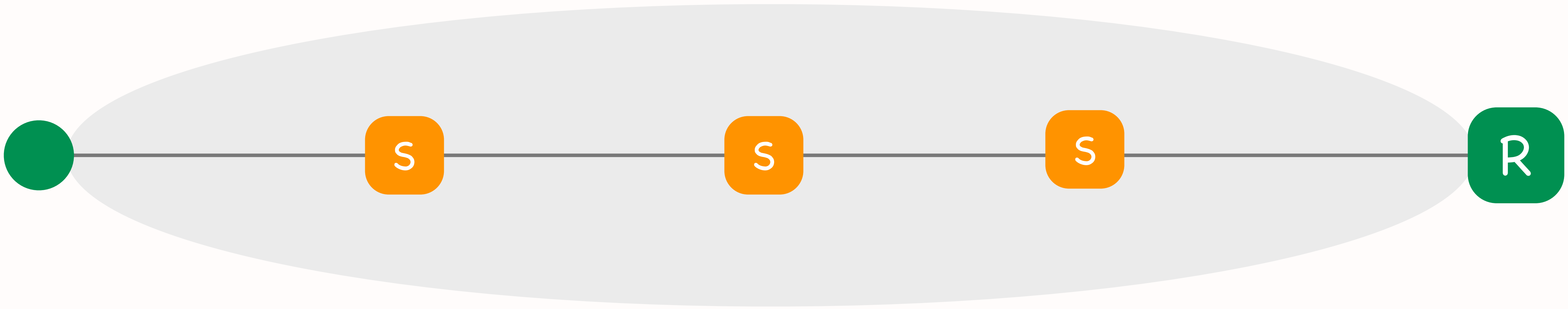
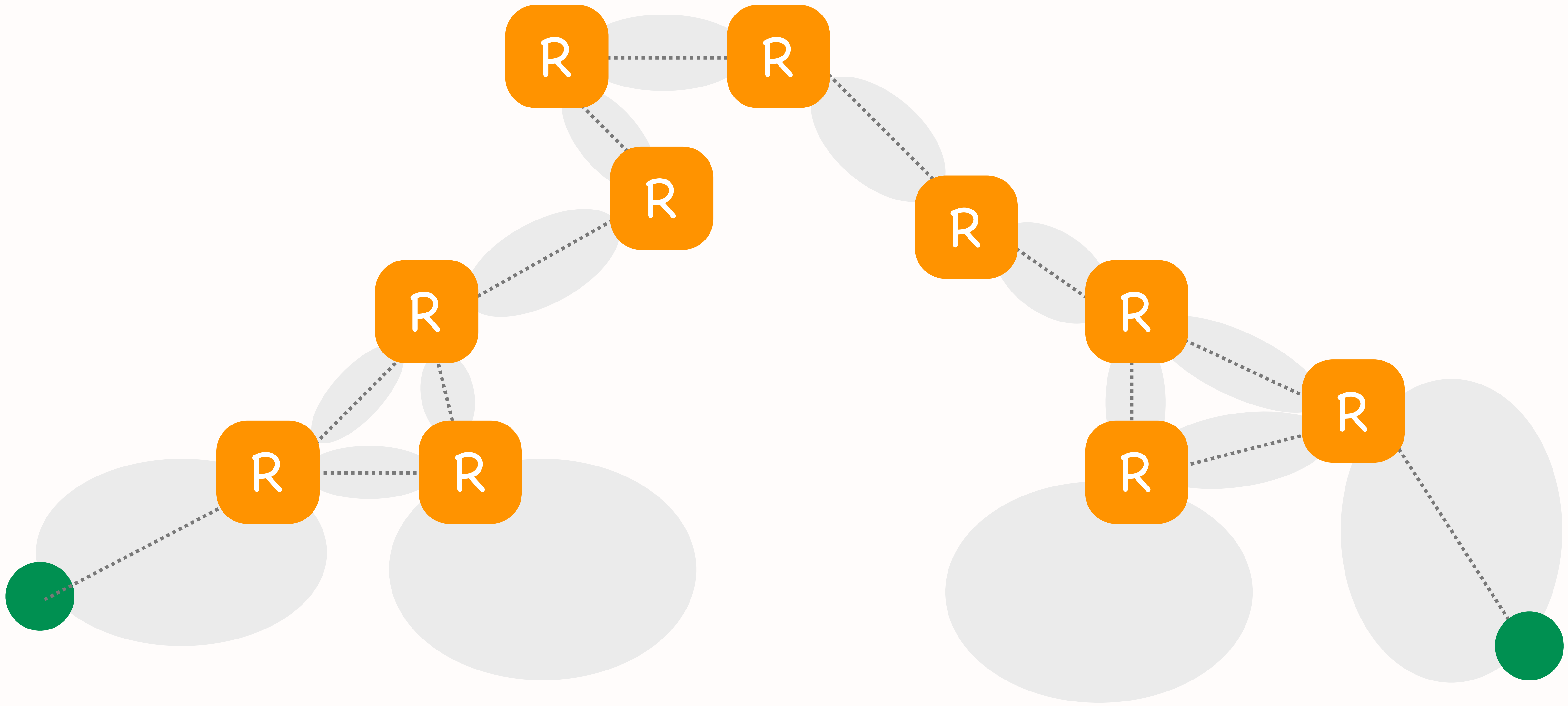
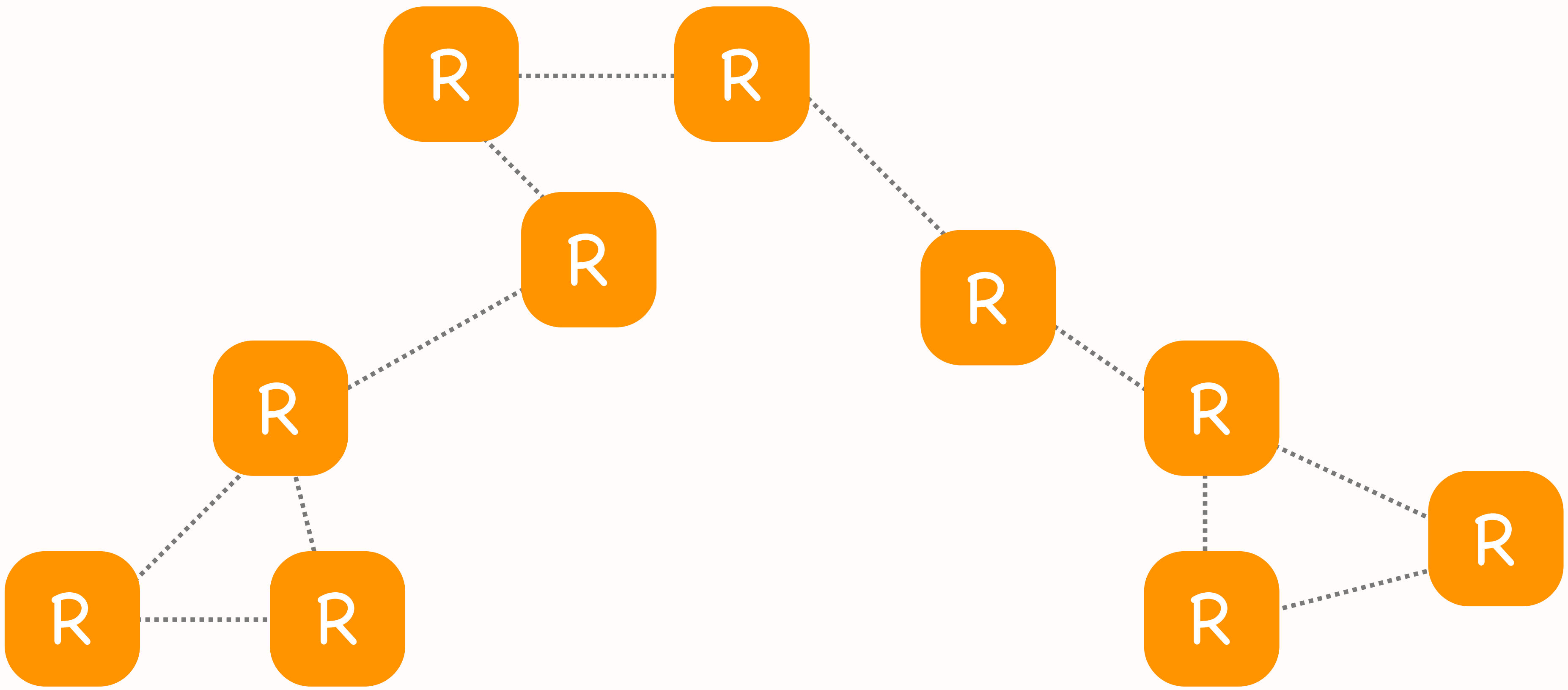
Three levels of hierarchy

