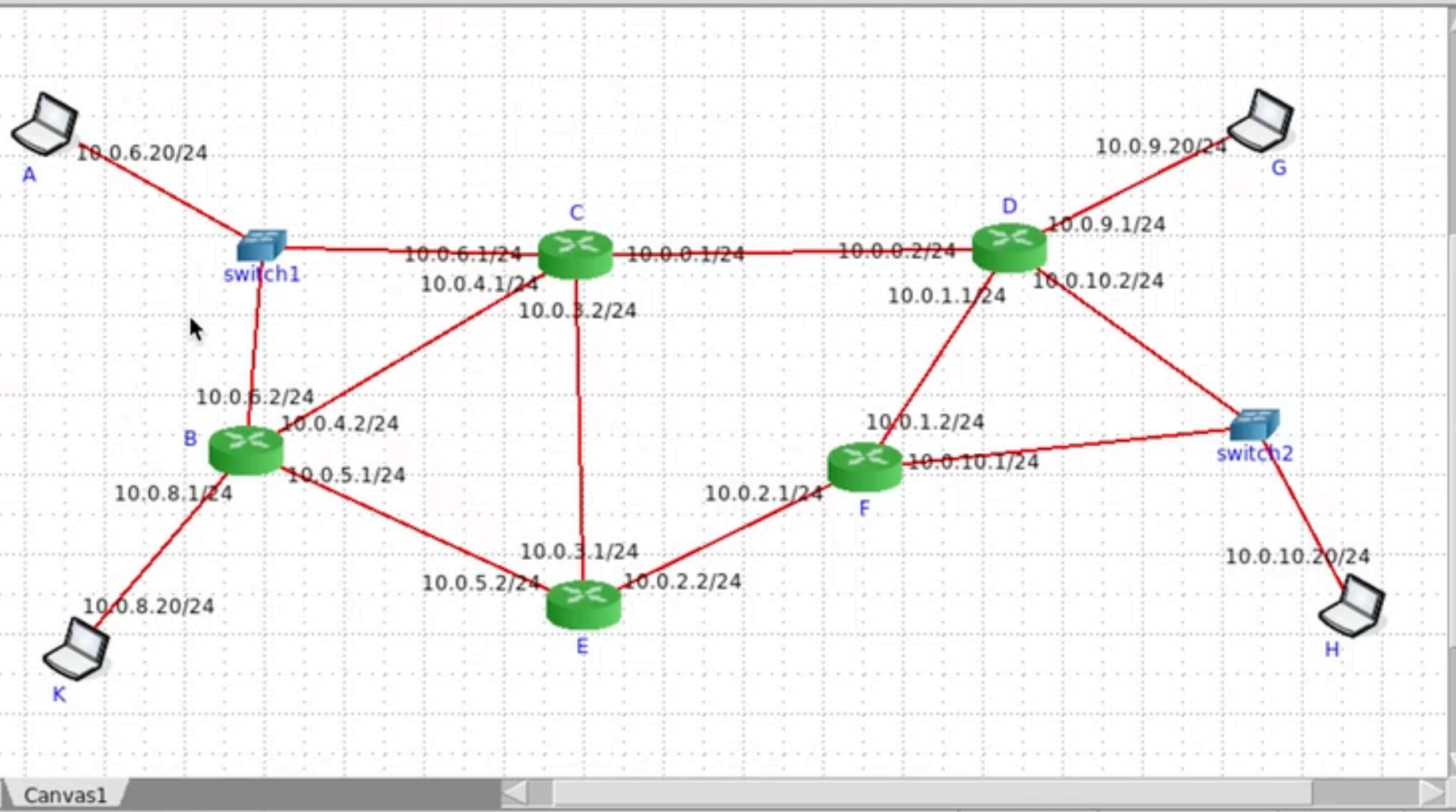
Static routing

- Network manager prepares **fixed routing tables**
- Manually updated when the network changes
- Used in simple networks that don't change a lot

Static routing demo

CORE (60497 on virtual-core) route_static.imn

File Edit Canvas View Tools Widgets Session Help



Canvas1

Cleanup completed in 0 seconds.

zoom 100%

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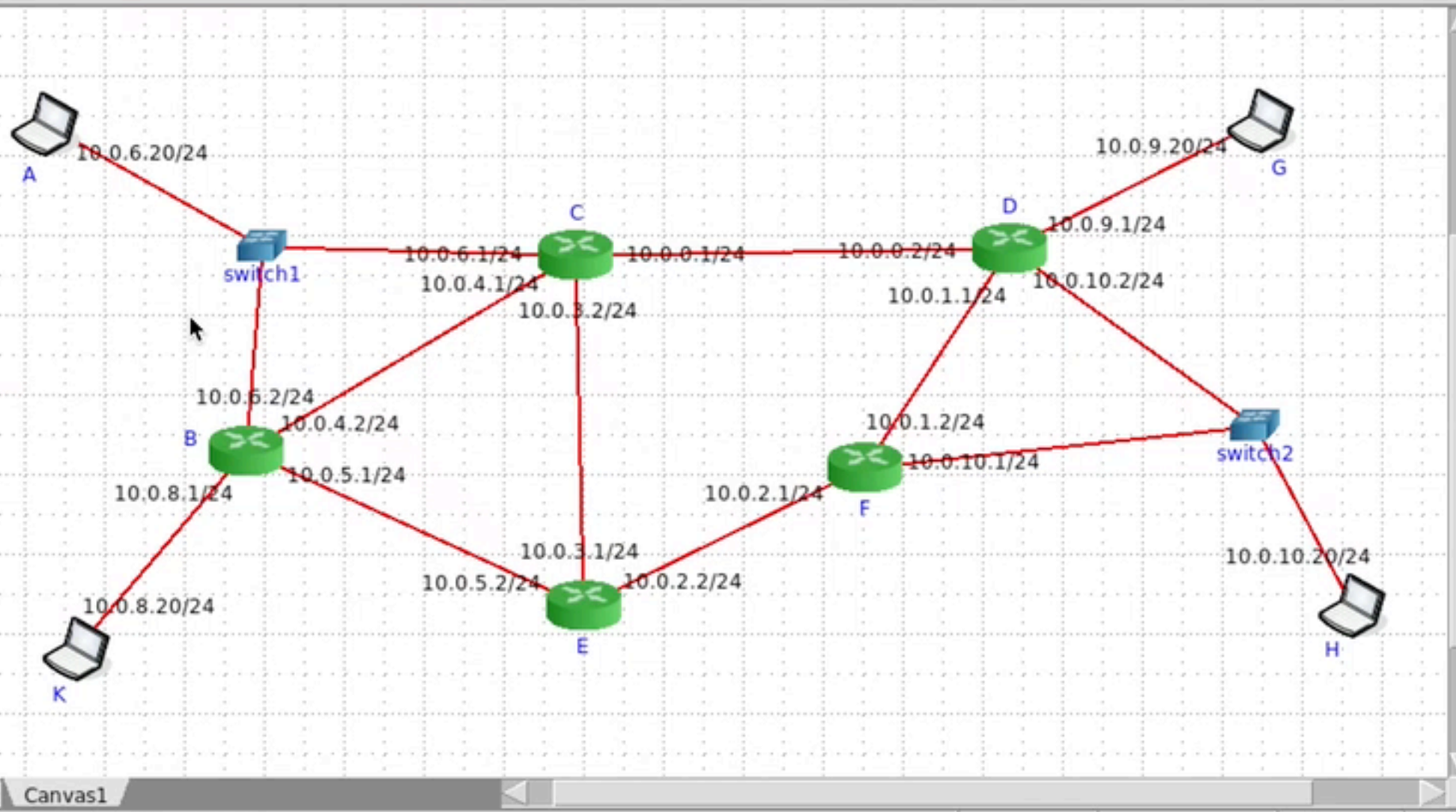

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- Used in simple networks that don't change a lot

Dynamic routing

- Routers **exchange information** to build routing tables **dynamically**
- Initial tables can be set up by network managers

Dynamic routing algorithms

Distance vector

- Exchange information about **distance to destination**, choose **shortest route**
- EIGRP (Enhanced Interior Gateway Routing Protocol)
- RIP (Routing Information Protocol)
- BGP (Border Gateway Protocol)

Dynamic routing algorithms

Distance vector

- Exchange information about **distance to destination**, choose **shortest route**
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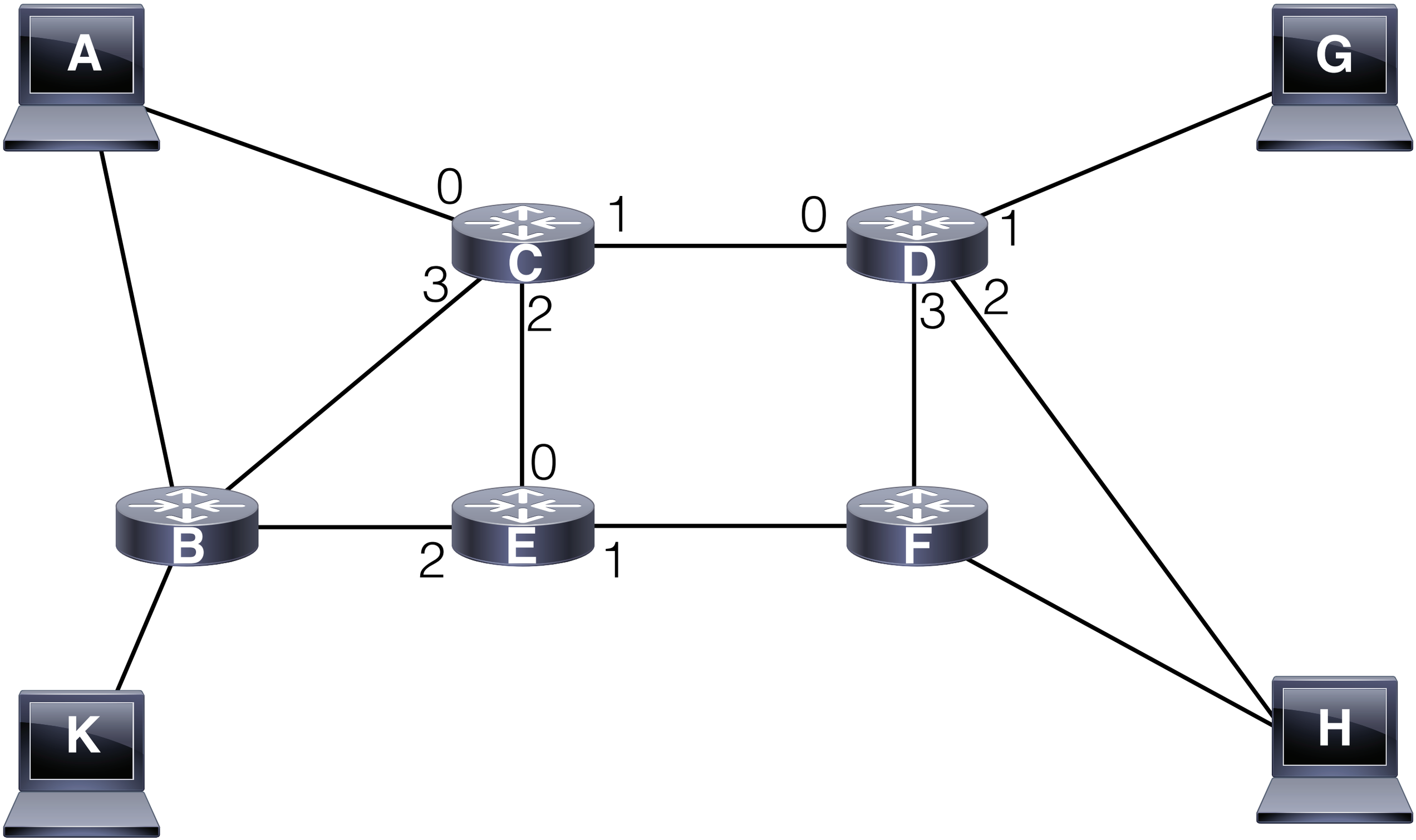
Link state

- Exchange information about **quality of links**, choose **fastest route**
- OSPF (Open Shortest Path First)

Distance vector routing



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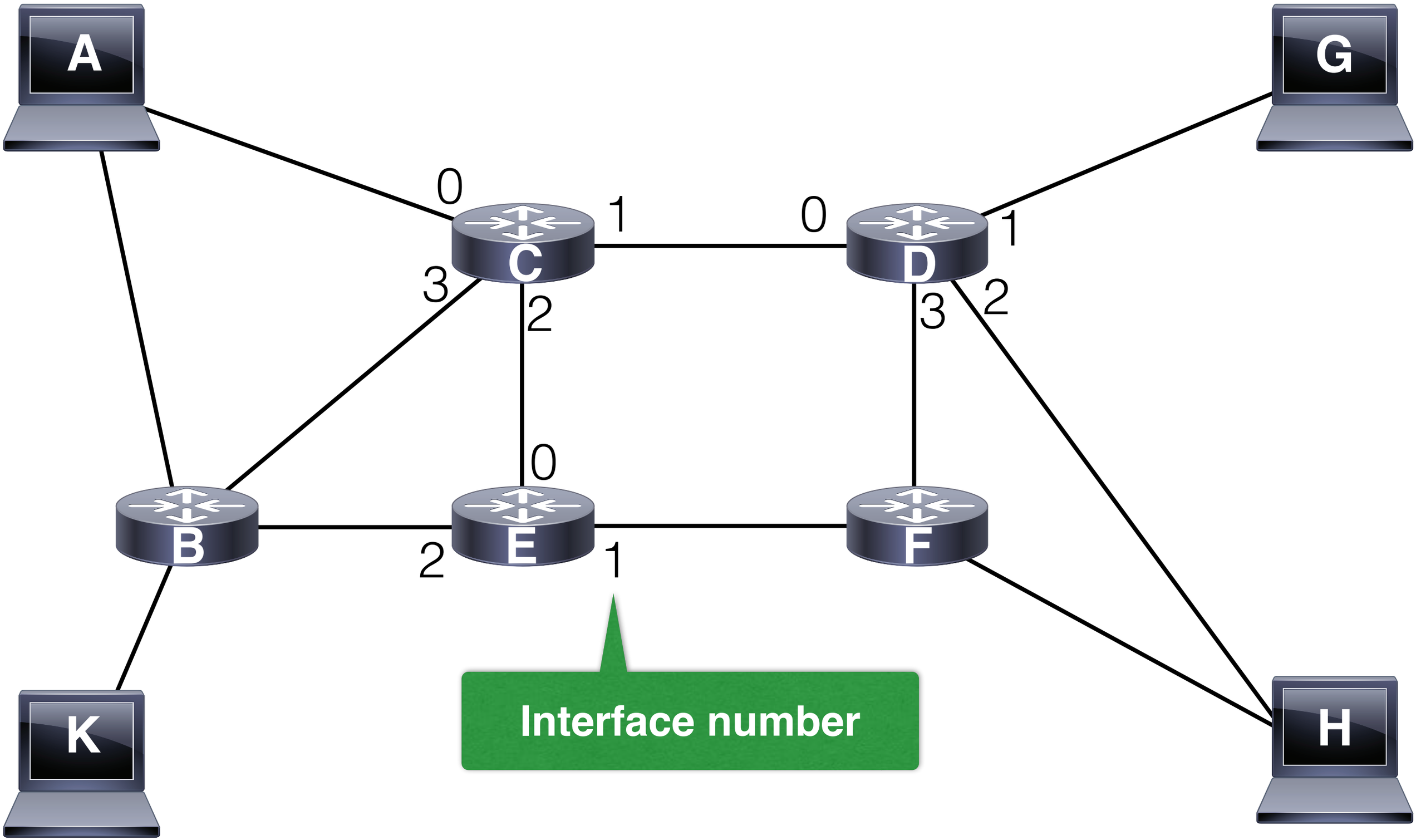

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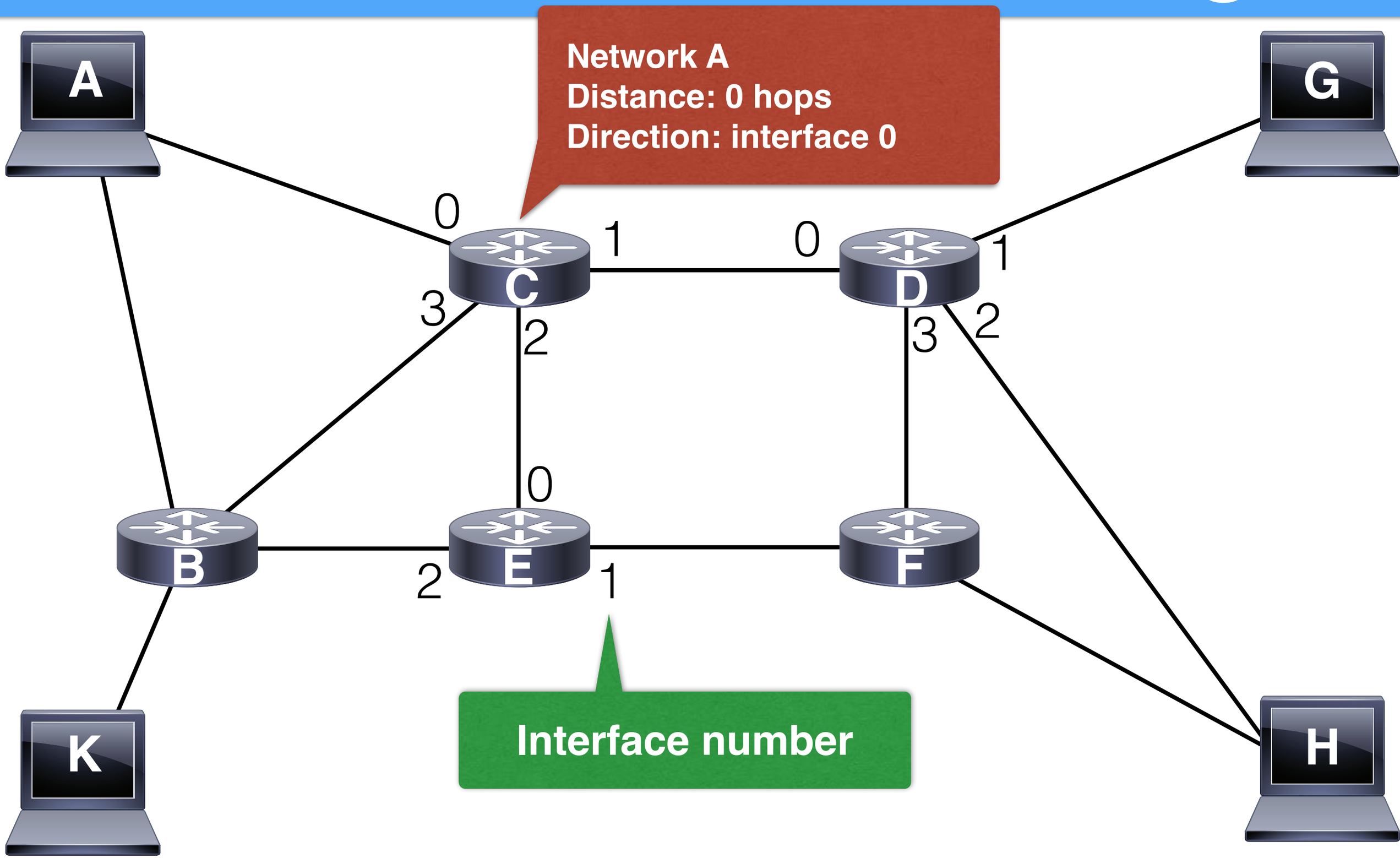