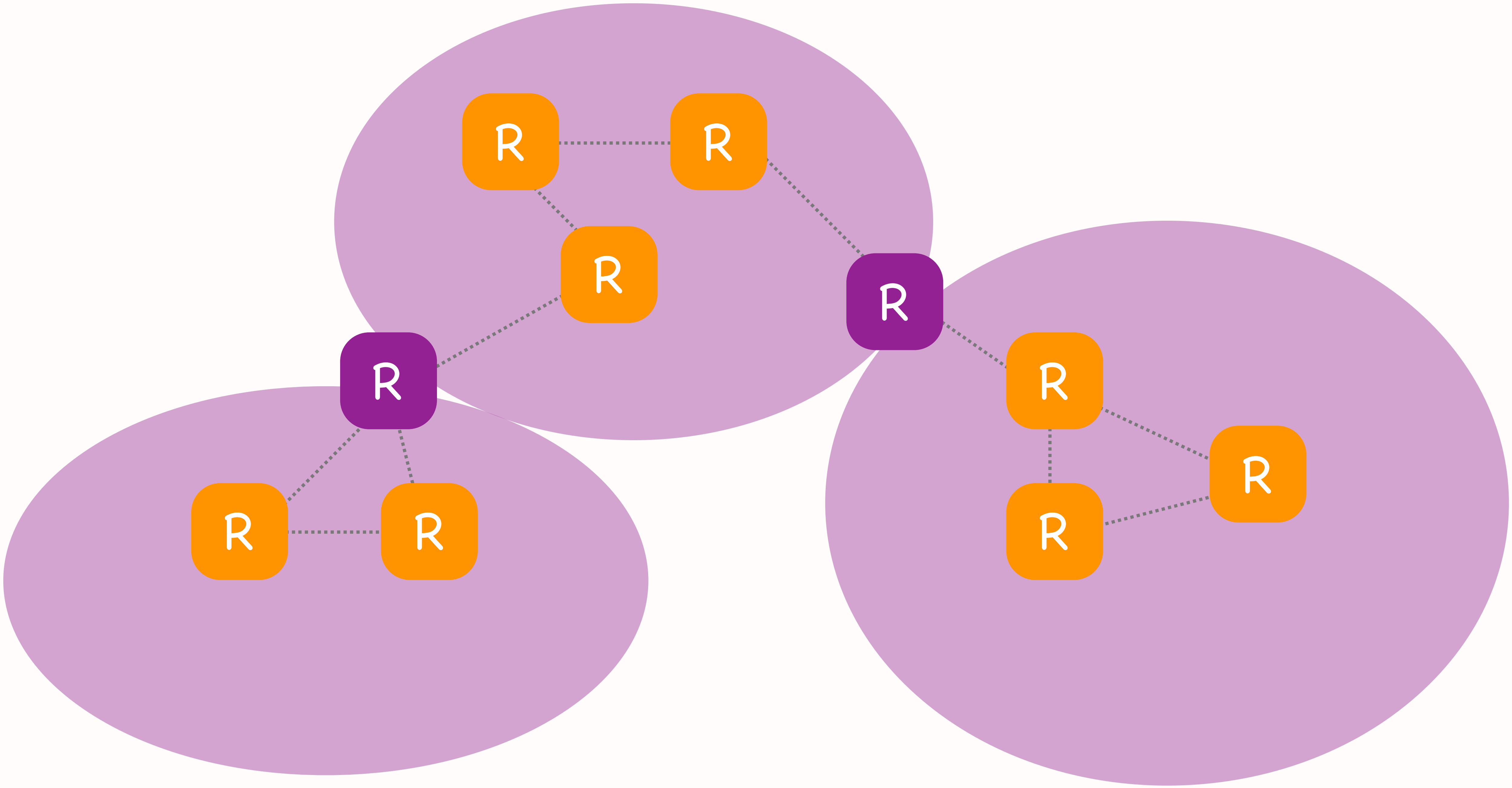
- IP subnet
  - L2 forwarding
  - L2 learning
- Autonomous System (AS)
  - IP (L3) forwarding
  - intra-domain routing
- Internet
  - IP (L3) forwarding
  - inter-domain routing (BGP)


S
S
S
R


R


R
R
R
R
R
R
R
R
R
R
R


R
R
R
R
R
R
R
R
R
R


R
R
R
R
R
R
R
R
R
R
R
R

2 x two-level hierarchies

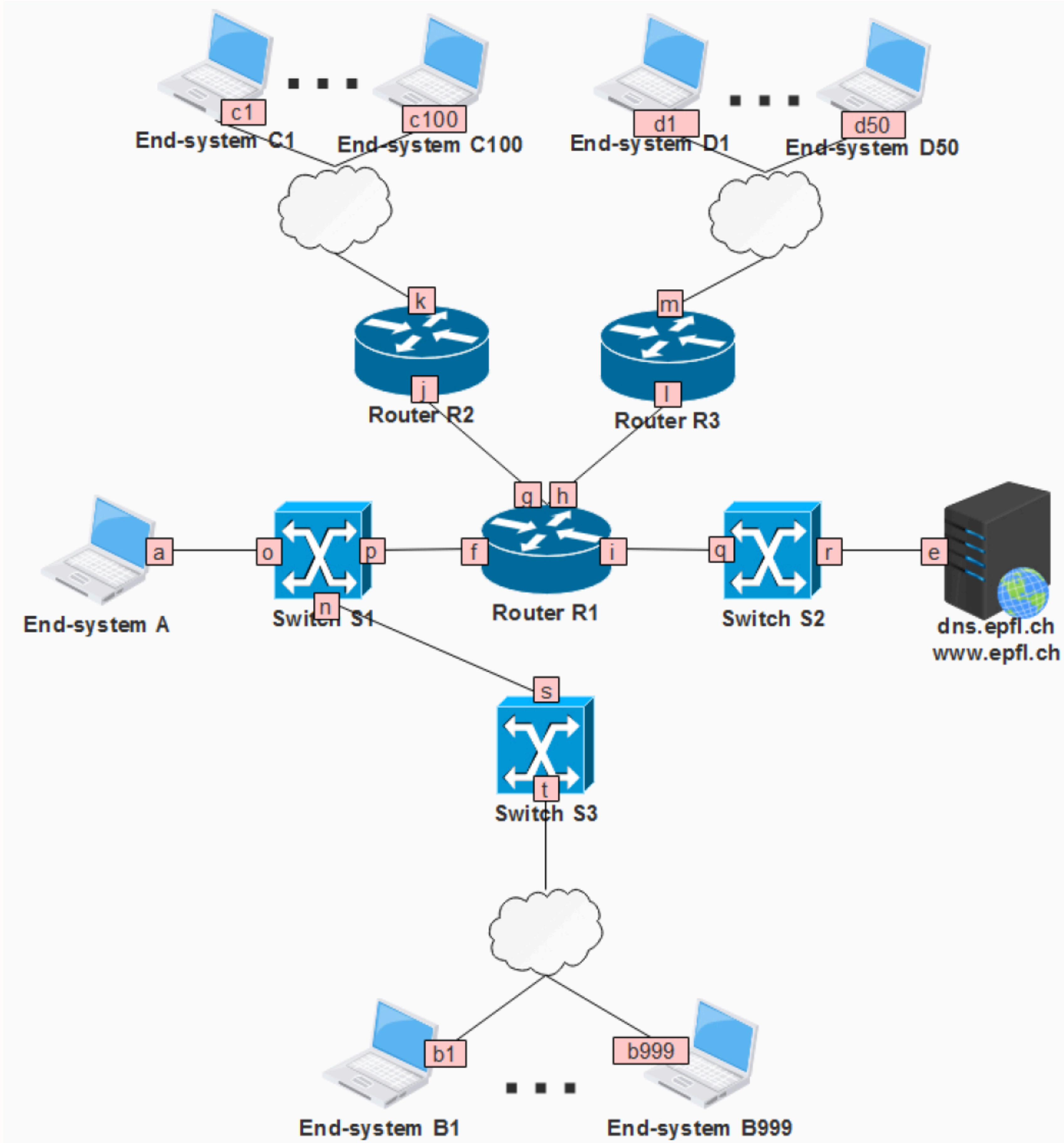
- IP subnet vs. Internet
  - L2 vs. IP forwarding
  - different forwarding processes,
    different layers => different packet headers

- Autonomous System (AS) vs. Internet
  - intra-domain vs. inter-domain routing
  - different routing protocols
  - same forwarding process (IP), same layer