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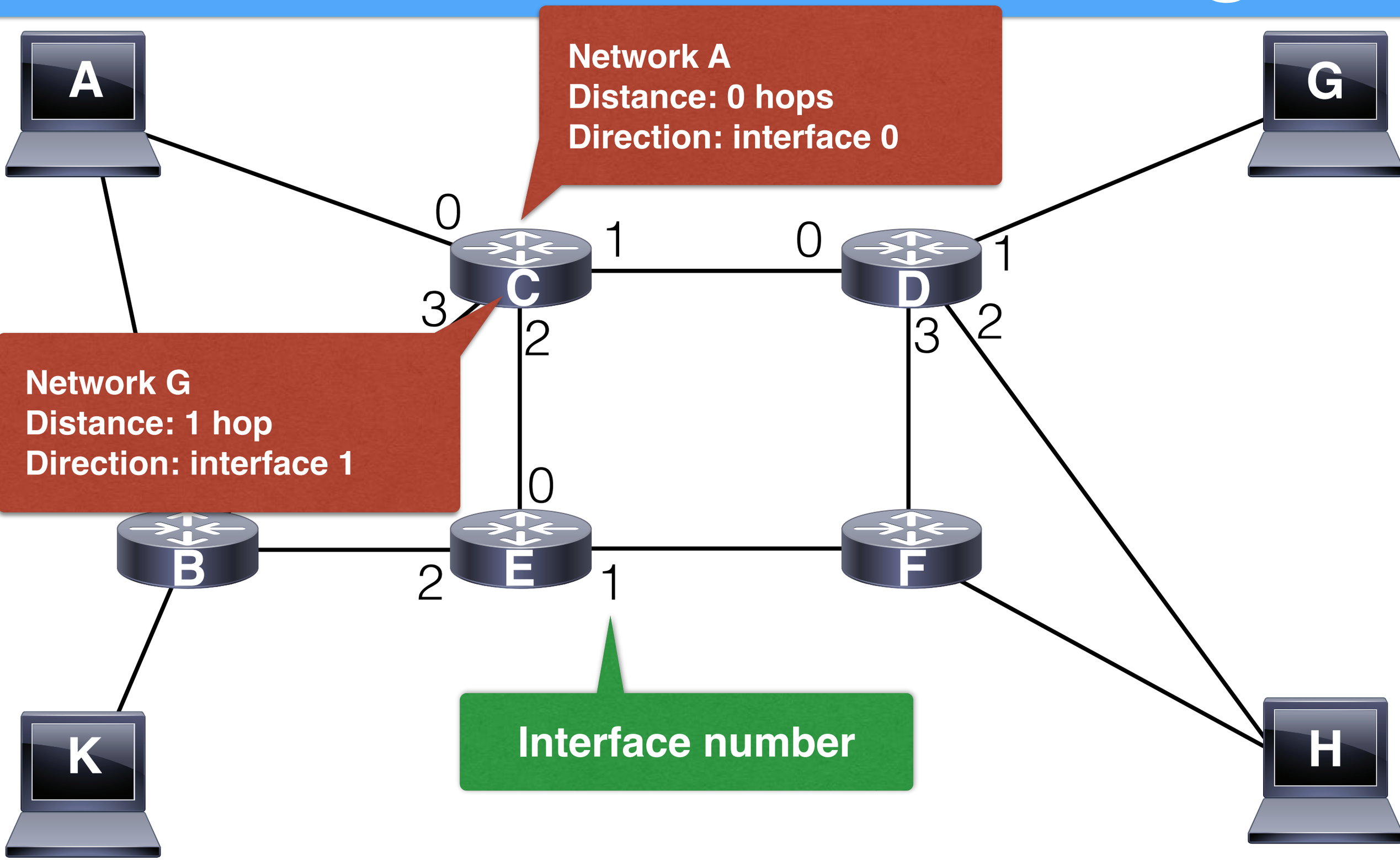

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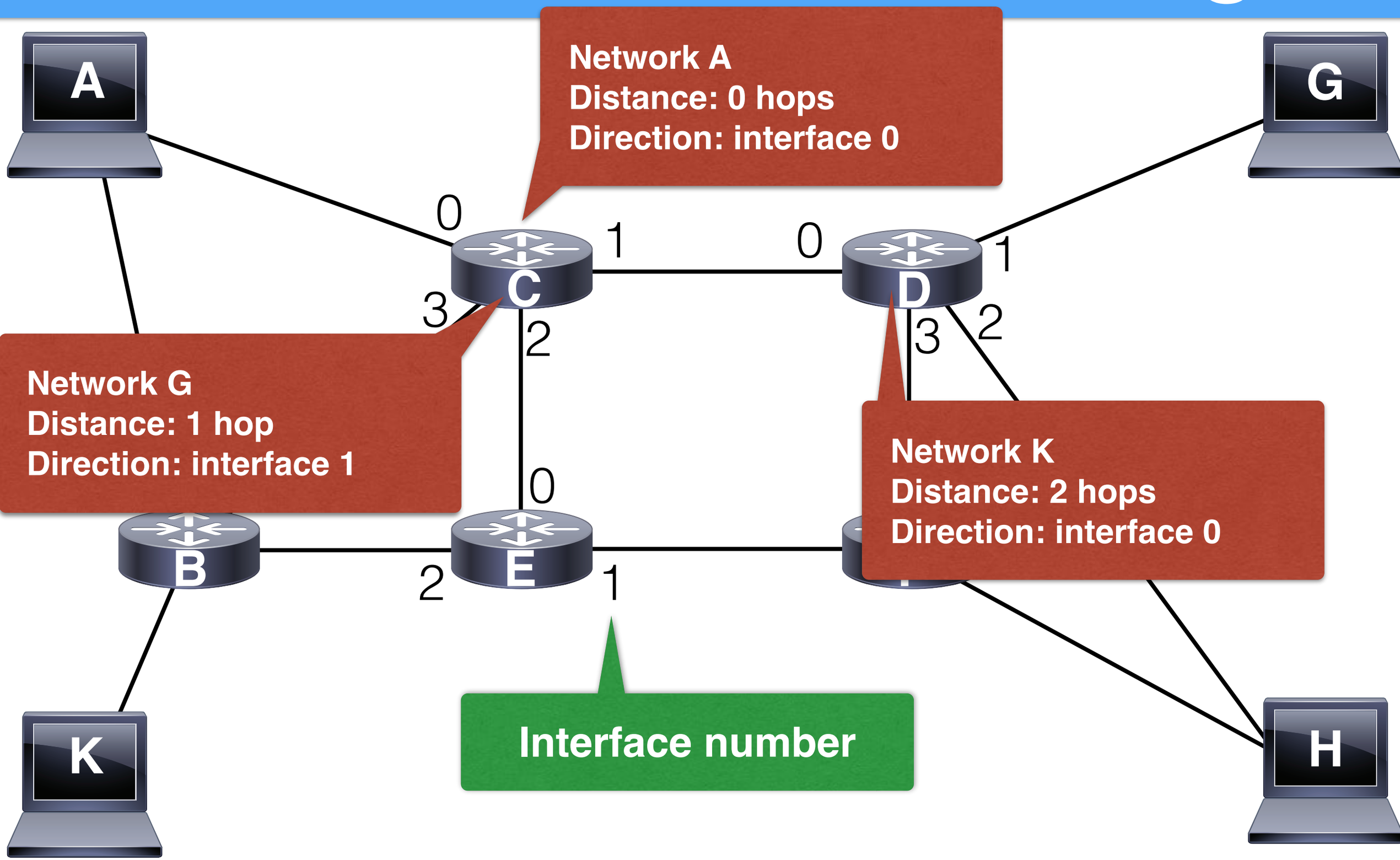
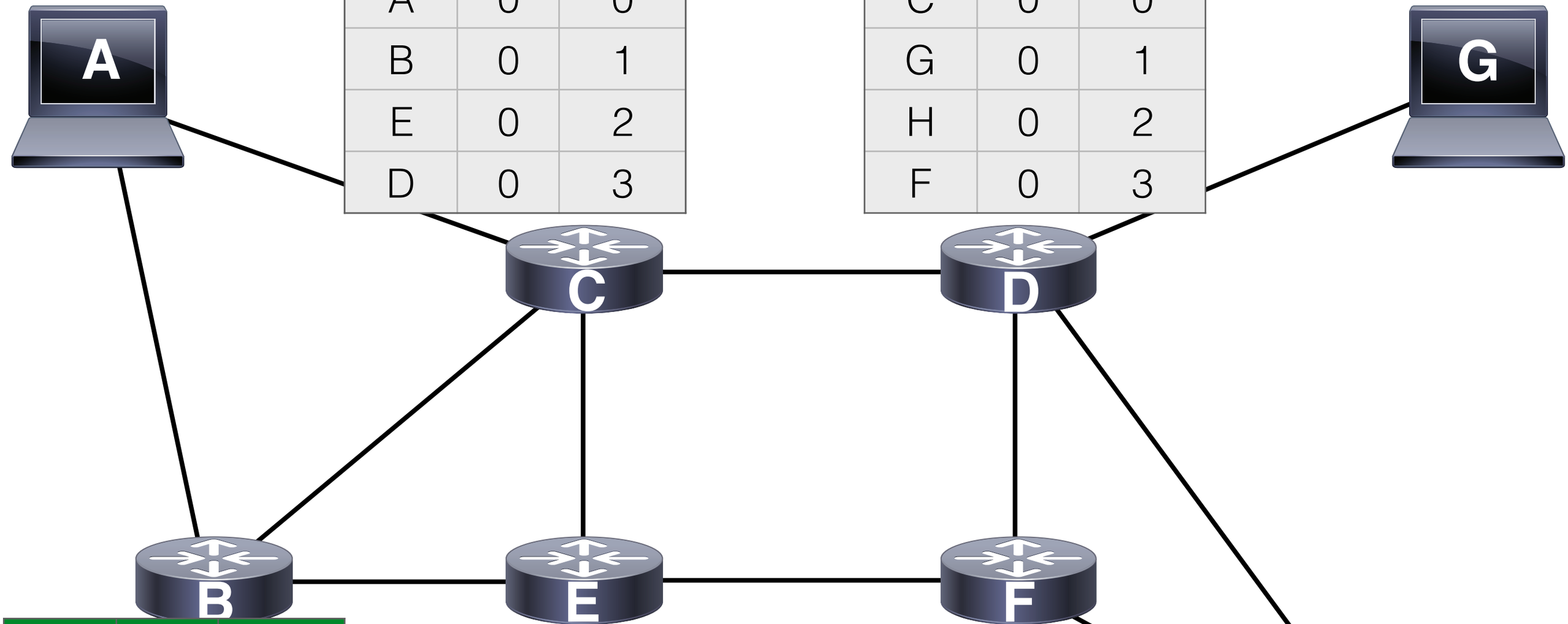


Routing Information Protocol (RIP)

Dest.	Dist.	Interf.
A	0	0
B	0	1
E	0	2
D	0	3

Dest.	Dist.	Interf.
C	0	0
G	0	1
H	0	2
F	0	3



Dest.	Dist.	Interf.
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C	0	1
E	0	2
K	0	3

All routers send their routing tables to all other routers.

Tables converge after some time.

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Dest.	Dist.	Interf.
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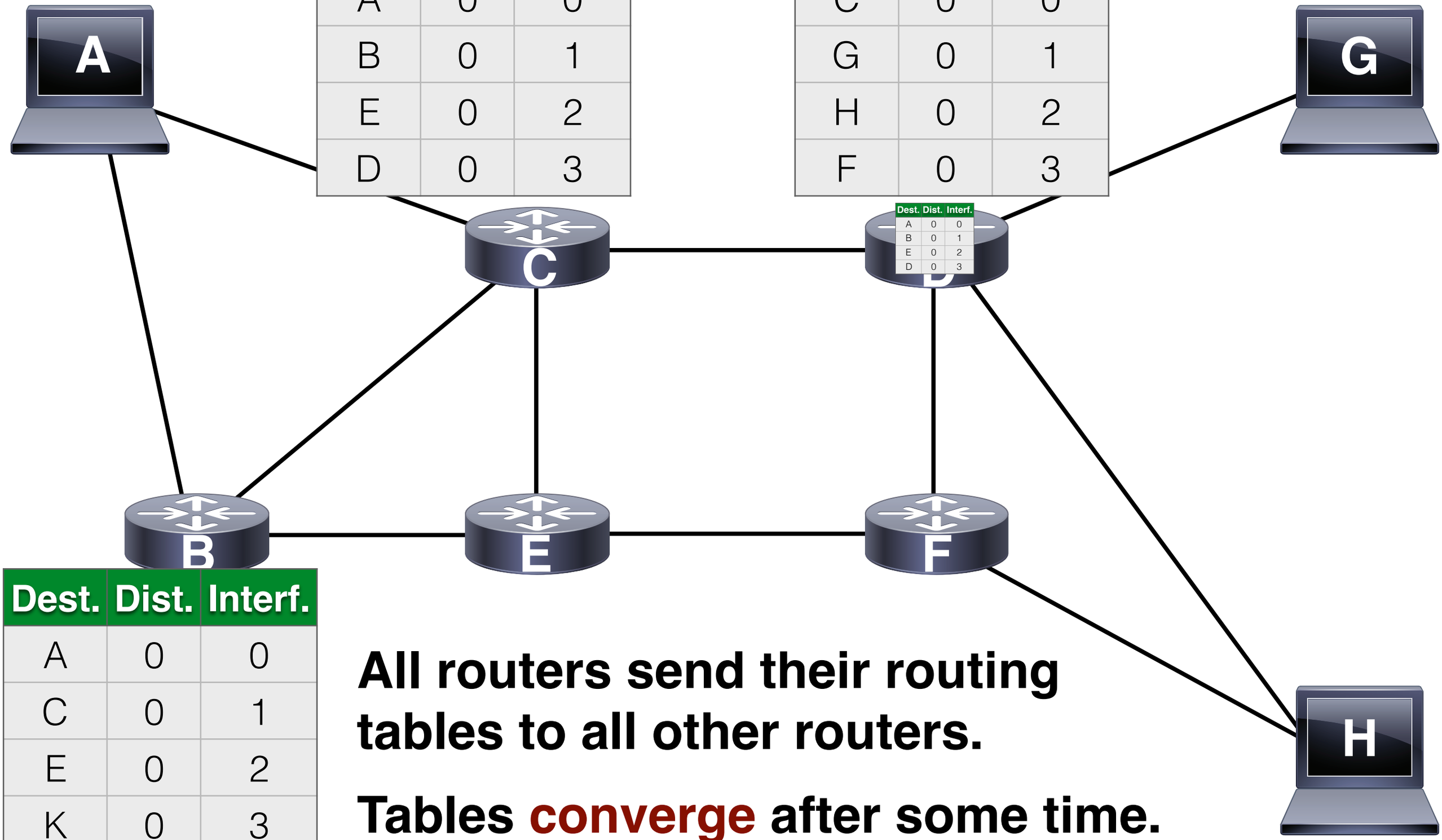

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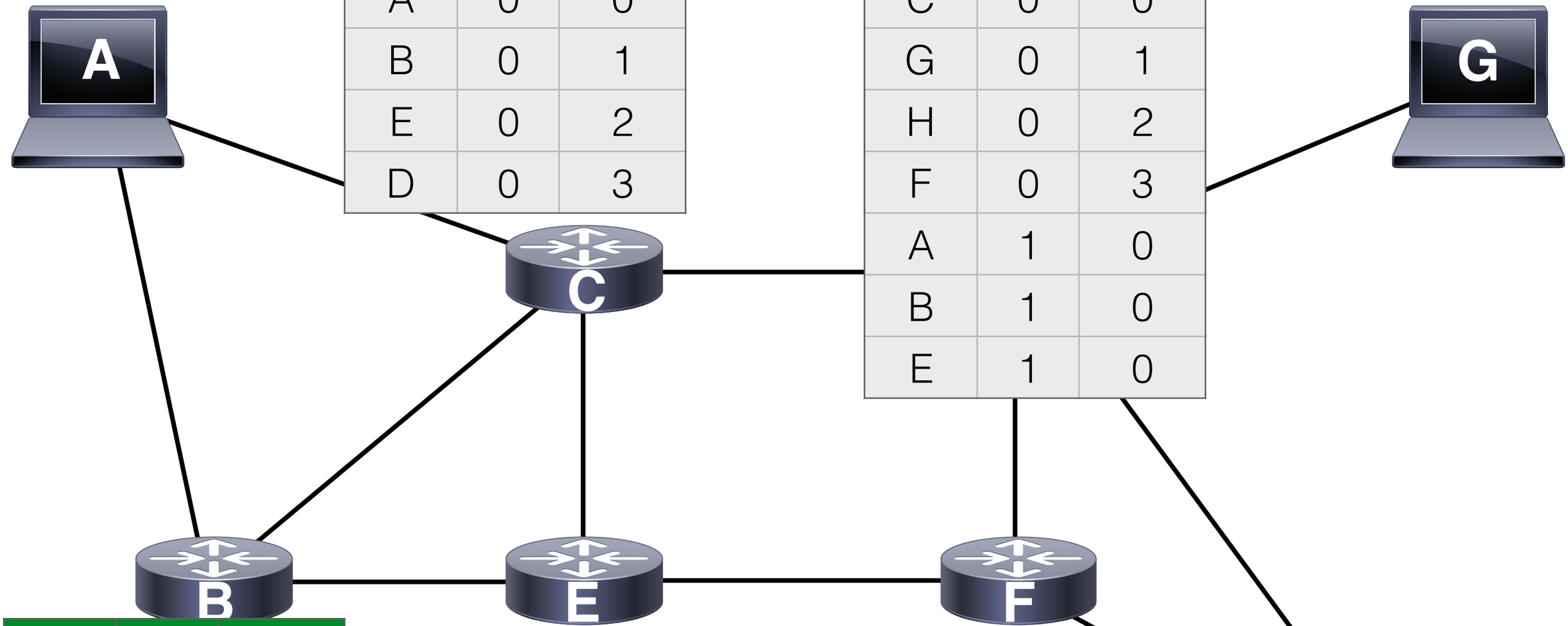

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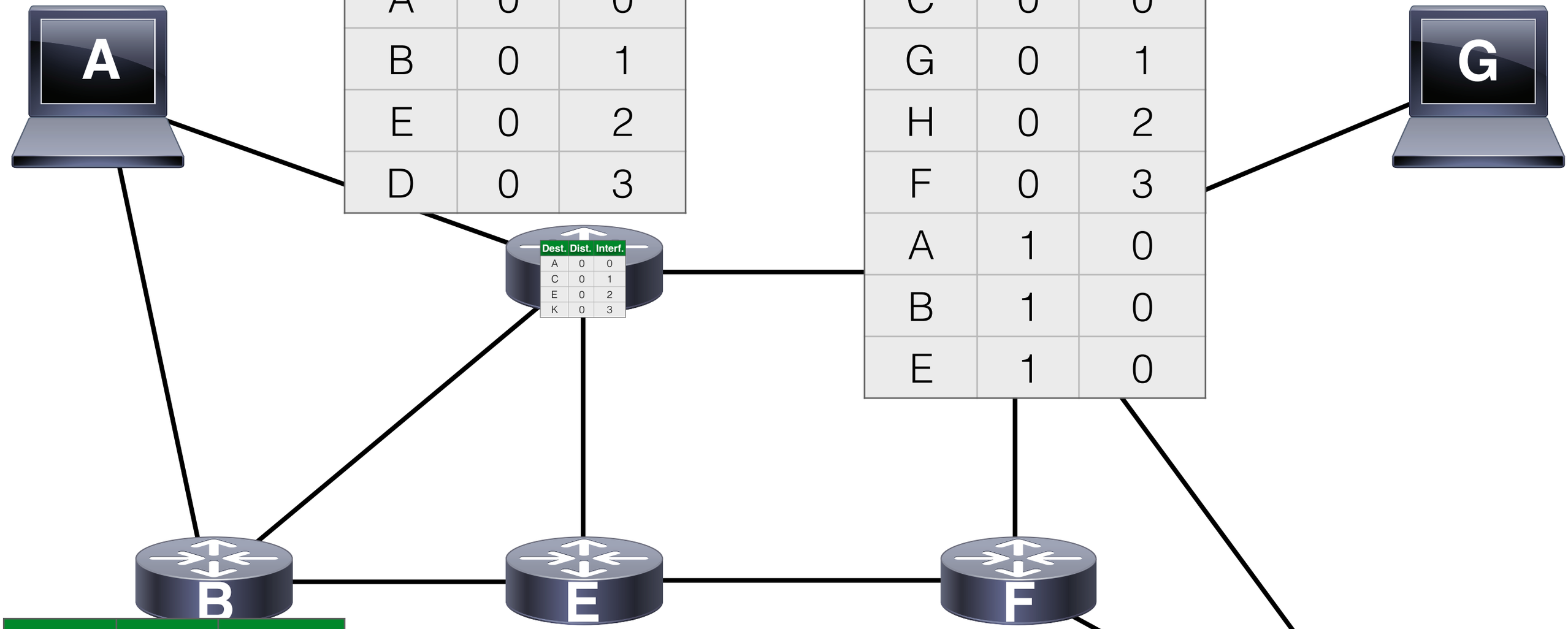

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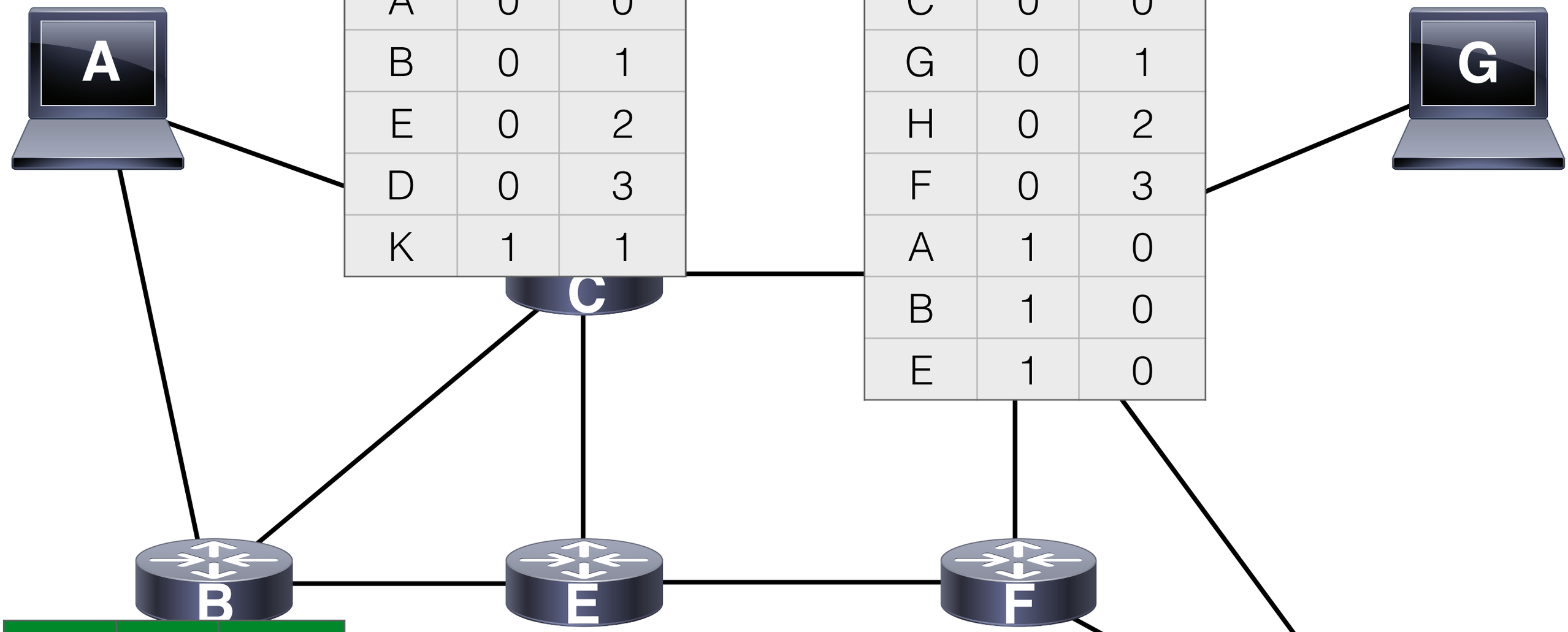

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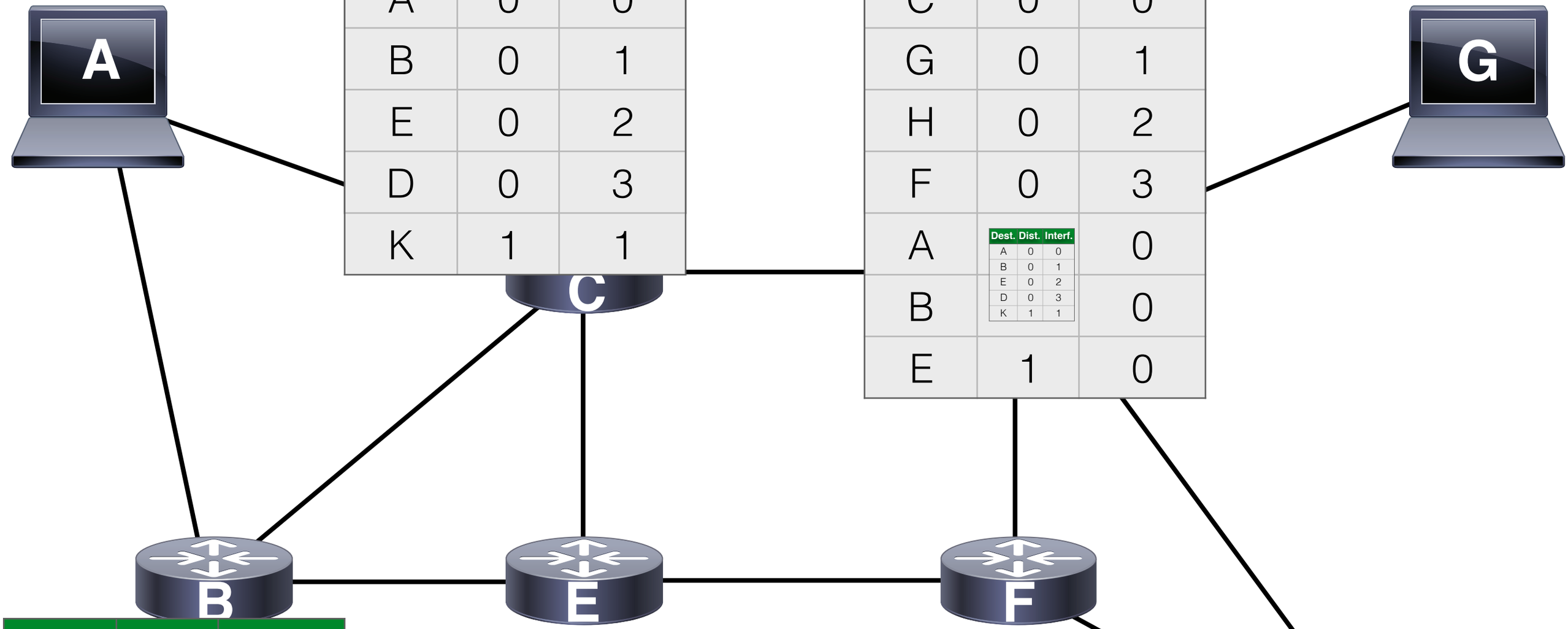
Tables converge after some time.

Routing Information Protocol (RIP)

Dest.	Dist.	Interf.
A	0	0
B	0	1
E	0	2
D	0	3
K	1	1

Dest.	Dist.	Interf.
C	0	0
G	0	1
H	0	2
F	0	3
A	Dest. Dist. Interf. A 0 0 B 0 1 E 0 2 D 0 3 K 1 1	0
B		0
E	1	0



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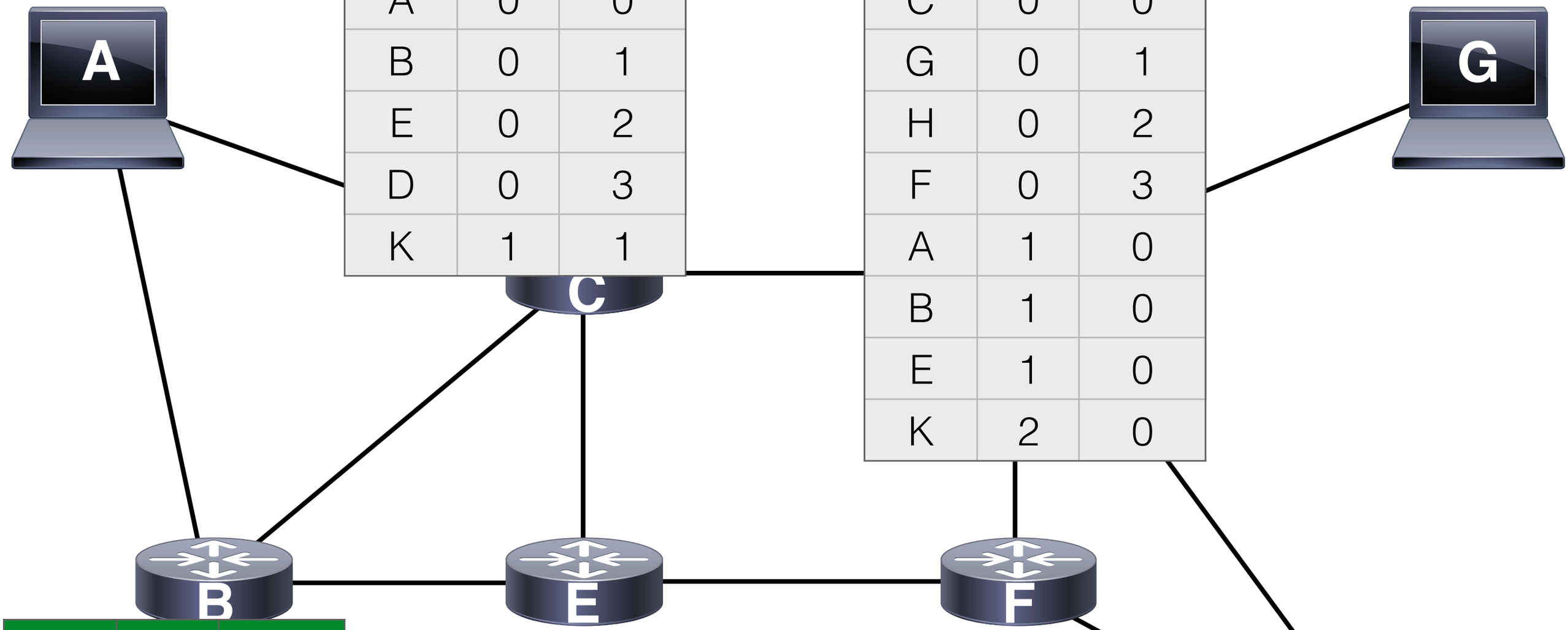

Dest.	Dist.	Interf.
A	0	0
B	0	1
E	0	2
D	0	3
K	1	1

Dest.	Dist.	Interf.
C	0	0
G	0	1
H	0	2
F	0	3
A	1	0
B	1	0
E	1	0
K	2	0

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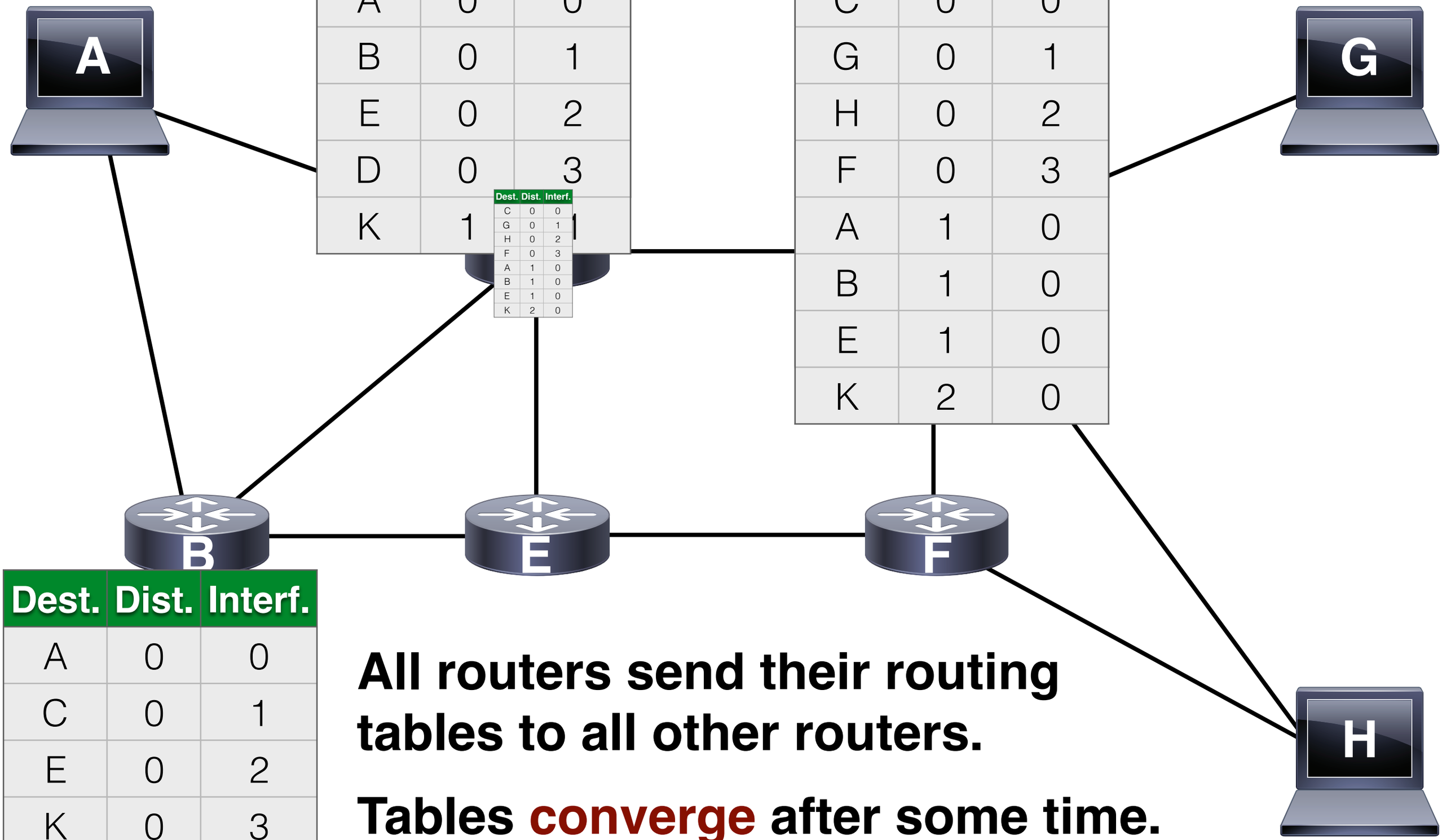

Dest.	Dist.	Interf.
A	0	0
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C	0	0
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Dest.	Dist.	Interf.
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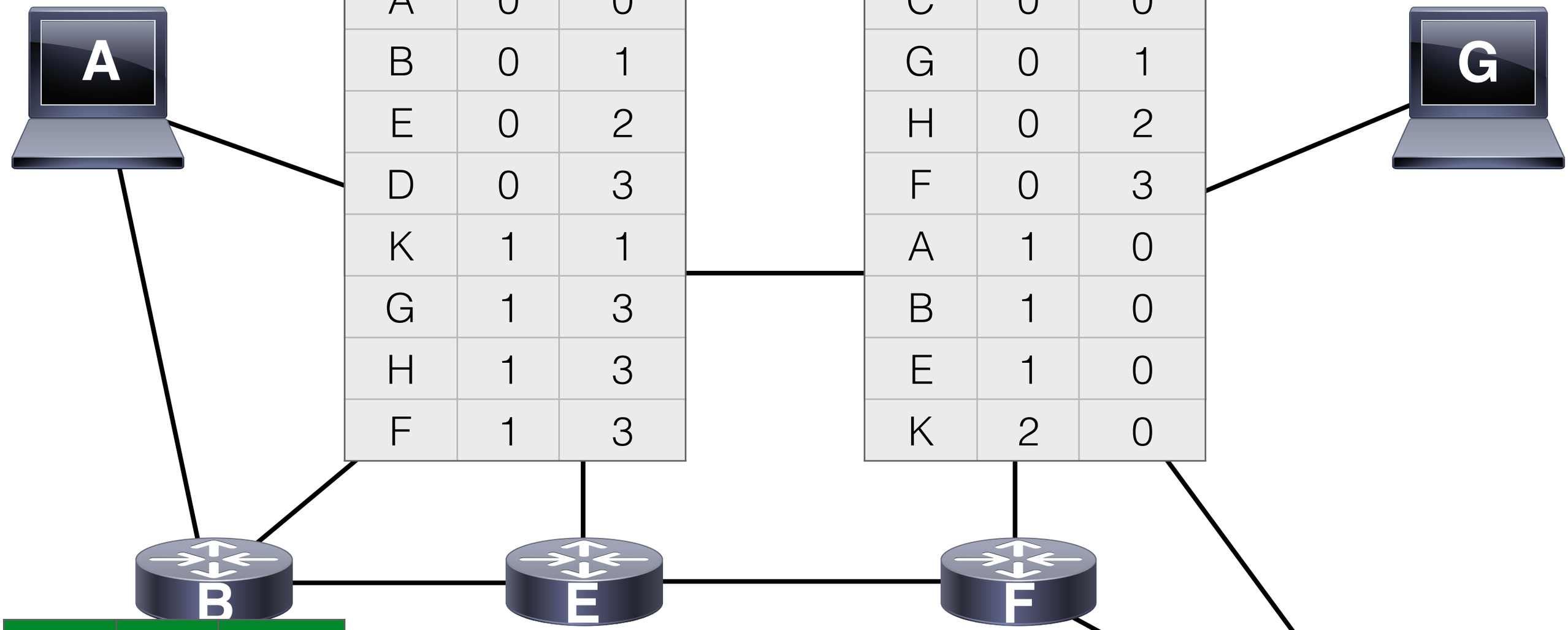

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A	0	0
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F	1	3

Dest.	Dist.	Interf.
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G	0	1
H	0	2
F	0	3
A	1	0
B	1	0
E	1	0
K	2	0

Dest.	Dist.	Interf.
A	0	0
C	0	1
E	0	2
K	0	3

All routers send their routing tables to all other routers.

Tables converge after some time.

Routing Information Protocol (RIP)

Distance = hop count

- Max. hop count 15
- Avoids loops

Only used in small networks

- At most 15 hops
- Updates transmit whole routing table
- Can be slow to converge

Link-state routing

Link-state routing

Routers exchange information about connectivity

- not just routing table (best routes)
- but **all** of the network it knows about
- use a **metric** (usually link speed) to describe the **quality** of each connection
- each router can **independently** compute best route to every subnet

Link-state routing

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- each router can **independently** compute best route to every subnet

Most common protocol: OSPF
(video available on Moodle in case you're interested)

Transport Layer

Transmission Control Protocol (TCP)

Connection-oriented

- A **virtual circuit** is established between two devices
- To the application it always looks like a **point-to-point full duplex** connection
- Messages split into **segments** for transmission

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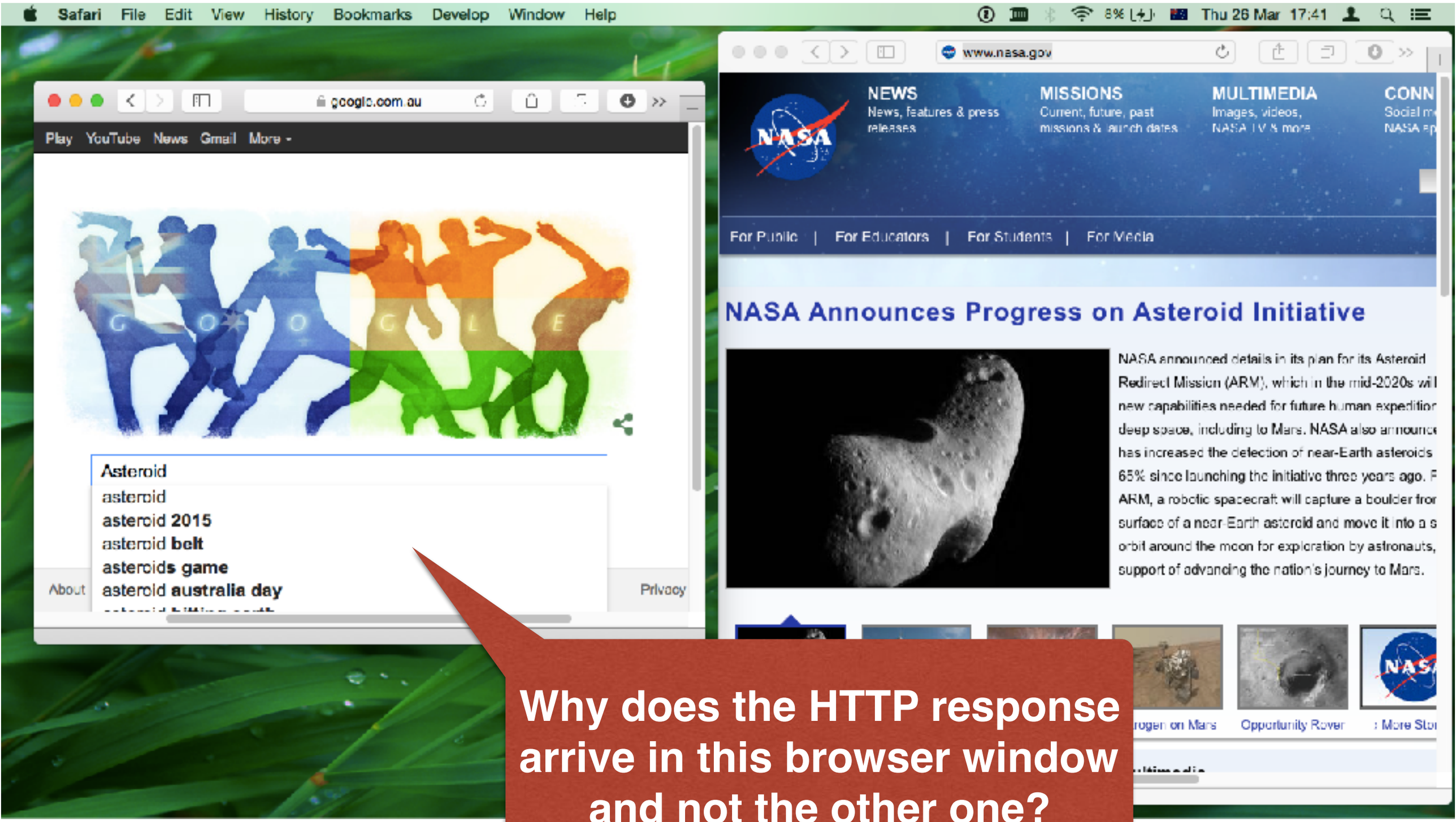
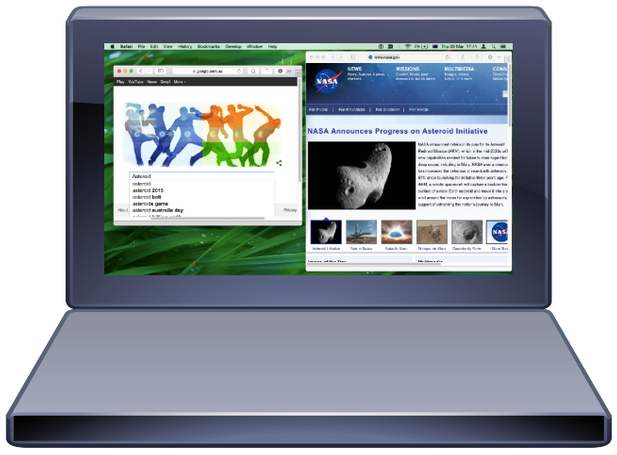
Used by e.g. HTTP, SMTP, IMAP, SSH

Addressing applications



Why does the HTTP response arrive in this browser window and not the other one?