Question: Allocate IP addresses

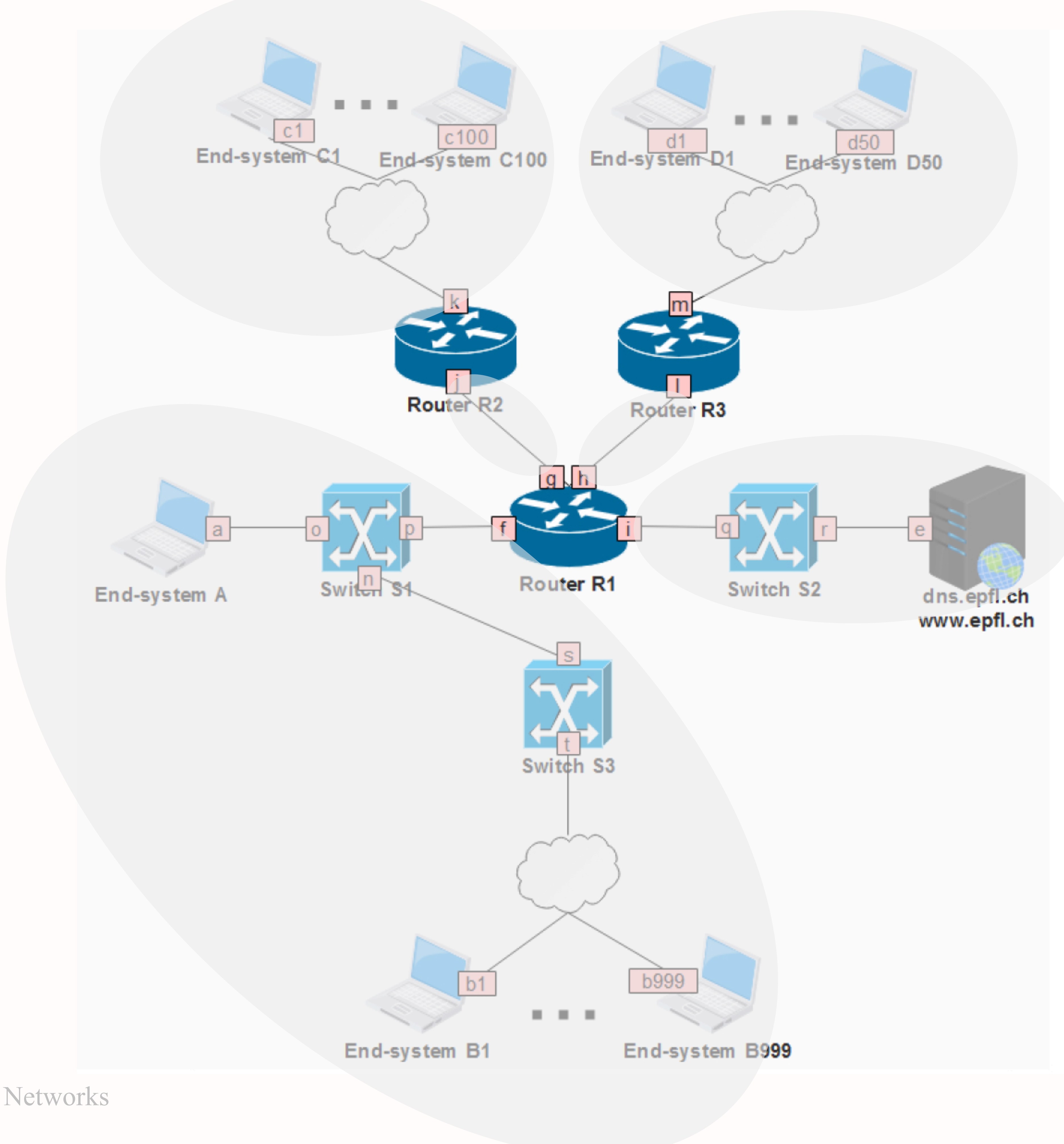
- Given network topology and IP prefix, allocate IP addresses using smallest possible range per IP subnet
- Final 2018, Problem 2, Question 1

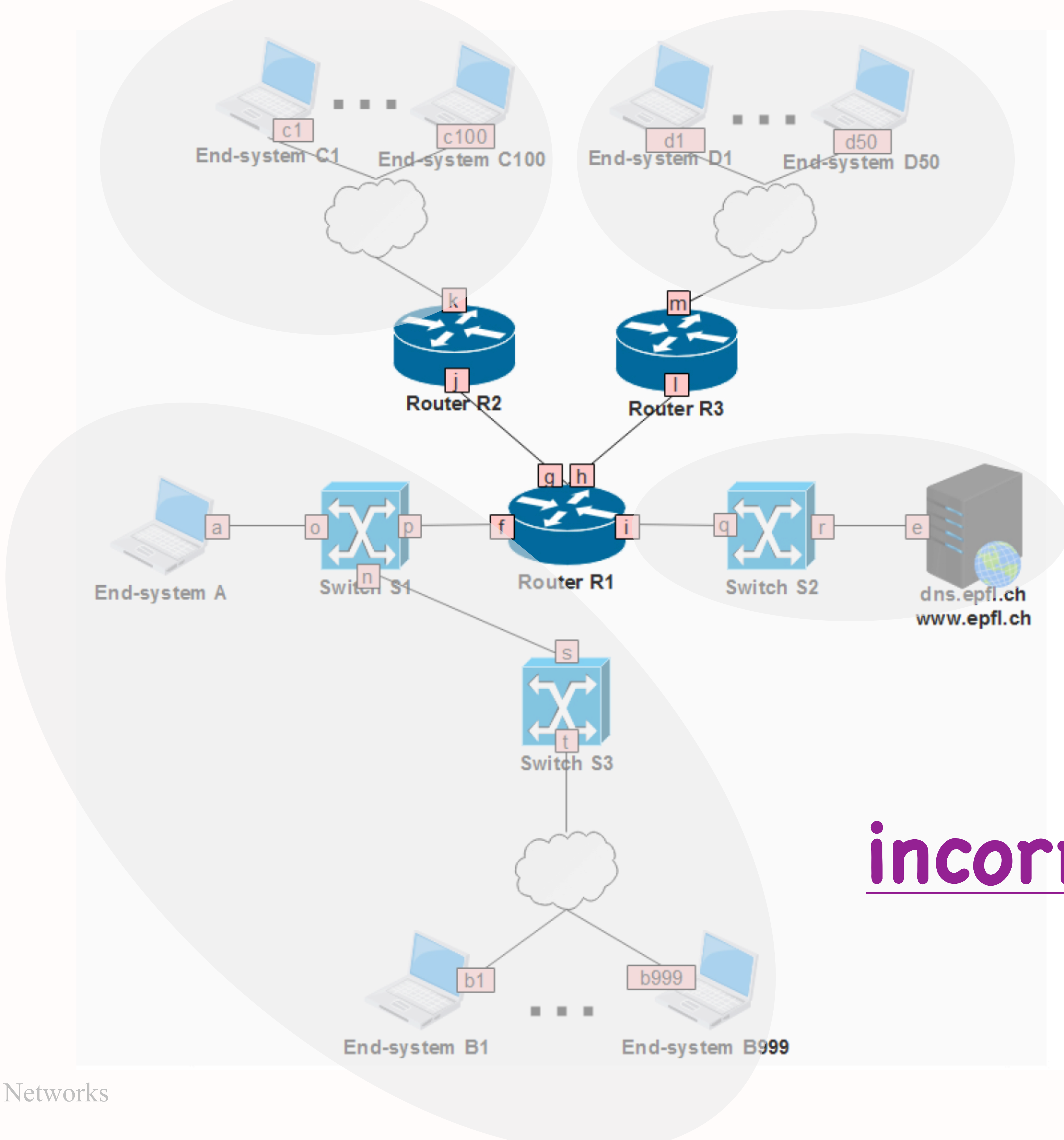
Allocate IP addresses from: 100.0.0.0/16



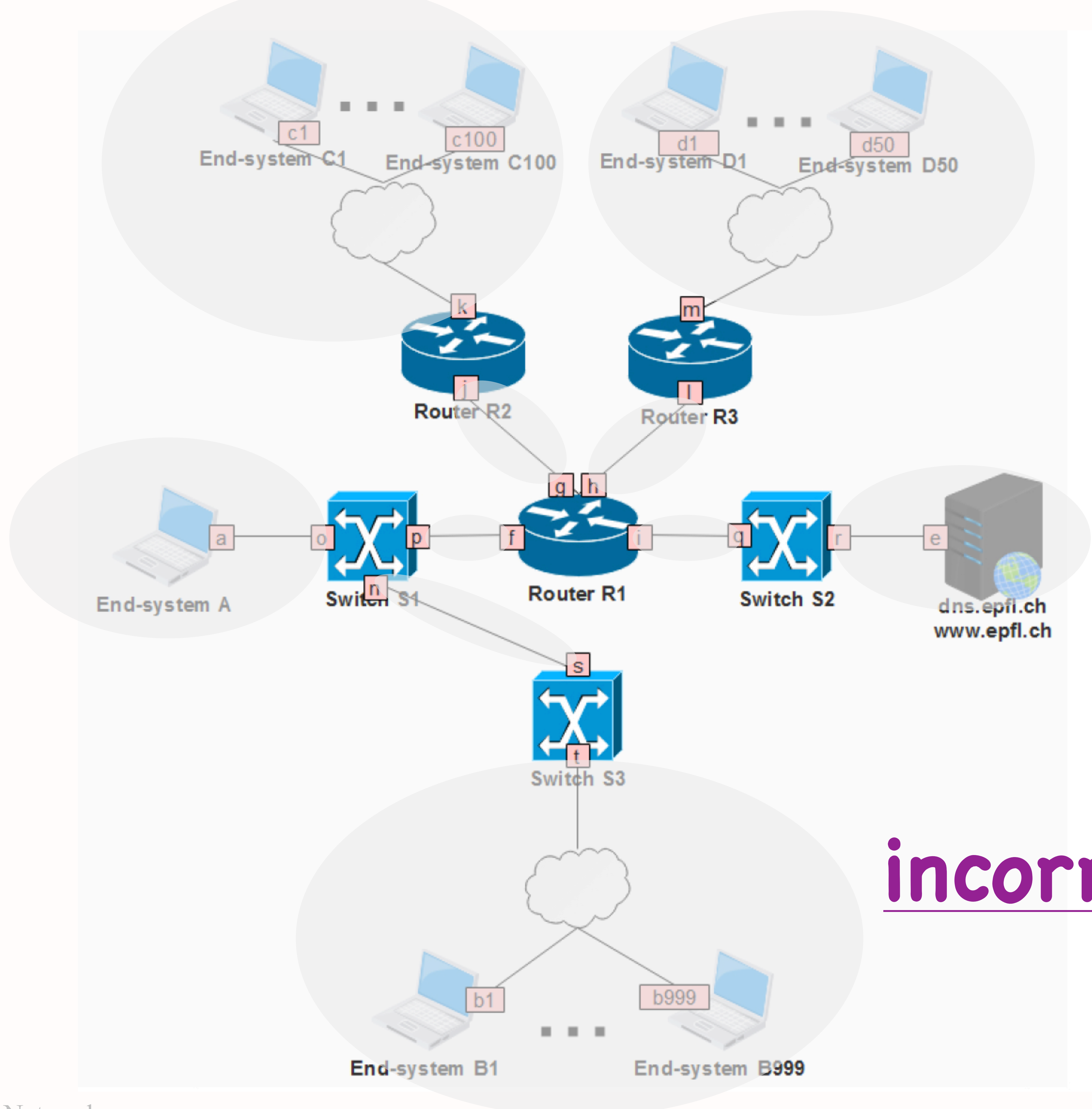
Step 1: Draw the IP subnets

- IP subnet = contiguous network area that has routers only at its boundaries
- Each interface of an IP router belongs to a different IP subnet