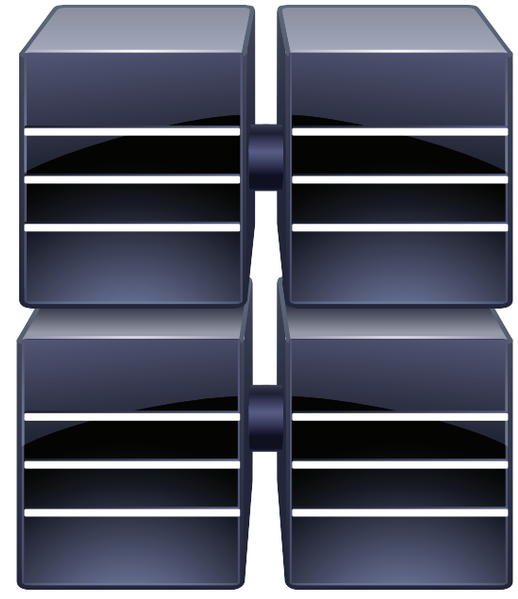
Addressing applications



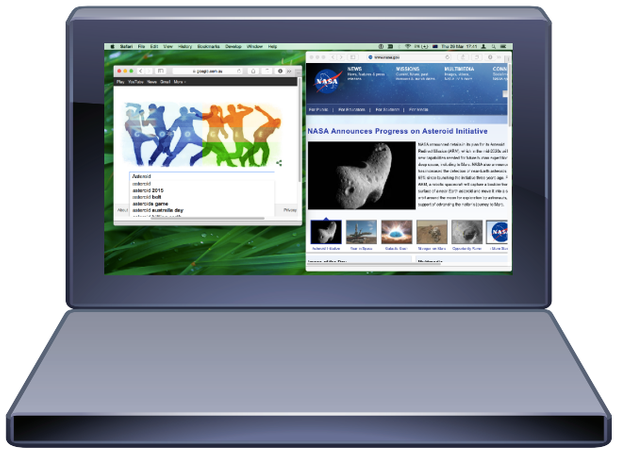
130.194.77.37

http://www.google.com.au

216.58.220.99

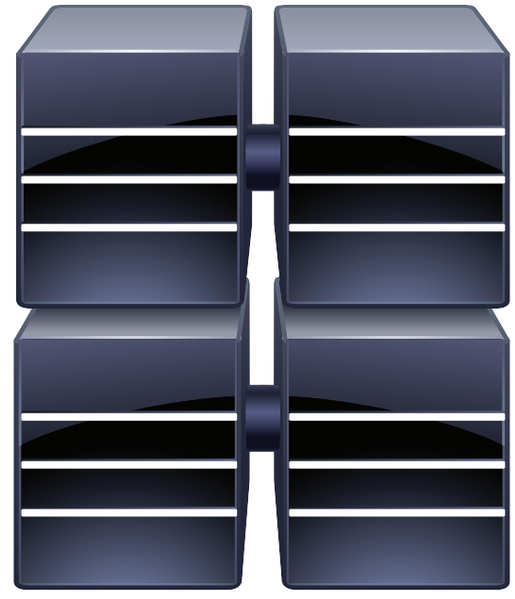


Addressing applications



http://www.google.com.au

216.58.220.99:80



130.194.77.37:57017

Addressing applications

http://www.google.com.au

216.58.220.99:80

Random client port, one per connection

130.194.77.37:57017

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Fixed server port (80 = HTTP)

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216.58.220.99:80

Random client port, one per connection

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130.194.77.37:57017

130.194.77.37:57018

111.119.8.38:80

http://www.nasa.gov

Addressing applications

Random client port, one per connection

http://www.google.com.au

216.58.220.99:80

Fixed server port (80 = HTTP)

130.194.77.37:57017

130.194.77.37:57018

130.194.77.37:57019

130.194.11.146:25

smtp.monash.edu

111.119.8.38:80

http://www.nasa.gov

Addressing applications

http://www.google.com.au

216.58.220.99:80

Random client port, one per connection

Fixed server port (80 = HTTP)

130.194.77.37:57017

130.194.77.37:57018

130.194.77.37:57019

130.194.11.146:25

smtp.monash.edu

Fixed server port (25 = SMTP)

111.119.8.38:80

http://www.nasa.gov

One address per layer

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Application Layer

- URL (e.g. http://www.csse.monash.edu)

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Transport Layer (TCP)

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- identifies the application that handles a message

Network Layer (IP)

- IP address (e.g. 130.194.66.43)
- used for identifying devices across networks

Data Link Layer (Ethernet)

- MAC address (e.g. 00:23:ae:e7:52:85)
- used for sending frames in a LAN

TCP ARQ

Error control

- Data Link Layer **discards** frames that have errors
- Frames may not arrive at all
- But TCP should be a **reliable channel!**

TCP ARQ

Error control

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- Frames may not arrive at all
- But TCP should be a **reliable channel!**

Solution: Automatic **R**epeat Re**Q**uest

- Exchange **acknowledgements (ACK)**, letting sender know that packets were received correctly
- Sender re-transmits if no ACK within certain time

TCP ARQ

When we send a TCP packet, it includes two numbers.

Sequence number:

- how many bytes we've already transmitted (before this one)

Acknowledgement number:

- how many bytes we've received from the other side

Sender can therefore check how many bytes have been received correctly!

Establishing a connection

Three-way handshake:

Establishing a connection

Three-way handshake:

- Client sends a **SYN** packet with **random sequence number *A***

Establishing a connection

Three-way handshake:

- Client sends a **SYN** packet with **random sequence number *A***
- Server replies with **SYN, ACK, acknowledgement number *A+1,*** and **random sequence number *B***

Establishing a connection

Three-way handshake:

- Client sends a **SYN** packet with **random sequence number *A***
- Server replies with **SYN, ACK, acknowledgement number *A+1,*** and **random sequence number *B***
- Client sends **ACK** with **sequence number *A+1*** and **acknowledgement number *B+1***

Closing a connection

Four-way handshake:

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet
- Computer B acknowledges with an **ACK**

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet
- Computer B acknowledges with an **ACK**
- Computer B sends a **FIN** packet

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet
- Computer B acknowledges with an **ACK**
- Computer B sends a **FIN** packet
- Computer A acknowledges with an **ACK**

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet
- Computer B acknowledges with an **ACK**
- Computer B sends a **FIN** packet
- Computer A acknowledges with an **ACK**
- **Can be simplified to three-way** (combining a FIN/ACK)

Closing a connection

Four-way handshake:

- Computer A (client or server!) sends a **FIN** packet
- Computer B acknowledges with an **ACK**
- Computer B sends a **FIN** packet
- Computer A acknowledges with an **ACK**
- **Can be simplified to three-way** (combining a FIN/ACK)

Necessary because TCP is full duplex!

TCP session

Client

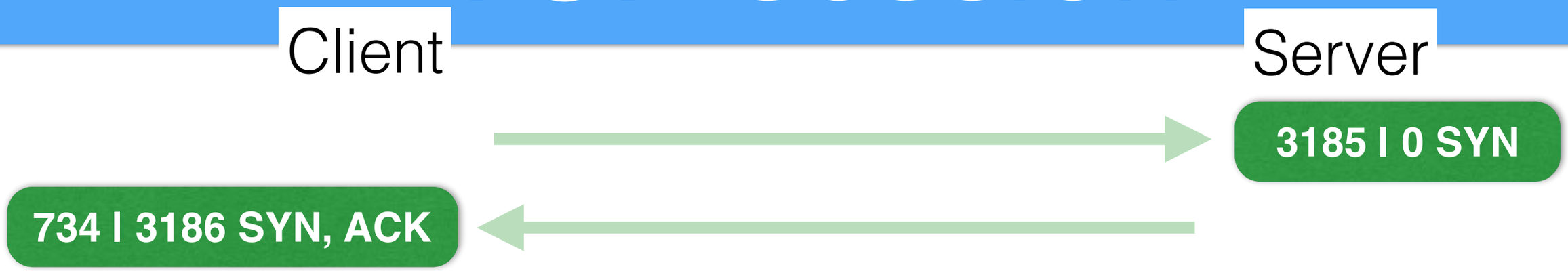
Server

TCP session

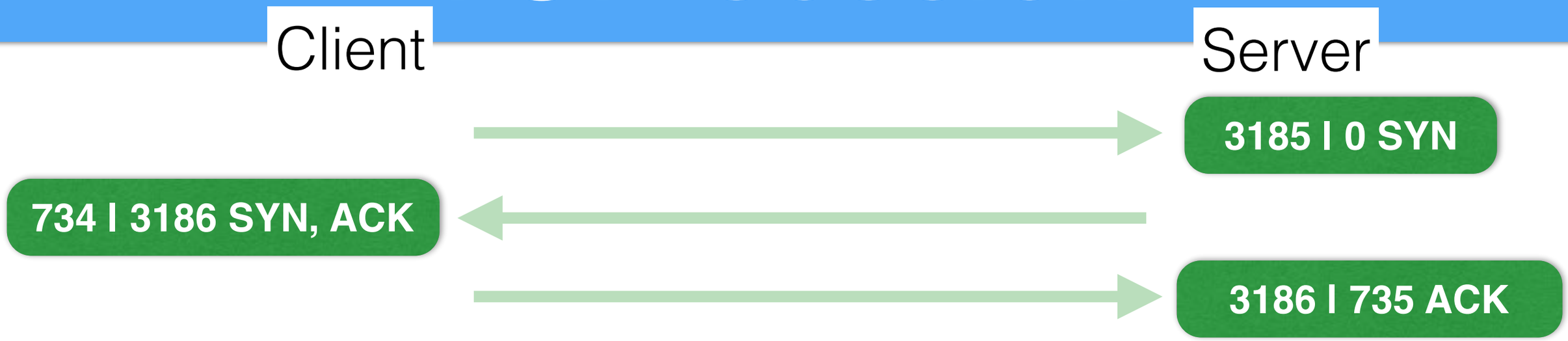
Client

Server

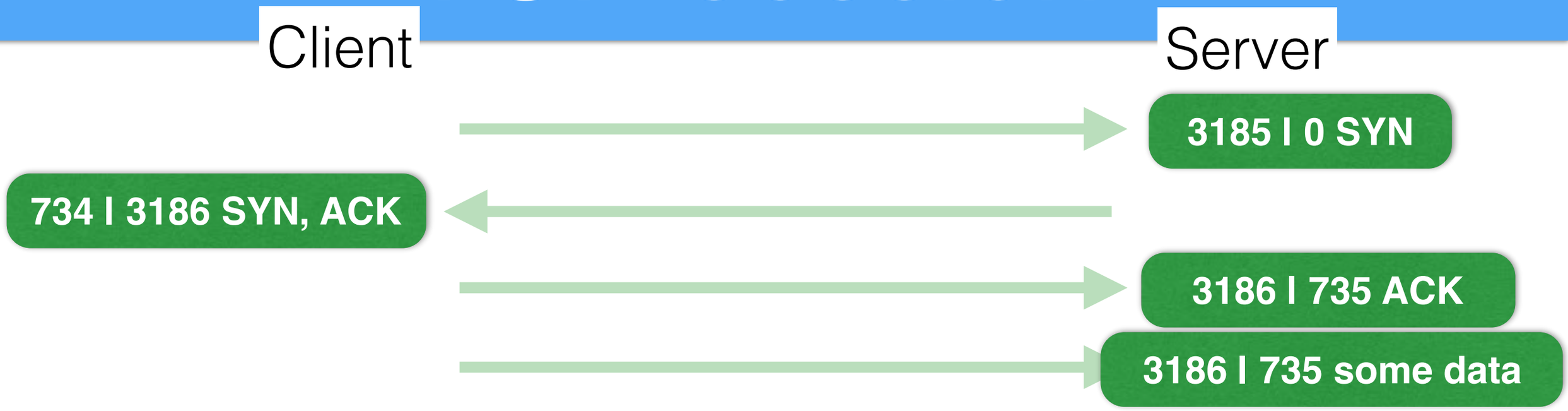
TCP session



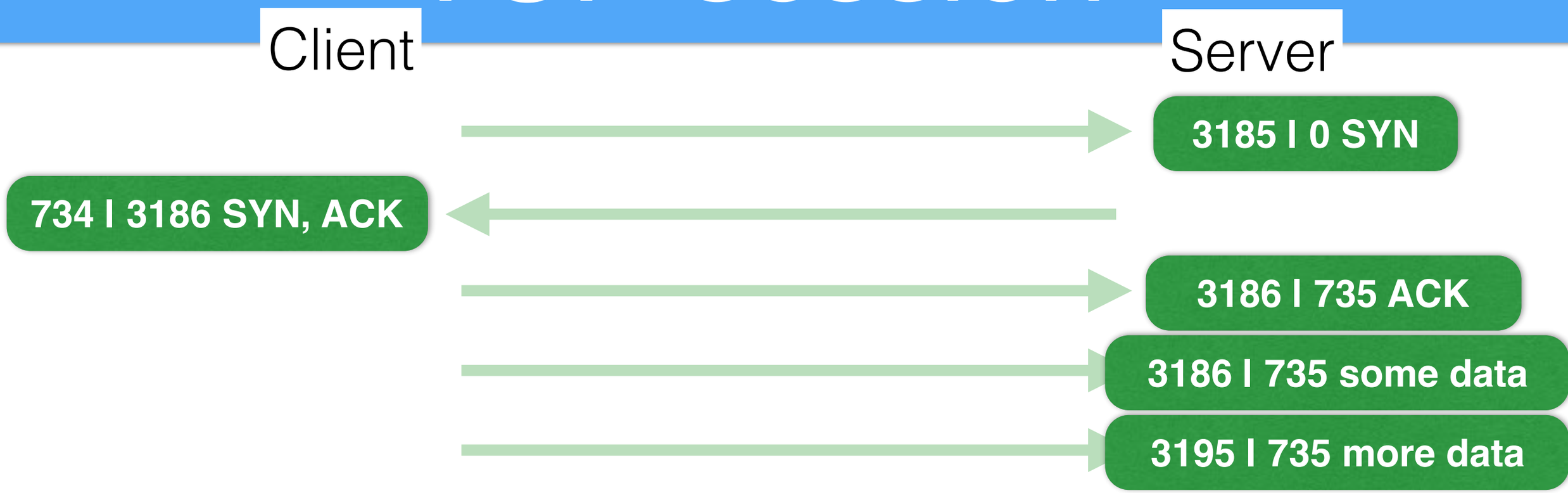
TCP session



TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data

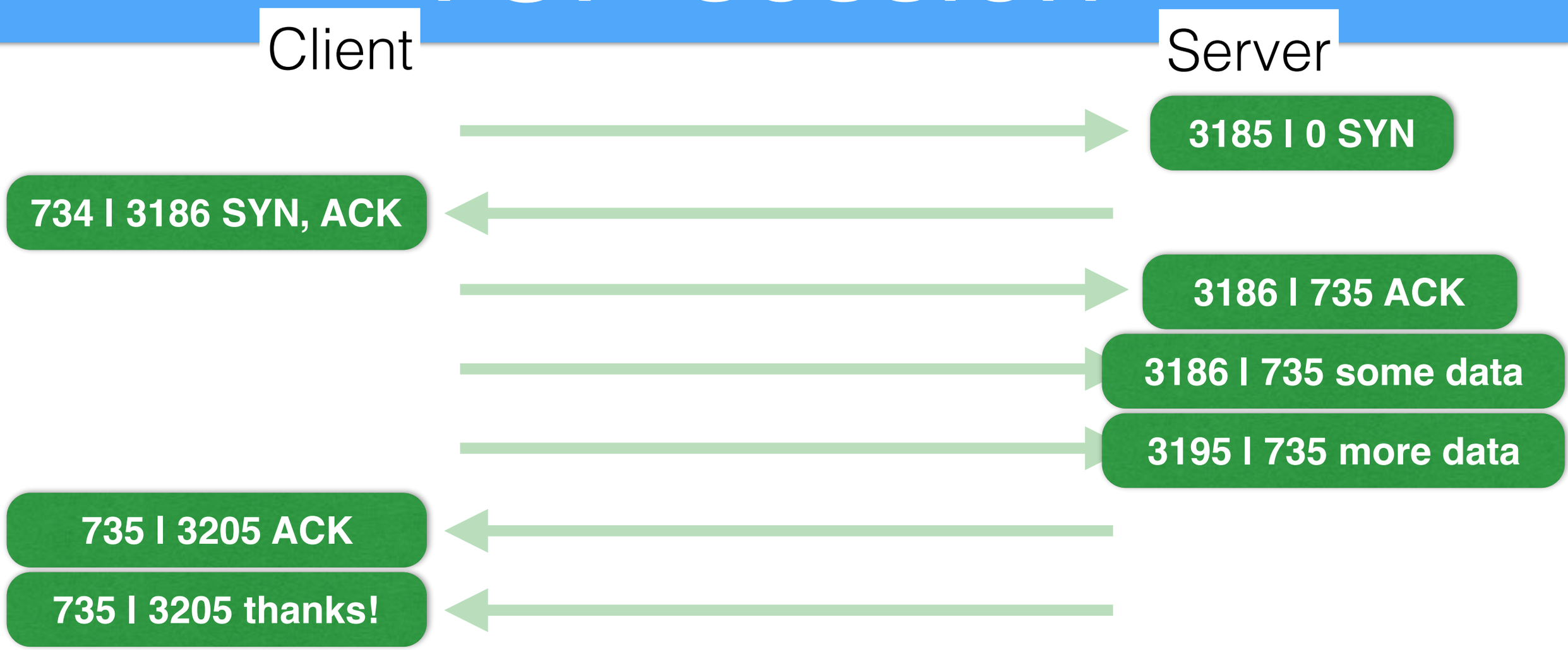
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data

TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK

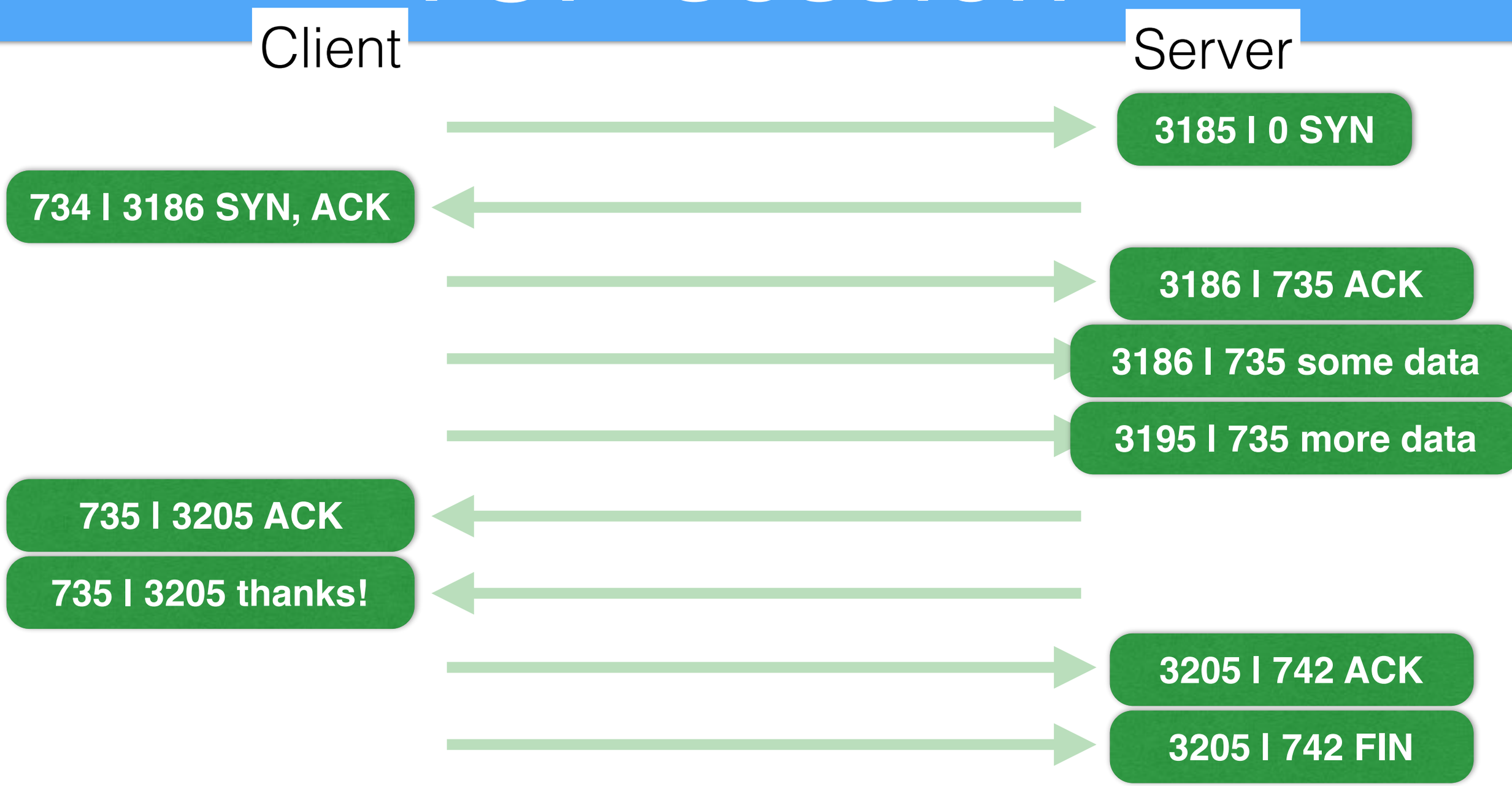
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!

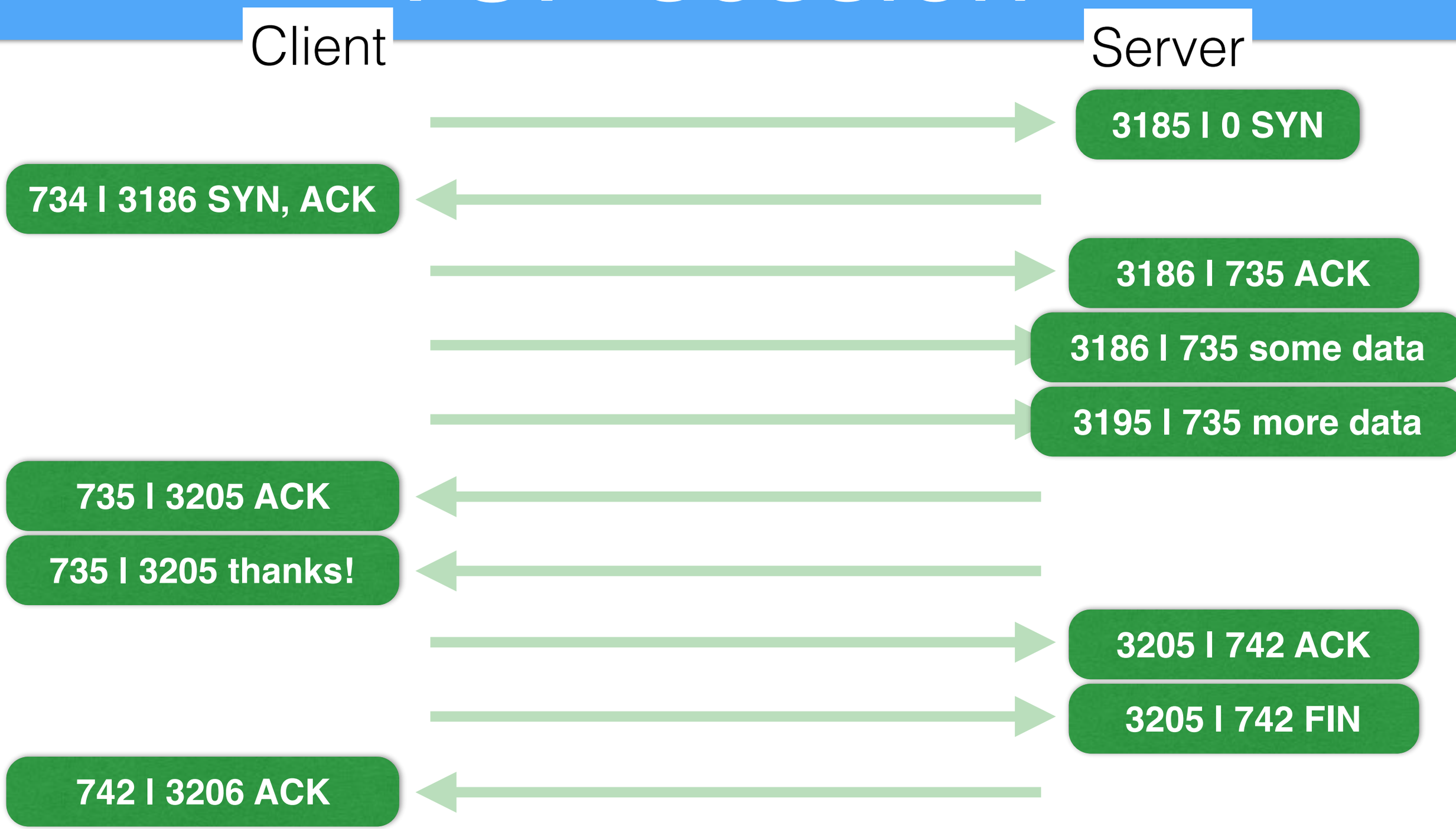
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK

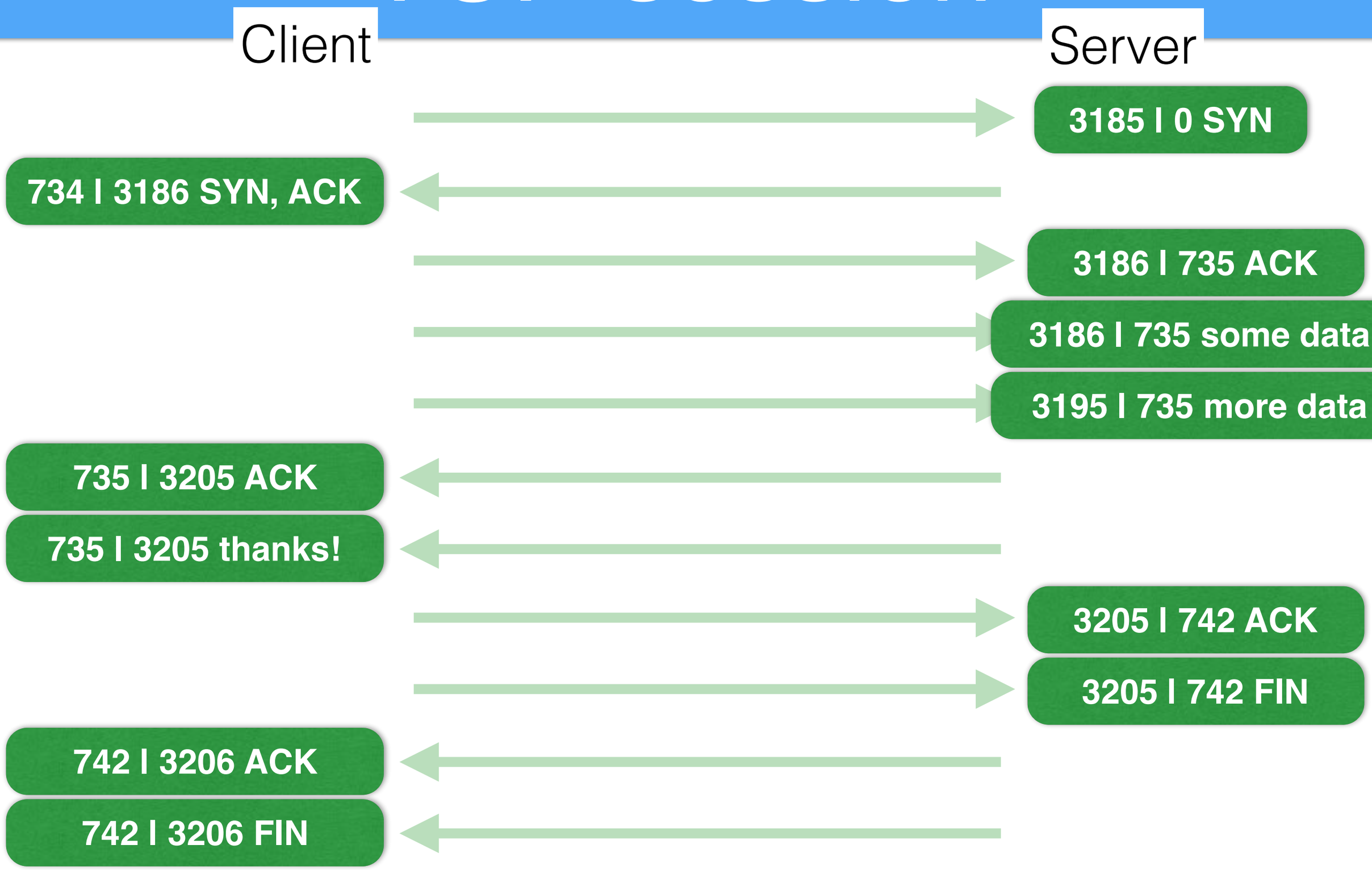
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN

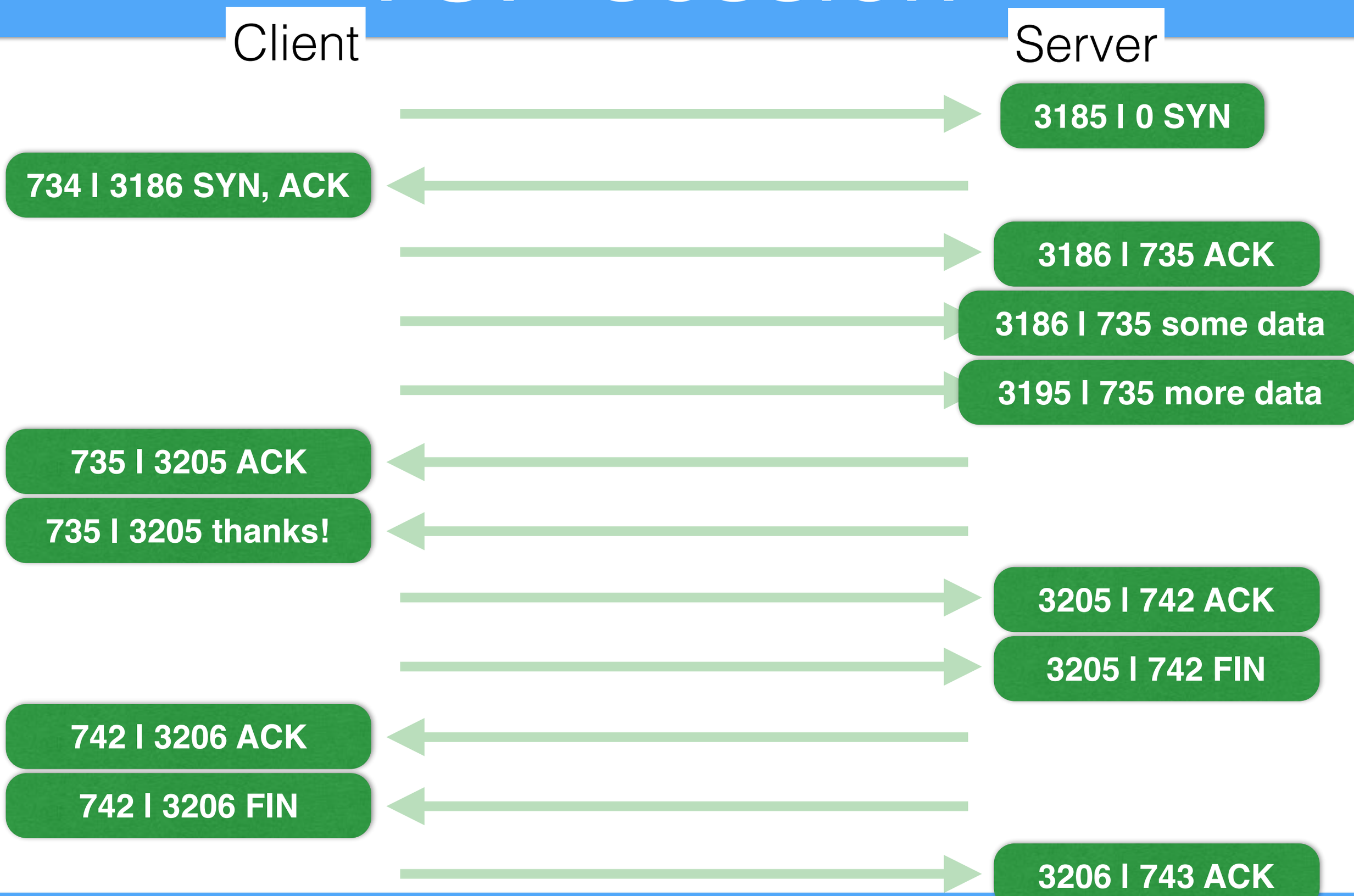
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK

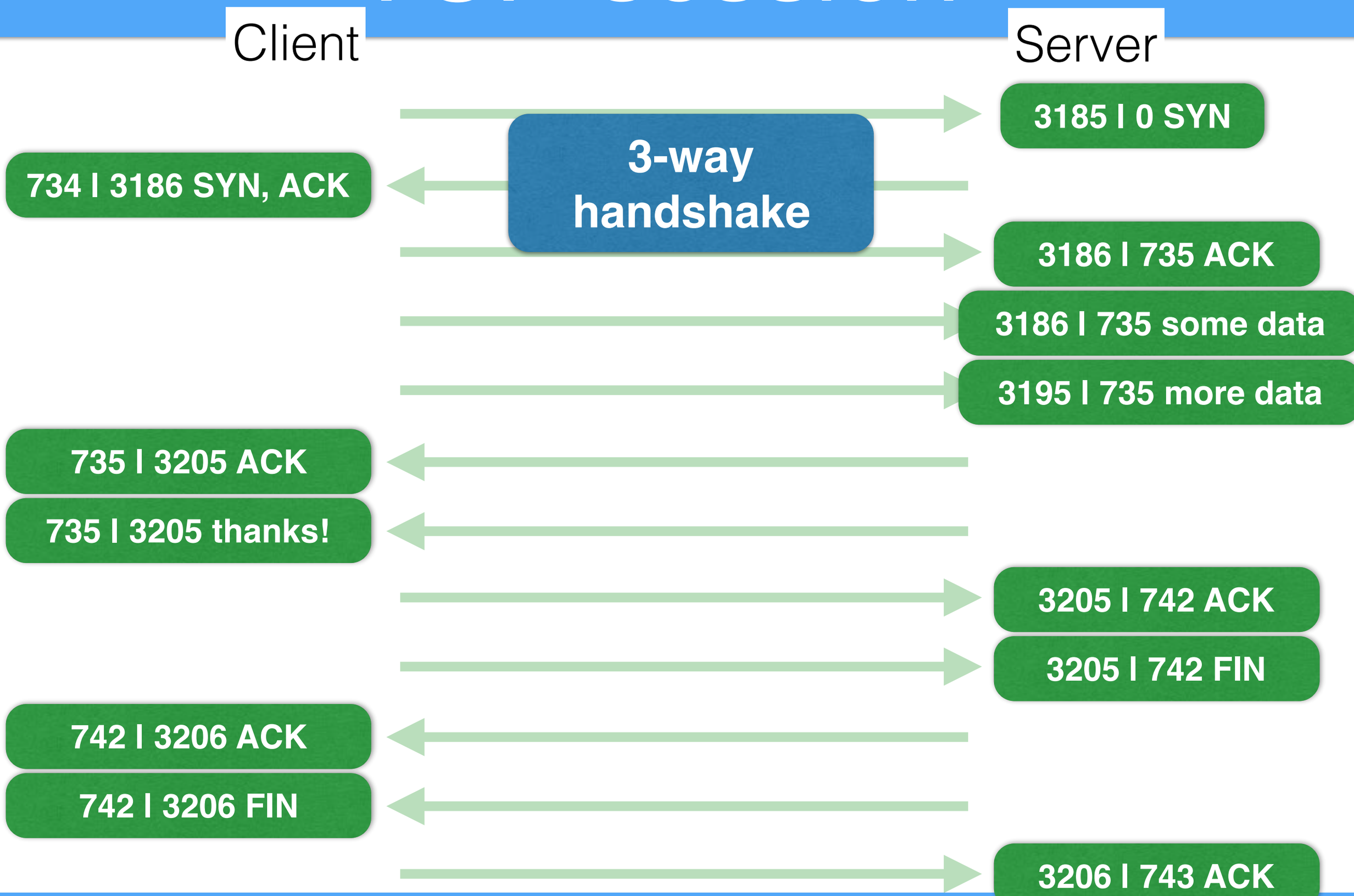
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK
742 I 3206 FIN

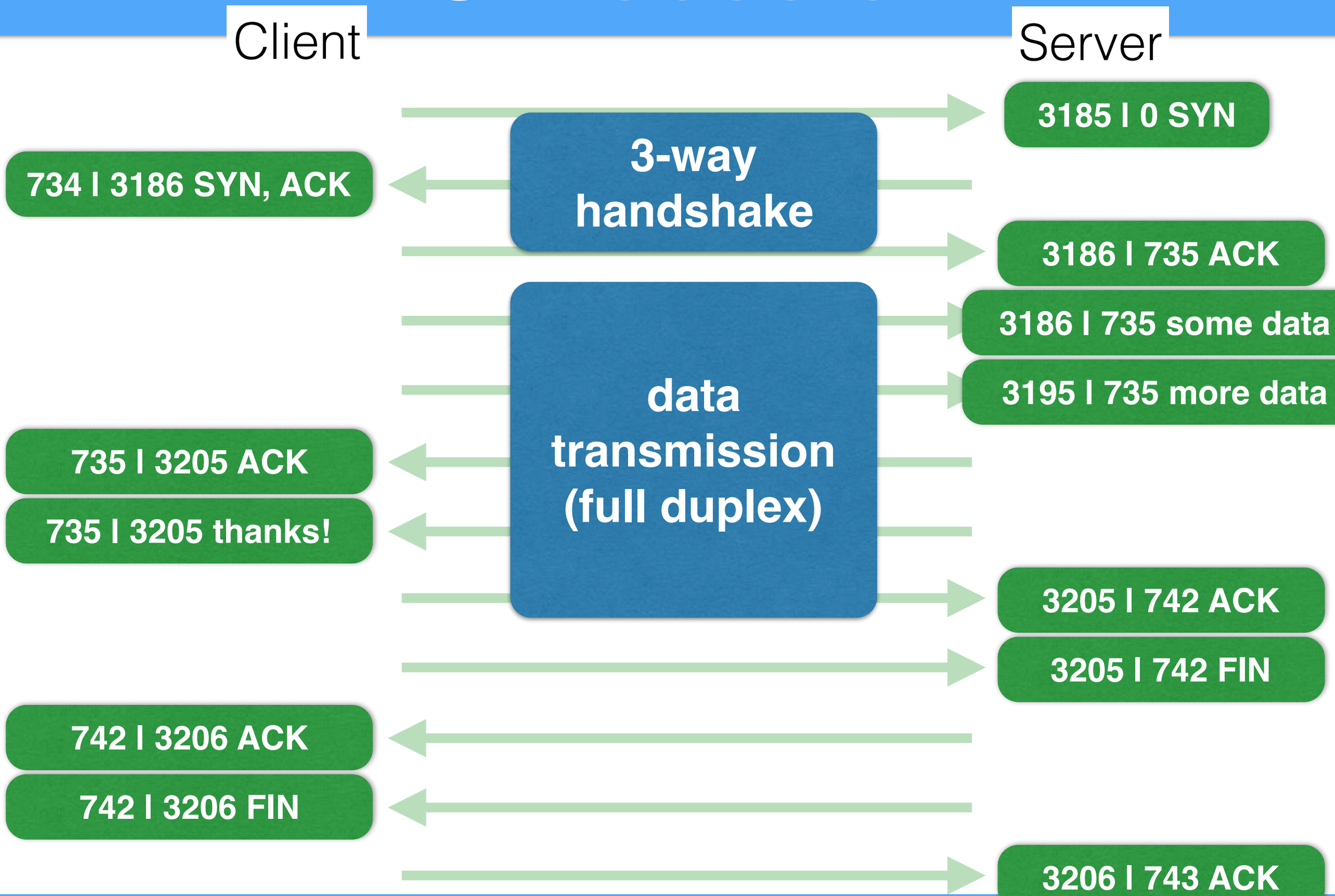
TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK
742 I 3206 FIN
3206 I 743 ACK