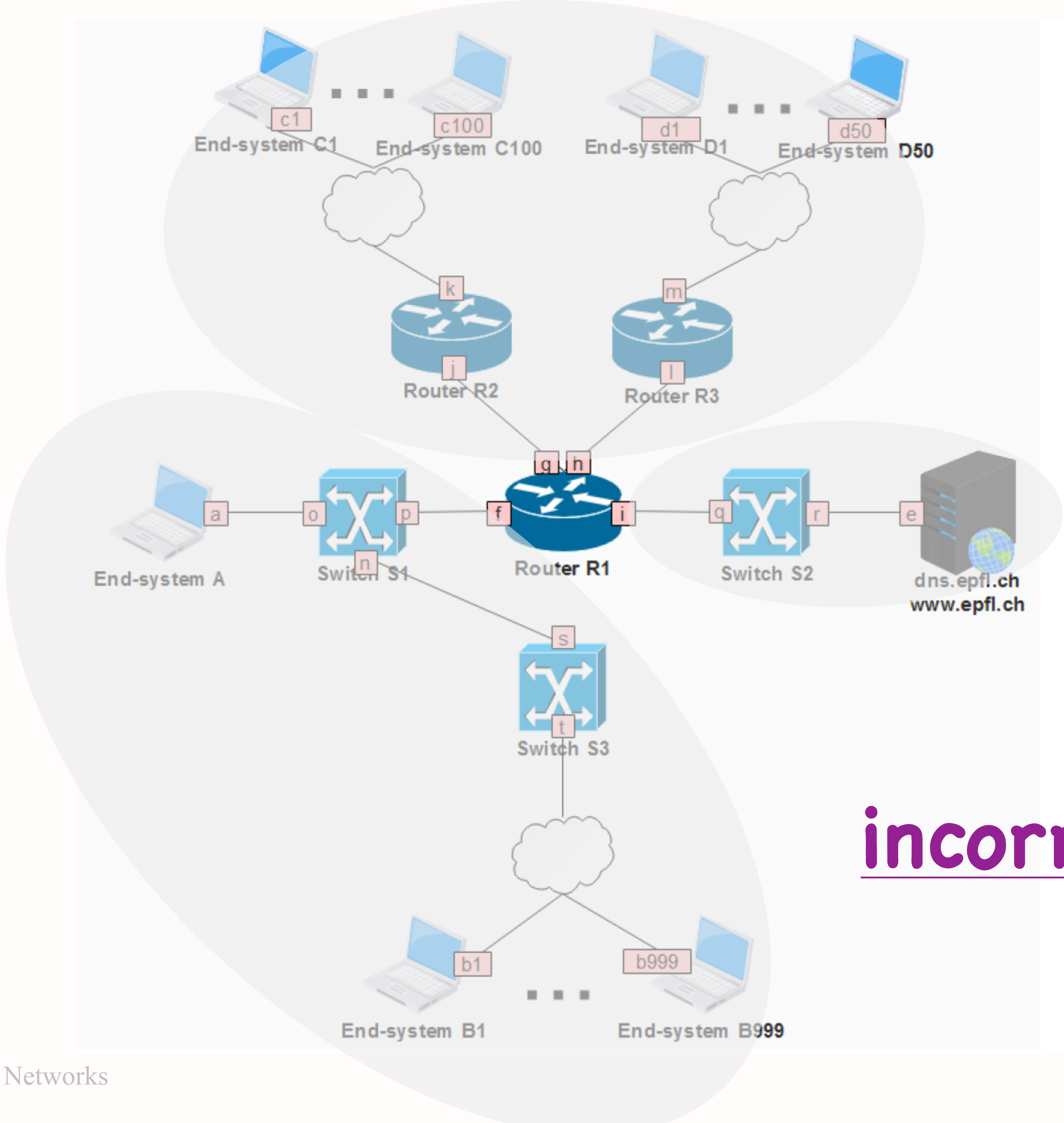

c1
c100
End-system C1
End-system C100
d1
d50
End-system D1
End-system D50
k
m
j
l
Router R2
Router R3
g
h
a
o
p
f
i
q
r
e
n
End-system A
Switch S1
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
b1
b999
End-system B1
End-system B999


c1
c100
End-system C1
End-system C100
d1
d50
End-system D1
End-system D50
k
m
j
l
Router R2
Router R3
g
h
a
o
p
f
i
q
r
e
n
End-system A
Switch S1
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
b1
b999
End-system B1
End-system B999

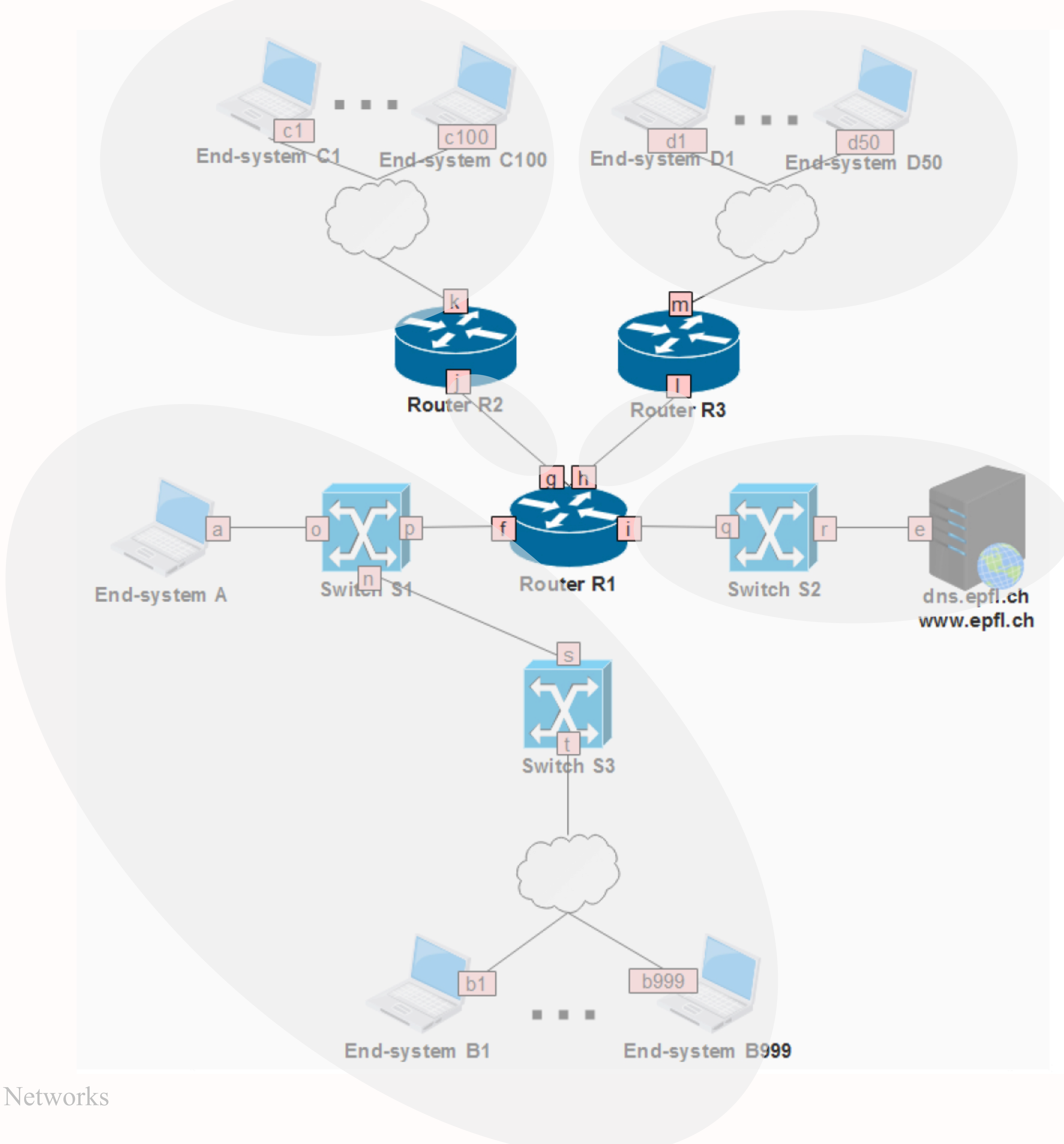
incorrect


c1
c100
End-system C1
End-system C100
d1
d50
End-system D1
End-system D50
k
m
Router R2
j
l
Router R3
g
h
a
o
p
f
i
q
r
e
End-system A
Switch S1
n
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
b1
b999
End-system B1
End-system B999

incorrect


c1
End-system C1
c100
End-system C100
d1
End-system D1
d50
End-system D50
k
m
j
Router R2
l
Router R3
g
h
a
o
p
f
i
q
r
e
End-system A
n
Switch S1
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
b1
b999
End-system B1
End-system B999