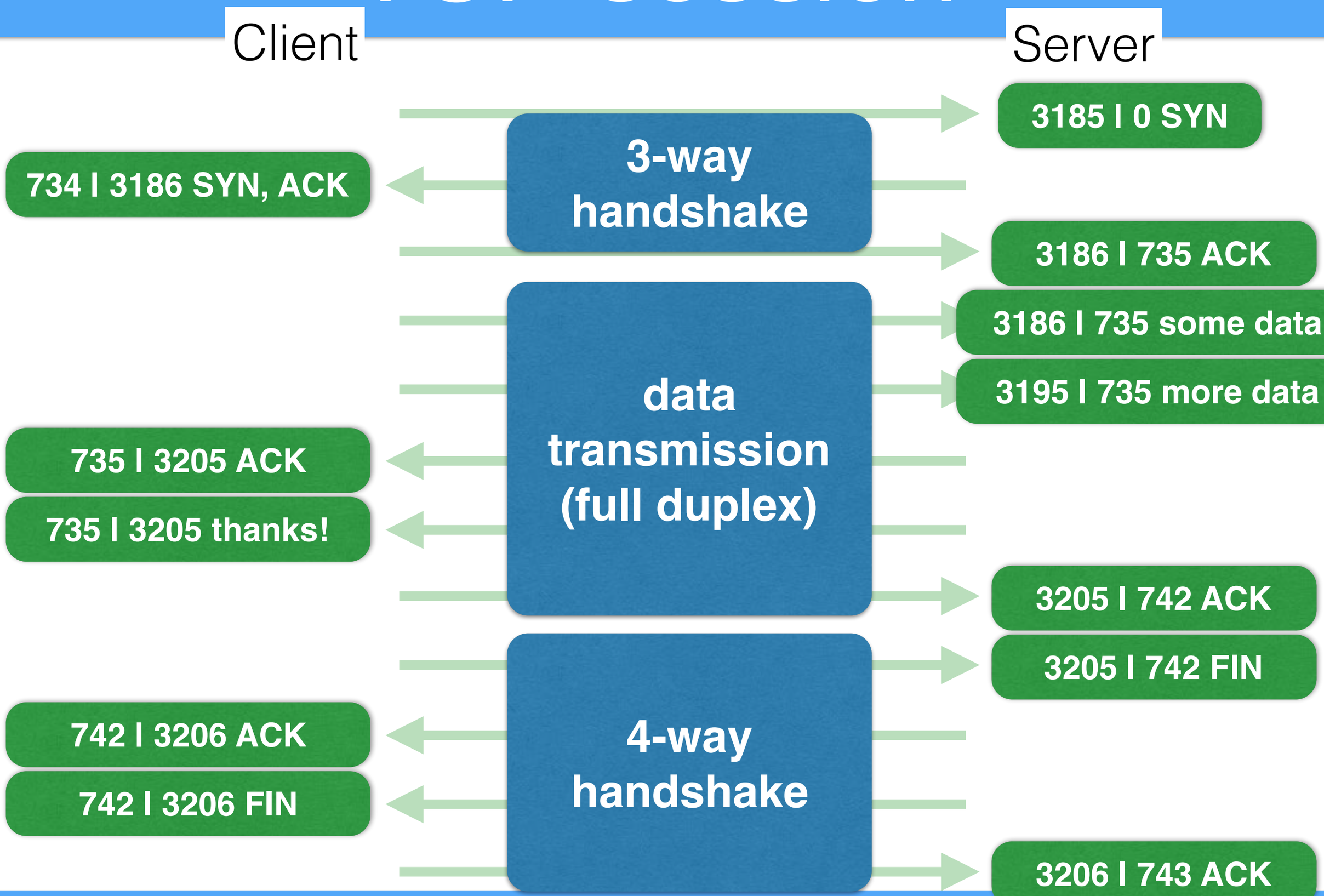
TCP session


Client
Server
3185 I 0 SYN
3-way handshake
734 I 3186 SYN, ACK
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK
742 I 3206 FIN
3206 I 743 ACK

TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3-way handshake
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
data transmission (full duplex)
735 I 3205 ACK
735 I 3205 thanks!
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK
742 I 3206 FIN
3206 I 743 ACK

TCP session


Client
Server
3185 I 0 SYN
734 I 3186 SYN, ACK
3-way handshake
3186 I 735 ACK
3186 I 735 some data
3195 I 735 more data
735 I 3205 ACK
735 I 3205 thanks!
data transmission (full duplex)
3205 I 742 ACK
3205 I 742 FIN
742 I 3206 ACK
742 I 3206 FIN
4-way handshake
3206 I 743 ACK

TCP parameters

TCP implements segmentation

- large application layer messages are split into segments

TCP parameters

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How fast to send segments?

- Sending too many at once may overload receiver or intermediate path with lower bandwidth

TCP parameters

TCP implements segmentation

- large application layer messages are split into segments

How fast to send segments?

- Sending too many at once may overload receiver or intermediate path with lower bandwidth

How to decide the segment size?

- Sending too large segments requires IP to **fragment**
- Large segments also increase errors

TCP segment size

Two approaches:

- use “reasonable” MTU, accept that IP sometimes needs to fragment

TCP segment size

Two approaches:

- use “reasonable” MTU, accept that IP sometimes needs to fragment
- use **Path MTU Discovery** (PMTUD):

TCP segment size

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- use **Path MTU Discovery** (PMTUD):
  - send IP packets to destination, asking routers to **never** fragment

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- use **Path MTU Discovery** (PMTUD):
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  - if router would have to fragment, it sends back an error message

TCP segment size

Two approaches:

- use “reasonable” MTU, accept that IP sometimes needs to fragment
- use **Path MTU Discovery** (PMTUD):
  - send IP packets to destination, asking routers to **never** fragment
  - if router would have to fragment, it sends back an error message
  - increase packet length until error occurs, then use last known error-free MTU

TCP congestion control

How fast to send?

- Receiver transmits its maximum buffer size
- Sender sends segments without waiting for ACK up to buffer size

TCP congestion control

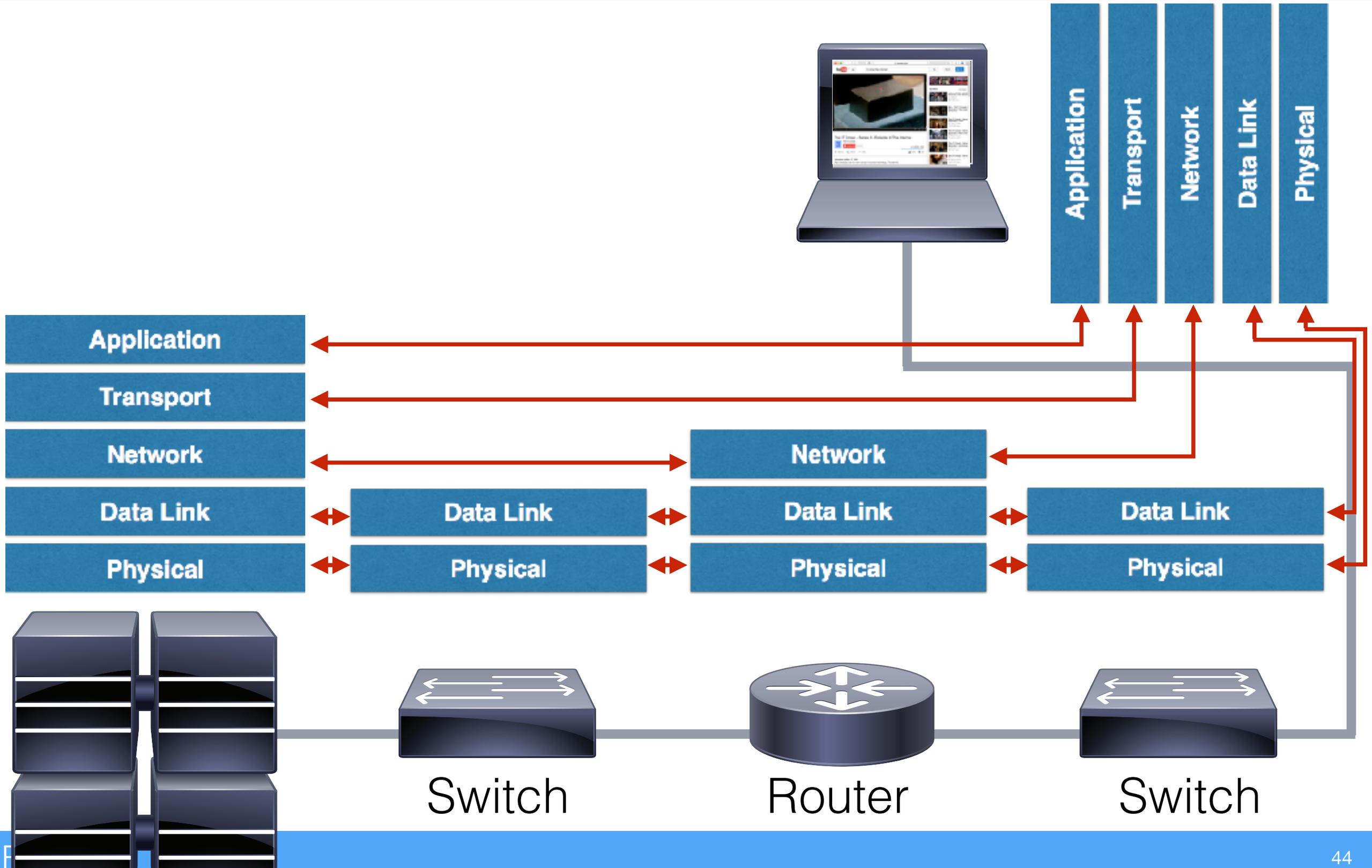
How fast to send?

- Receiver transmits its maximum buffer size
- Sender sends segments without waiting for ACK up to buffer size

What if network cannot cope?

- Start slow: wait for ACK after each segment
- Increase with every ACK: send two, four etc segments after each ACK
- Fall back to slower speed when no ACK arrives

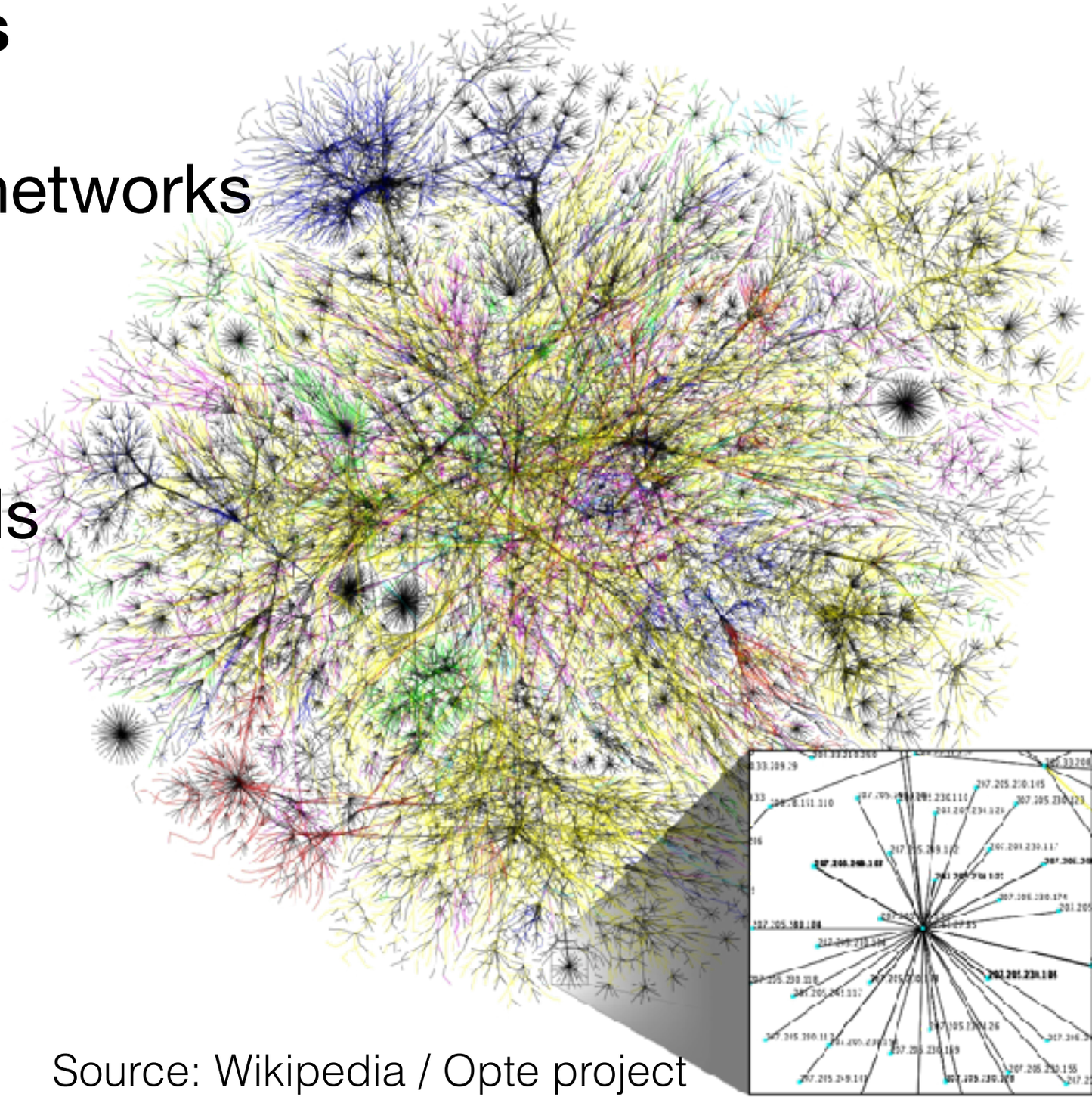
Layers of Abstraction



The Internet

The Internet

- A **network of networks**
- Connecting millions of networks and billions of devices
- Based on a common, standard set of protocols



Source: Wikipedia / Opte project

Autonomous Systems

Networks operated by a single organisation

- e.g. Monash University's or your ISP's network

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Exterior routing

- for routing packets **between** different AS
- Internet uses BGP (Border Gateway Protocol)

Internet Architecture

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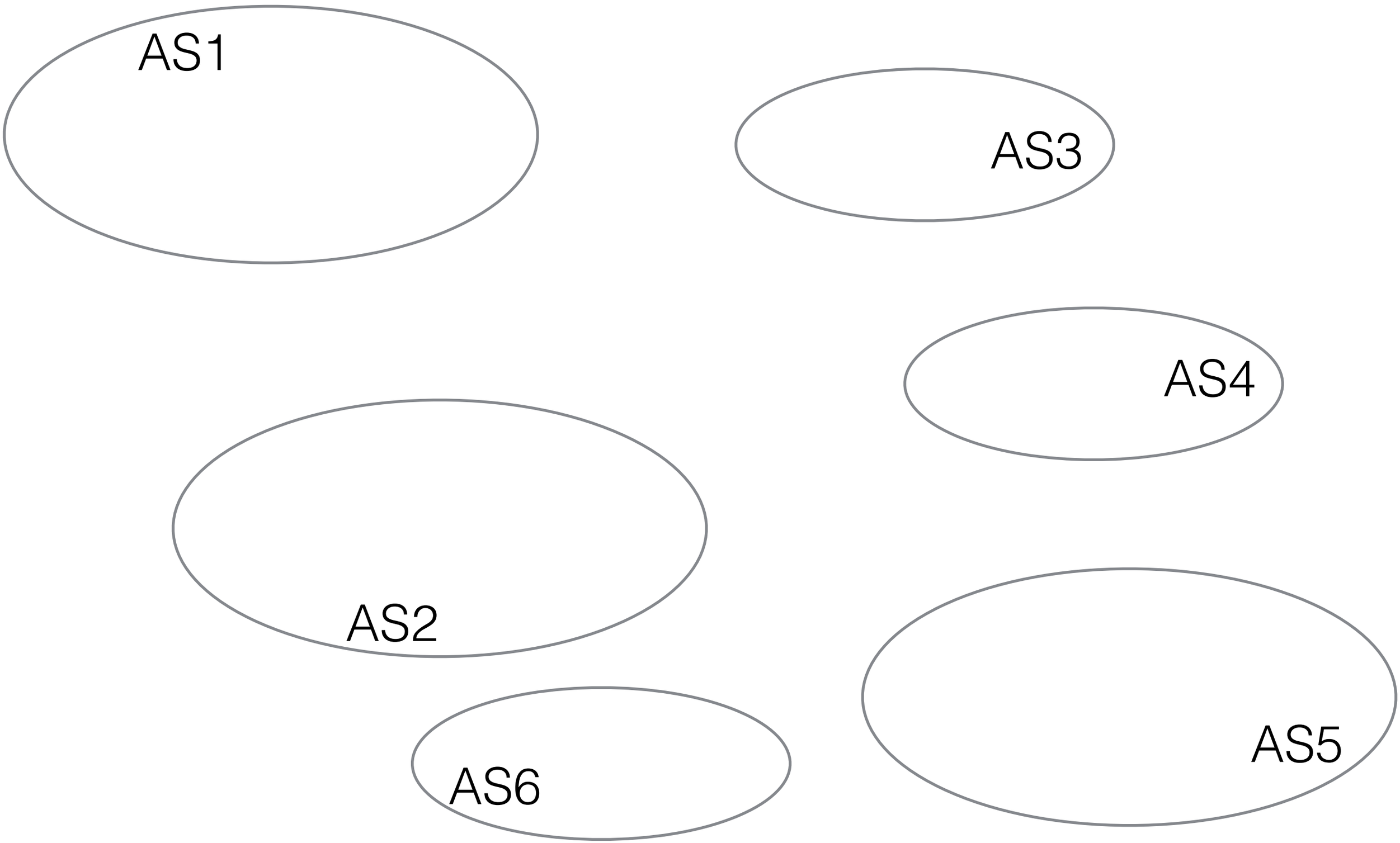

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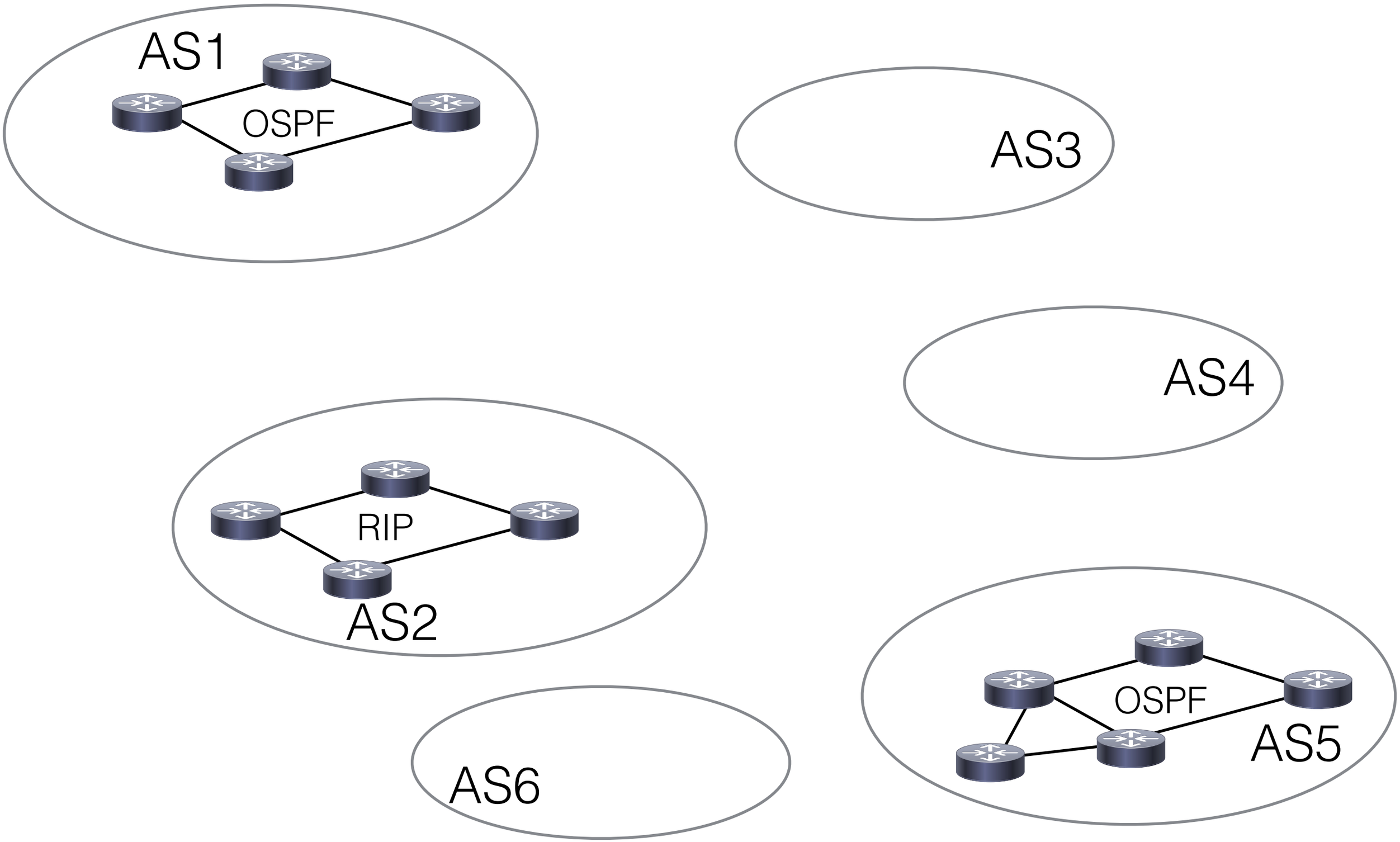

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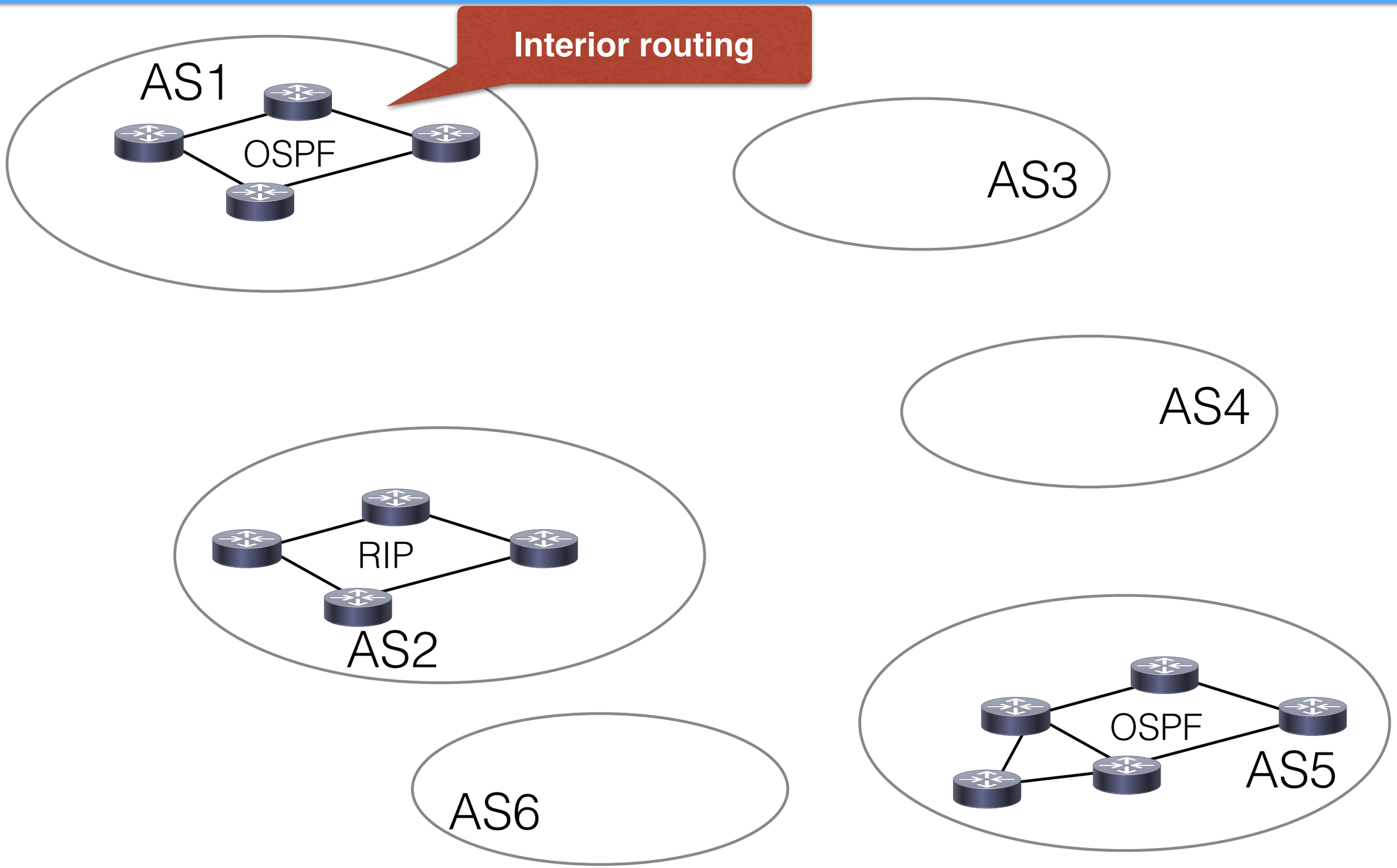

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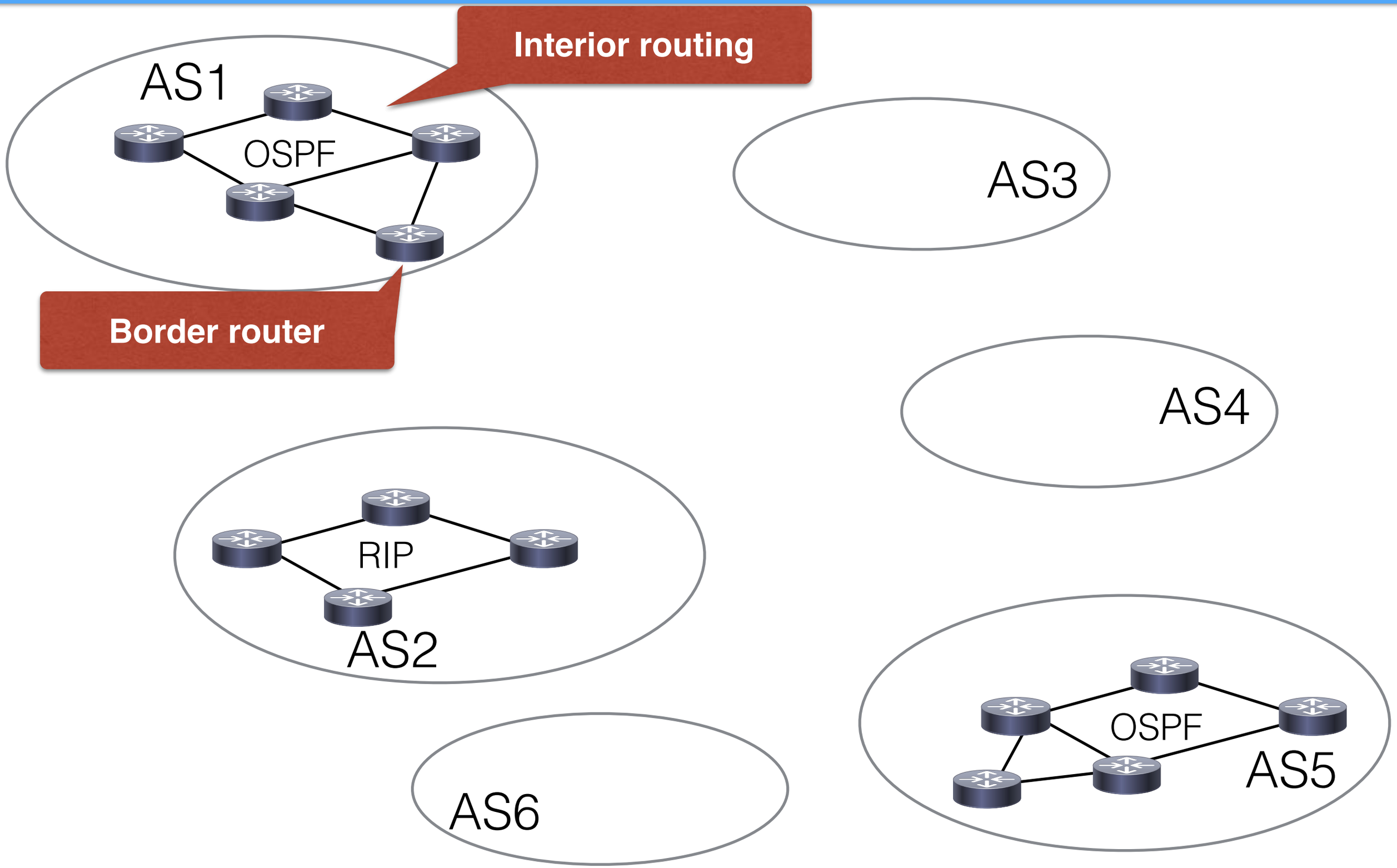

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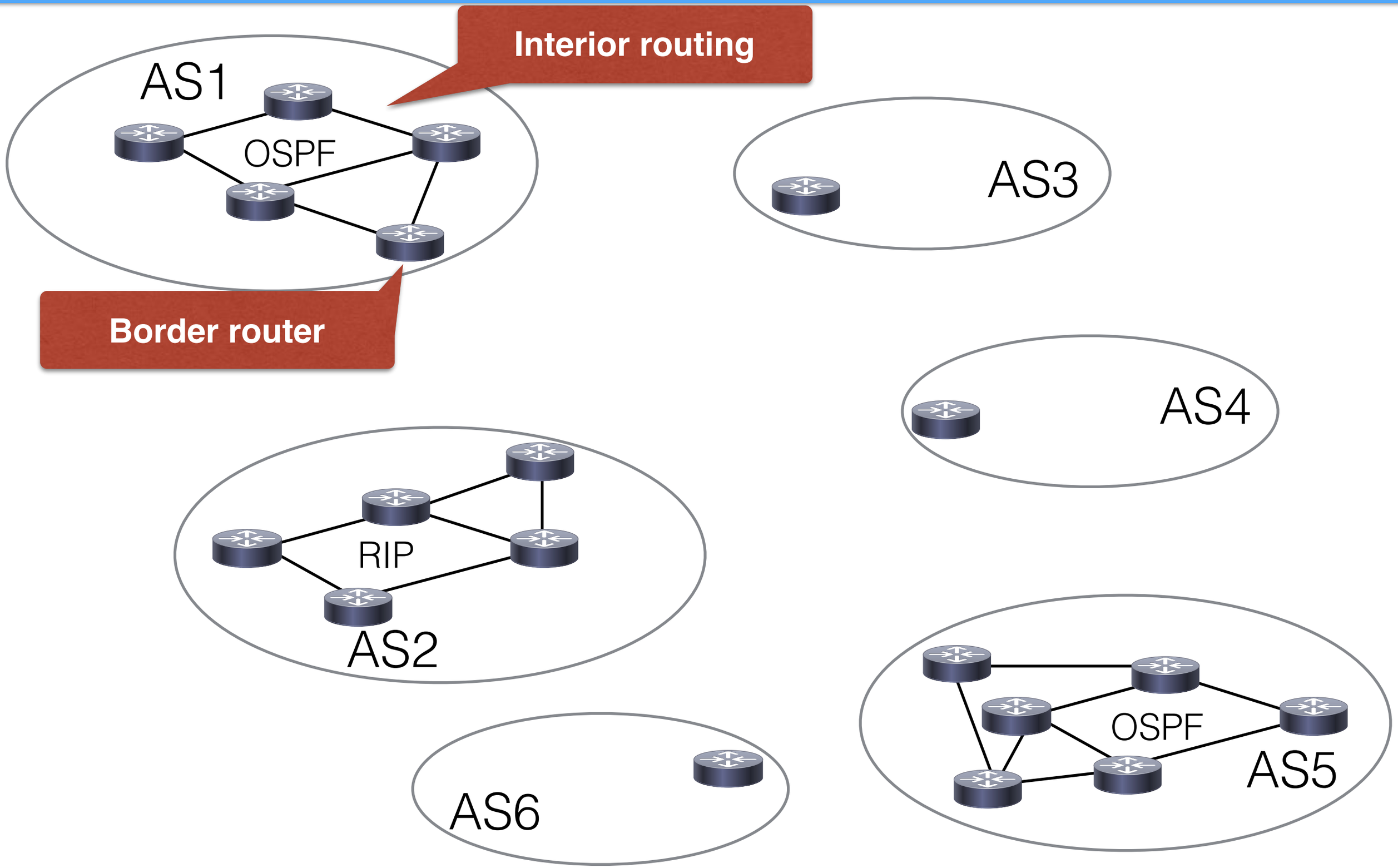

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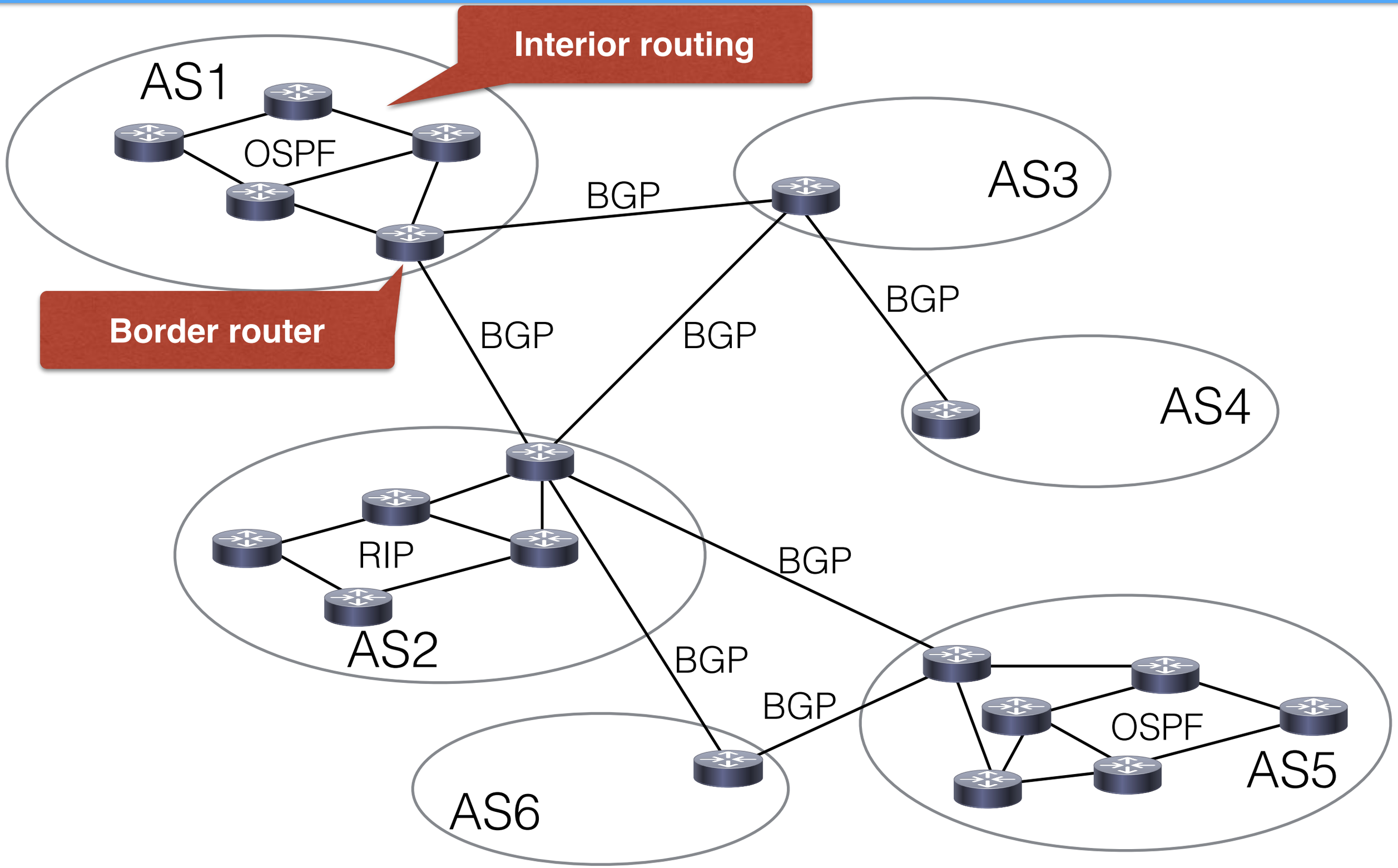

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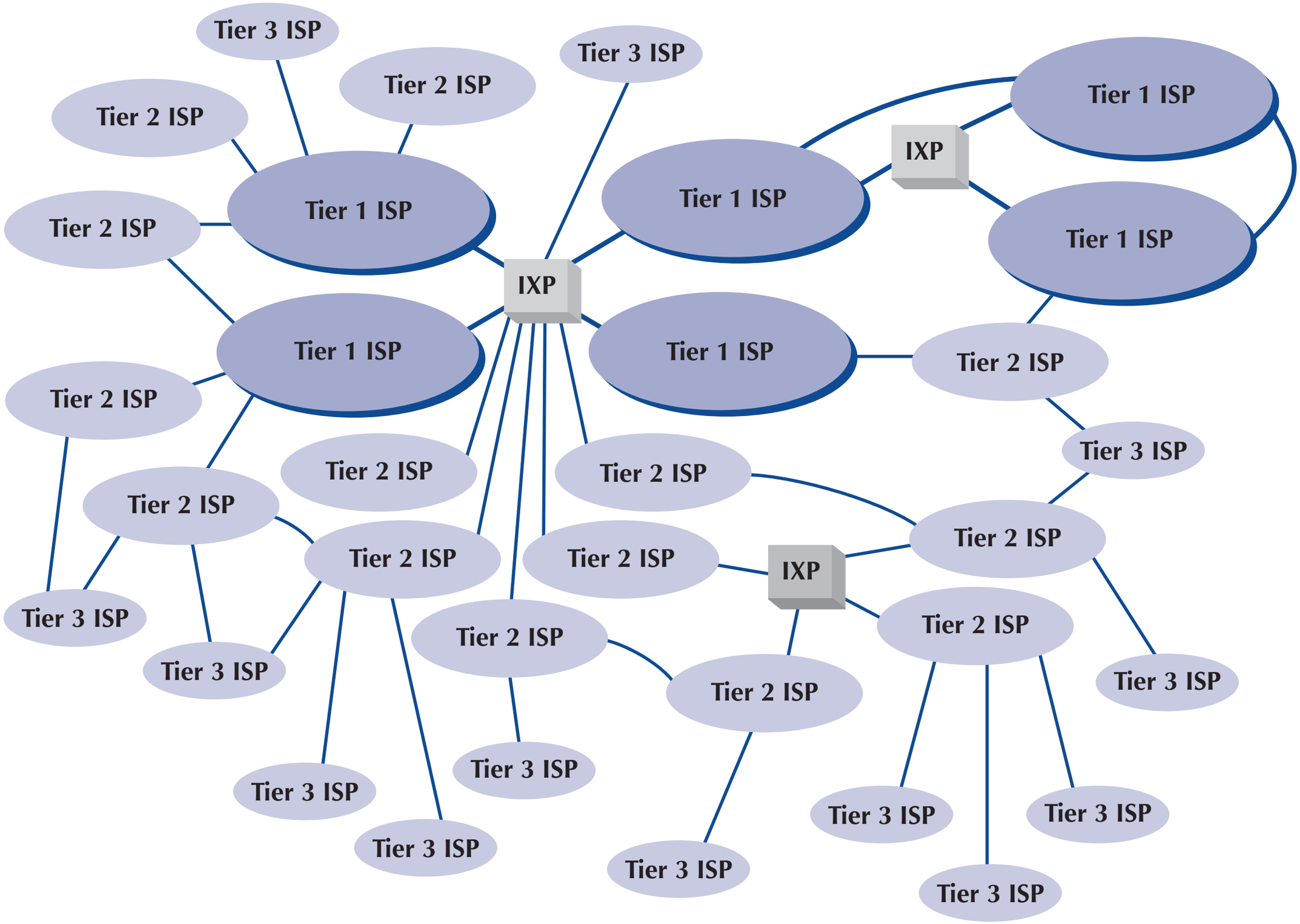
Hierarchy of ASs

- Each ISP operates an AS
- Routing information shared between ASs using BGP
- ISPs connect at **IXPs**