incorrect

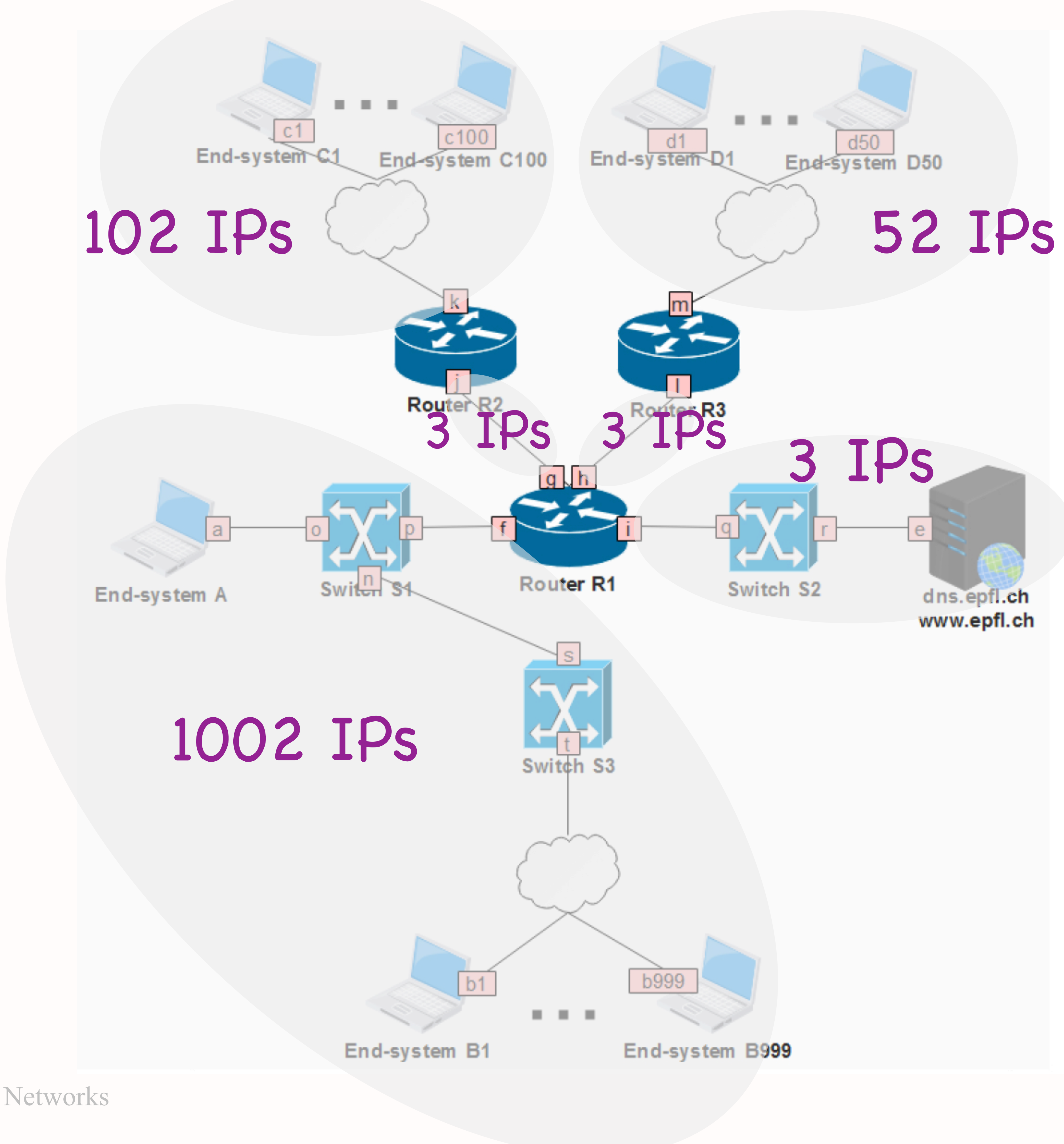

c1
c100
End-system C1
End-system C100
d1
d50
End-system D1
End-system D50
k
m
j
l
Router R2
Router R3
g
h
a
o
p
f
i
q
r
e
n
End-system A
Switch S1
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
b1
b999
End-system B1
End-system B999

Step 2: Count IPs per subnet

- One IP address per end-system interface
- One IP address per router interface
  - not needed for IP forwarding,
    but needed for other practical reasons
- No IP addresses for link-layer switches
  - in reality they have IP addresses,
    but ignore to simplify exam

Step 2: Count IPs per subnet

- One broadcast IP address
  - the very last IP address covered by the IP prefix
  - addresses all entities with an IP address in the local subnet
- No network IP address
  - the very first IP address covered by the IP prefix
  - meant to have special meaning, but not typically used


c1
End-system C1
c100
End-system C100
d1
End-system D1
d50
End-system D50
102 IPs
52 IPs
k
m
j
l
Router R2
Router R3
3 IPs
3 IPs
3 IPs
g
h
a
o
p
f
i
q
r
e
n
End-system A
Switch S1
Router R1
Switch S2
dns.epfl.ch
www.epfl.ch
s
t
Switch S3
1002 IPs
b1
b999
End-system B1
End-system B999

Step 3: Allocate IP prefixes

- One approach: start from the largest IP subnet, allocate consecutive prefixes

- Whatever approach you choose:
  IP prefixes allocated to different IP subnets must not overlap

Step 3: Allocate IP prefixes

- 1st IP subnet: 100.0.0.0/22
  - 1002 IPs => we need 10 bits (22-bit mask)
  - available IP prefix: 100.0.0.0/16
  - 01100100 00000000 xxxxxxxx xxxxxxxx
  - 01100100 00000000 000000xx xxxxxxxx
  - allocated IP prefix: 100.0.0.0/22
  - we get 1024 addresses
  - we are "wasting" some address space because the number of addresses is not a power of 2

Step 3: Allocate IP prefixes

- 2nd IP subnet: 100.0.4.0/25
  - 102 IPs => we need 7 bits (25-bit mask)
  - last allocated IP prefix: 100.0.0.0/22
  - 01100100 00000000 000000xx xxxxxxxx
  - 01100100 00000000 000001xx xxxxxxxx
  - 01100100 00000000 00000100 0xxxxxxx
  - 100.0.4.0/25