Internet Structure



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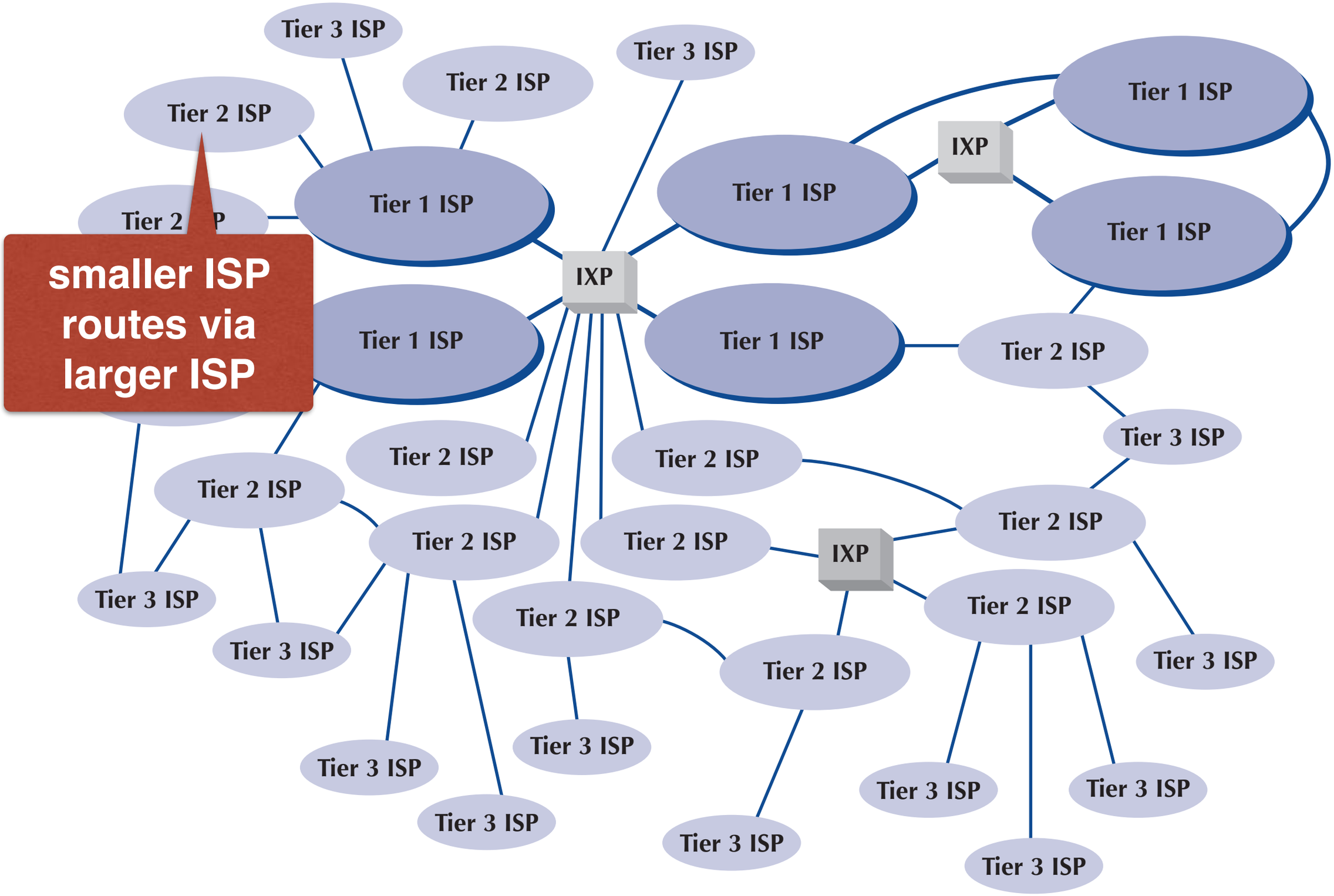

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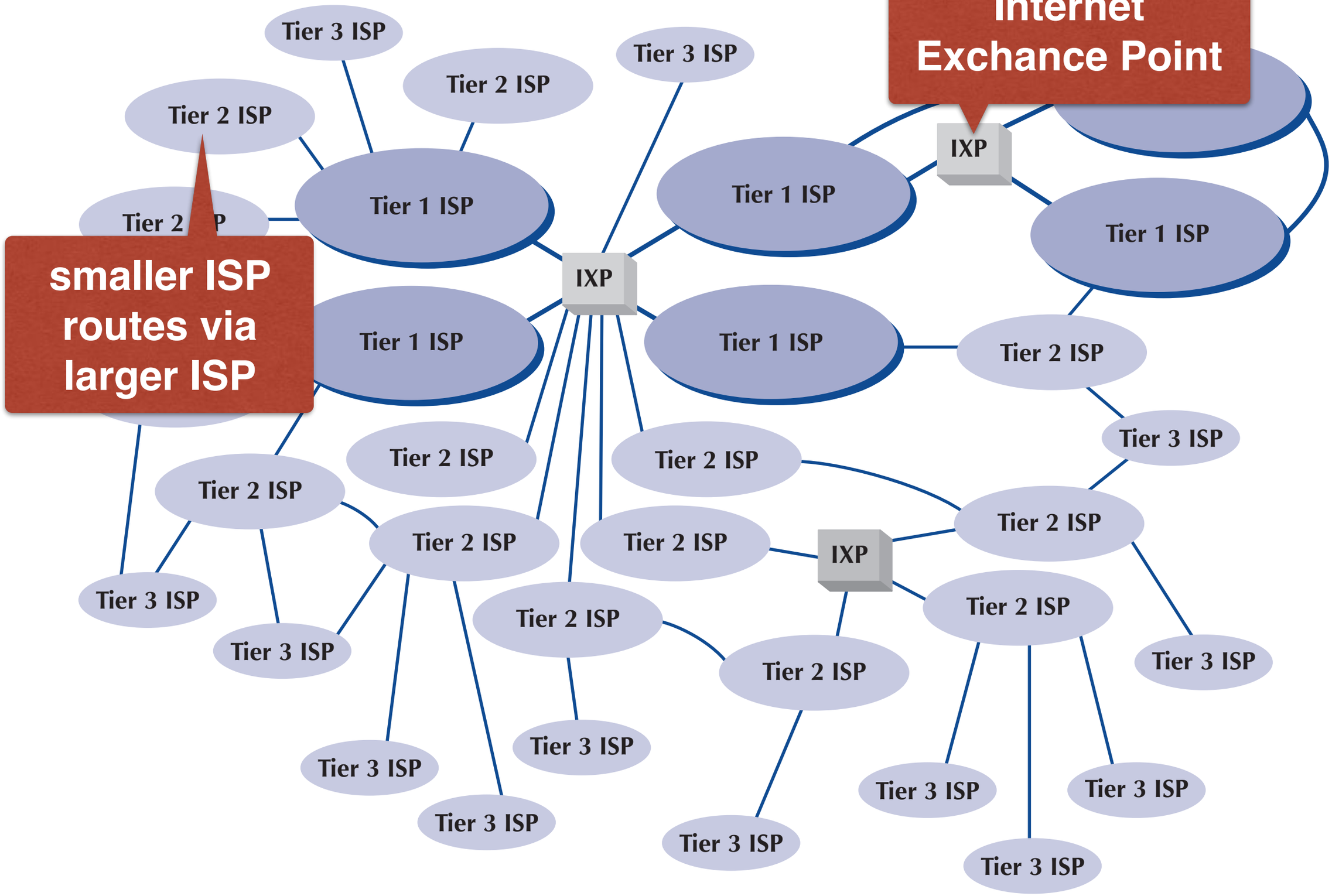

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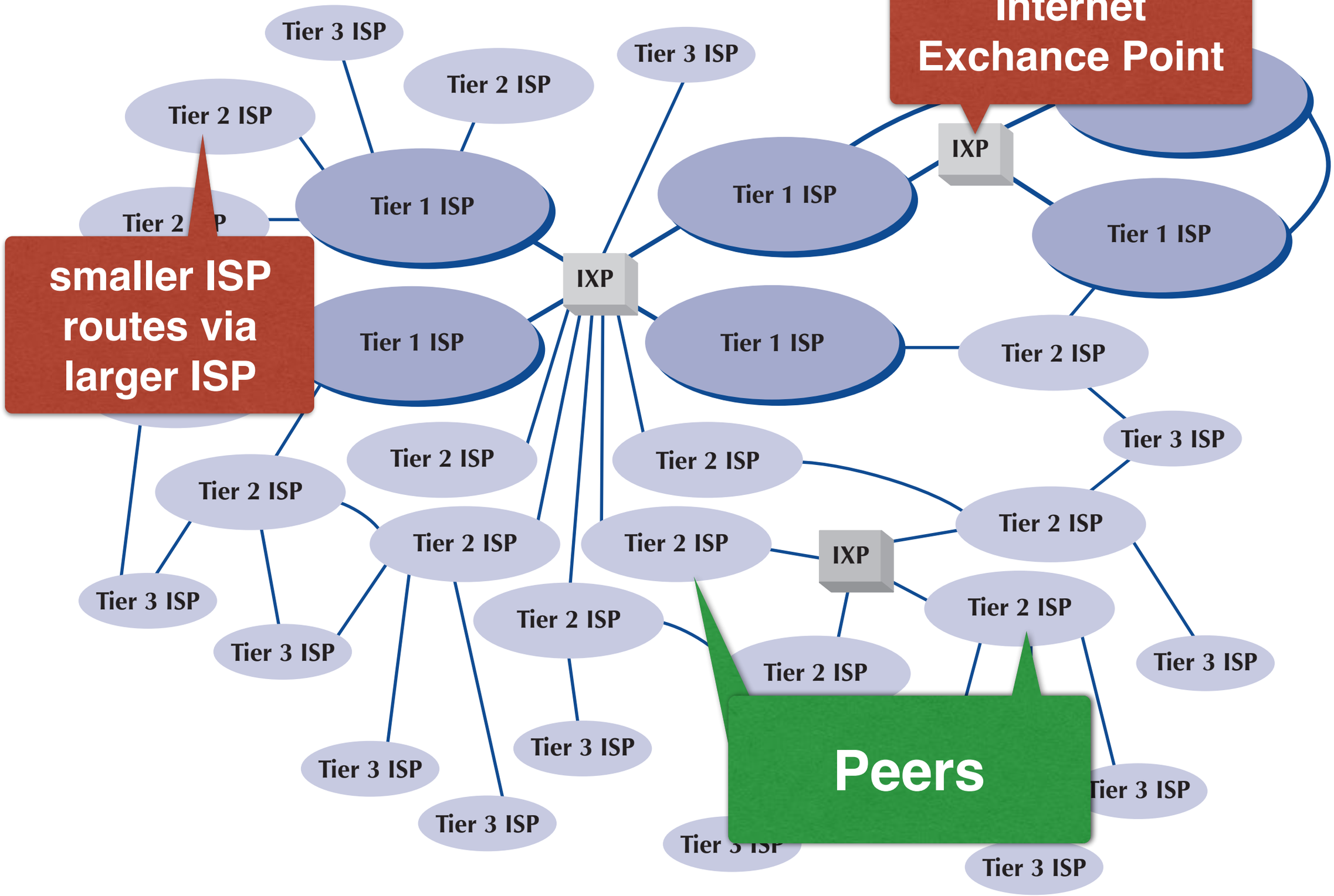

Peering

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- Large ISPs with large WANs
- Charge smaller ISPs for routing their traffic

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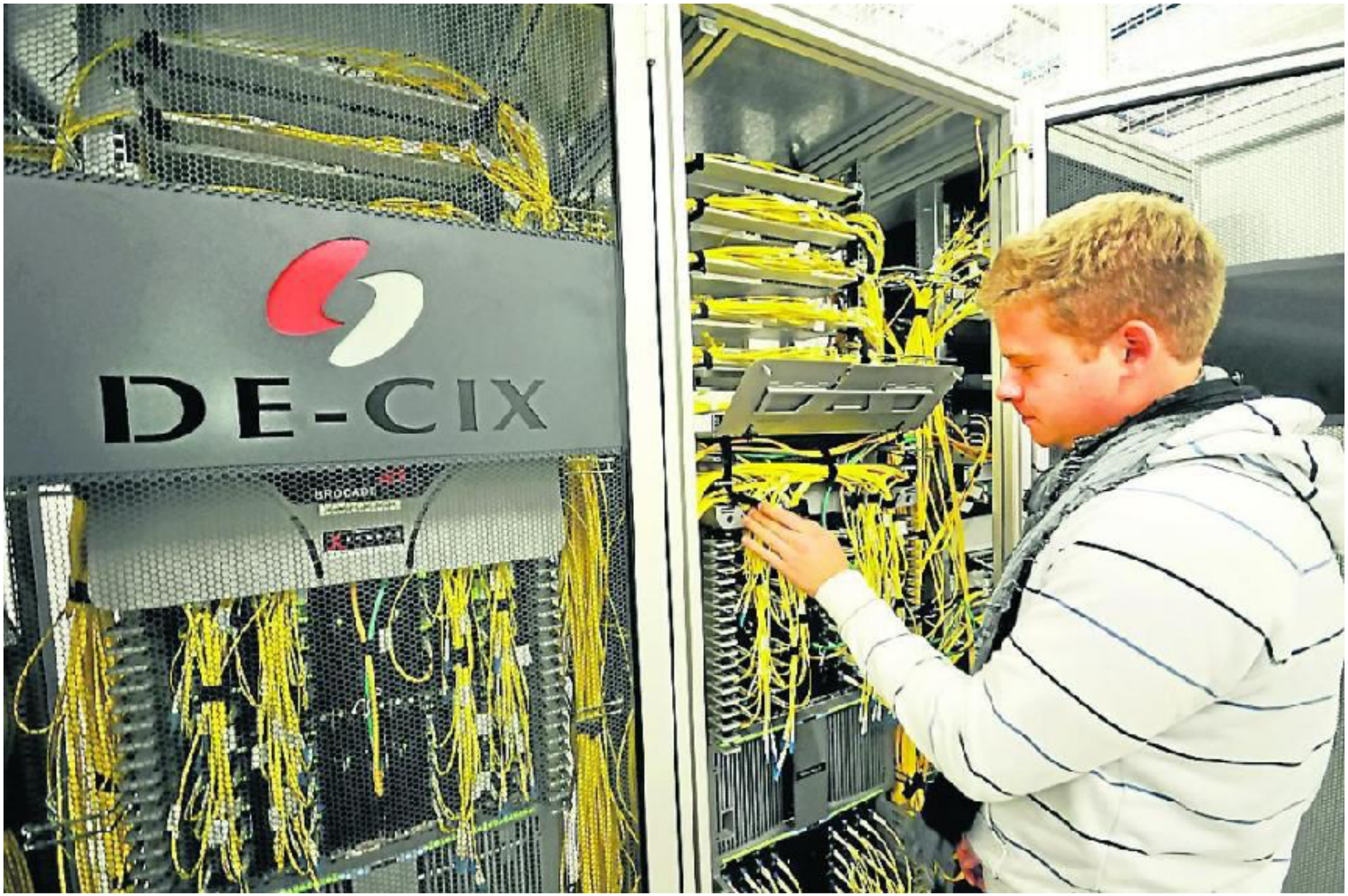
IXP

- provides the hardware for several ISPs to connect
- often owned by a consortium of ISPs

Inside an IXP



Delivering Content over the Internet

The problem

The Internet has grown

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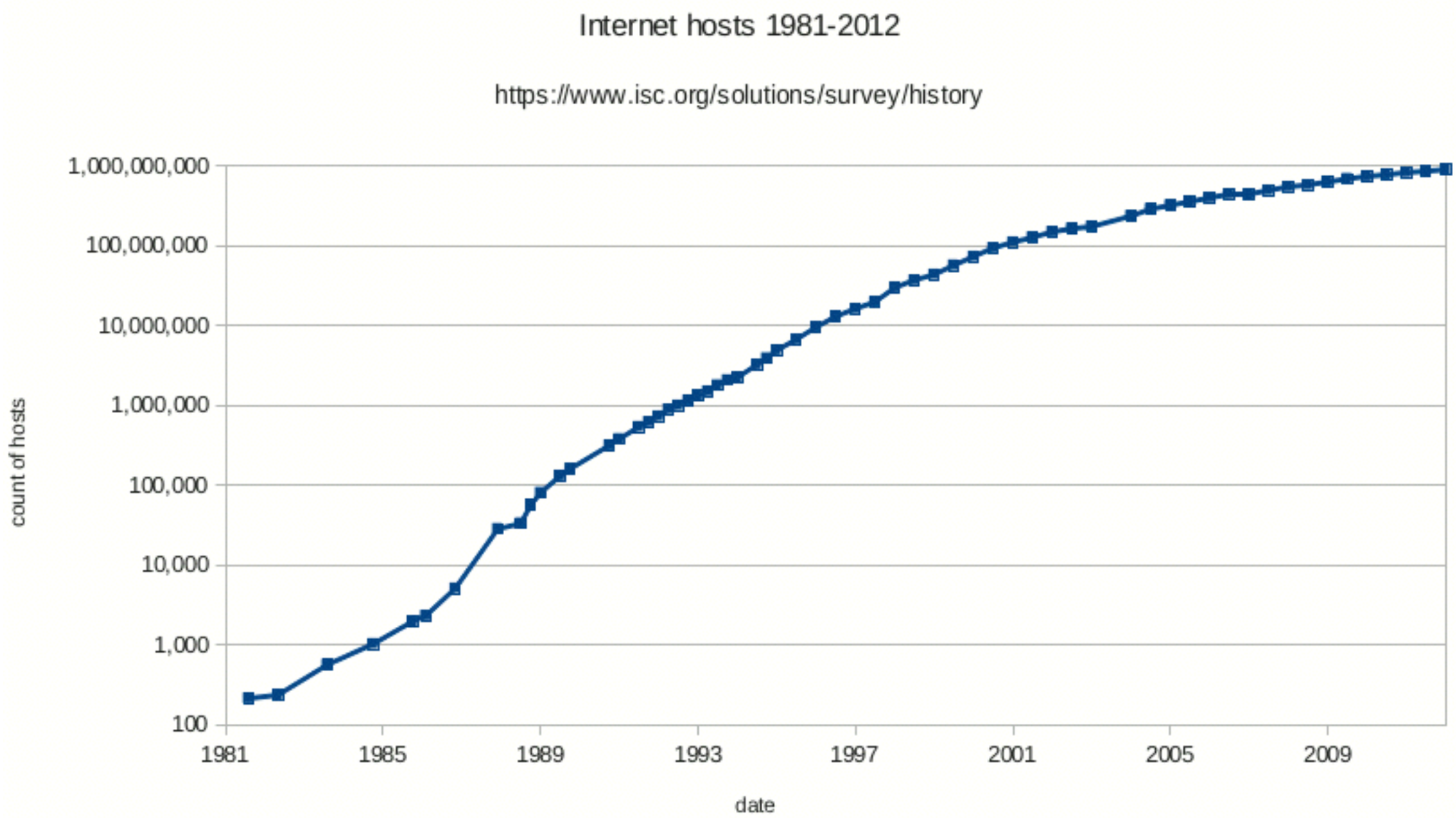

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The Internet has grown

- not only the number of hosts, but also their **distance**
- many applications rely on **low latency**
  (video, streaming music, modern web sites)
- some services have millions of users
- the main protocols (HTTP, TCP/IP and BGP) were not designed for this growth

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So why does it still work?

- Load balancing
- Content Delivery Networks (CDNs)

Load Balancing

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Many services impossible for single server

- Google processes over 40,000 search queries per second
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Spread load over multiple servers

- DNS-based: host name maps to multiple IPs
- Special hardware: load balancer accepts requests, routes them to different servers

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Inside Monash network:

- PING www.google.com (216.58.220.132)
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Content Caching

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Store web data closer to users

- replicate web pages etc. in *caches*
- can be implemented *transparently:*
  - user makes request
  - router on path to server queries *cache engine*
  - if content available, serve from local cache

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This is explicitly supported by HTTP

- GET requests can be cached
- HTTP headers can contain `Expires:` field
- Cache only serves GET requests that are not expired

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CDNs

- operate servers in multiple locations
- operate their own high-bandwidth network
- locate points of presence close to end users

CDNs and Peering

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Get close to your customers

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CDNs are present at IXPs

- peer with anybody for free
- small ISPs avoid paying e.g. for YouTube content downloaded from the upstream ISP
- Example: Netflix peers with Australian ISPs, which can offer “unmetered” access

Summary (I)

Network layer

- subnet mask identifies other devices in same subnet
- routers use routing tables to determine next hop
- static vs dynamic routing
- IPv4 vs IPv6

Transport layer

- splits up long messages into segments
- uses ARQ for error control
- uses ports to identify applications

Summary (II)

The Internet

- consists of Autonomous Systems
- connected by routers that use BGP for sharing routes
- ISPs run autonomous systems, connect at IXP
- Load balancing and Content Delivery Networks enabled the massive growth