Step 3: Allocate IP prefixes

- 3rd IP subnet: 100.0.4.128/26
  - 52 IPs => we need 6 bits (26-bit mask)
  - last allocated IP prefix: 100.0.4.0/25
  - 01100100 00000000 00000100 0xxxxxxx
  - 01100100 00000000 00000100 1xxxxxxx
  - 01100100 00000000 00000100 10xxxxxx
  - 100.0.4.128/25

Step 3: Allocate IP prefixes

- 4th IP subnet: 100.0.4.192/30
  - 3 IPs => we need 2 bits (30-bit mask)
  - last allocated IP prefix: 100.0.4.128/26
  - 01100100 00000000 00000100 10xxxxxx
  - 01100100 00000000 00000100 11xxxxxx
  - 01100100 00000000 00000100 110000xx
  - 100.0.4.192/30

Step 3: Allocate IP prefixes

- 5th IP subnet: 100.0.4.196/30
  - 3 IPs => we need 2 bits (30-bit mask)
  - last allocated IP prefix: 100.0.4.192/30
  - 01100100 00000000 00000100 110000xx
  - 01100100 00000000 00000100 110001xx
  - 100.0.4.196/30

Step 3: Allocate IP prefixes

- 6th IP subnet: 100.0.4.200/30
  - 3 IPs => we need 2 bits (30-bit mask)
  - last allocated IP prefix: 100.0.4.196/30
  - 01100100 00000000 00000100 110001xx
  - 01100100 00000000 00000100 110010xx
  - 100.0.4.200/30

Step 4: Allocate IP addresses

- 1st IP subnet: 1002 addresses from 100.0.0.0/22
  - 01100100 00000000 000000xx xxxxxxxx
  - 01100100 00000000 00000011 11111111
  - broadcast IP address: 100.0.3.255
  - 100.0.0.0 – 100.0.3.232

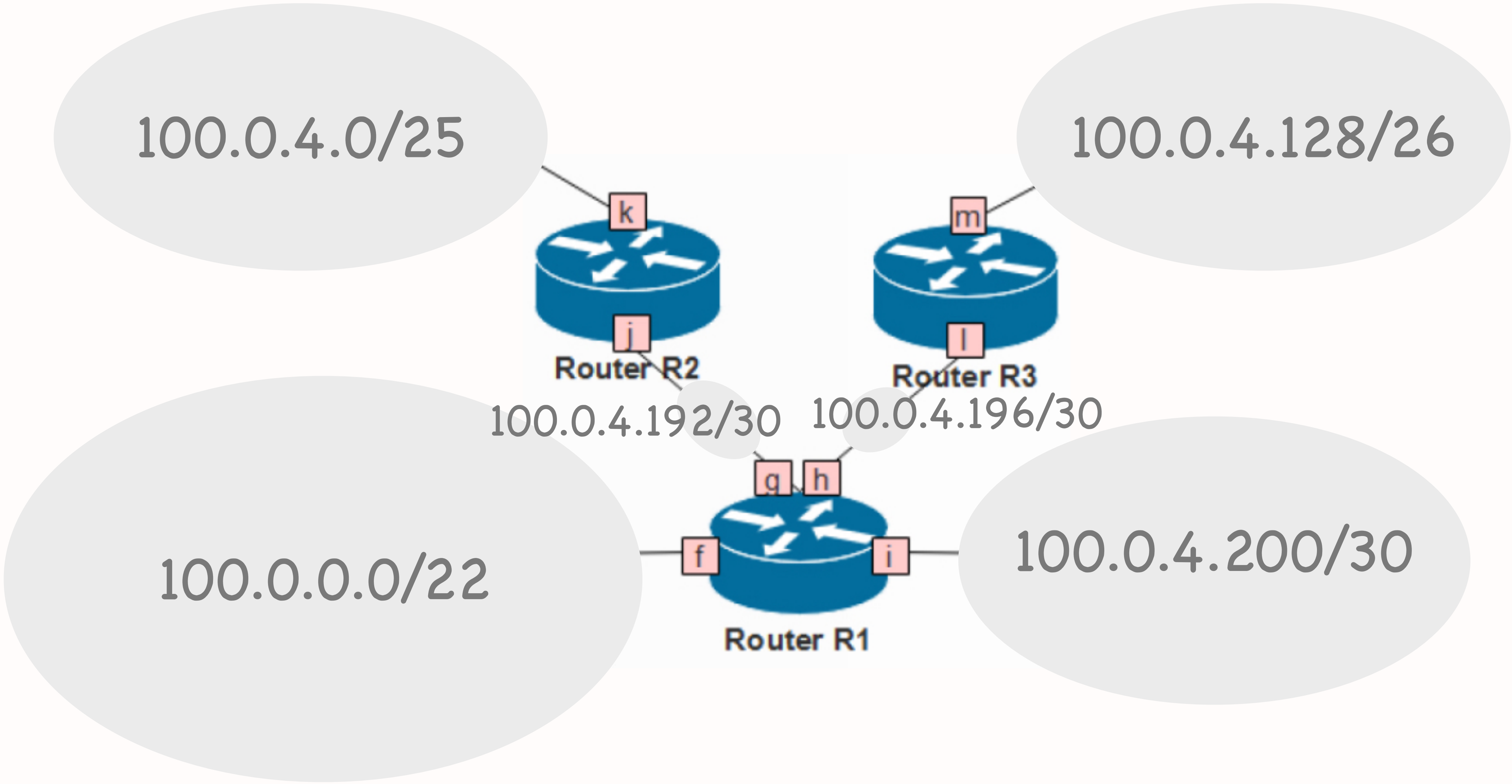
Step 4: Allocate IP addresses

- 2nd IP subnet: 102 addresses from 100.0.4.0/25
  - 01100100 00000000 00000100 0xxxxxxx
  - 01100100 00000000 00000100 01111111
  - broadcast IP address: 100.0.4.127
  - 100.0.4.0 – 100.0.4.100
- ...

Question: Show router tables

- Given network topology and allocated IPs, show router forwarding tables, assuming least-cost path routing protocol that has converged

- Final 2018, Problem 2, Question 2



100.0.0.0/22	f
100.0.4.0/25	g
100.0.4.128/26	h
100.0.4.192/30	g
100.0.4.198/30	h
100.0.4.200/30	i

Question: Show packets

- Given a communication scenario, show all the packets transmitted by end-systems and routers
- Final 2018, Problem 2, Question 3

DNS request from A to server

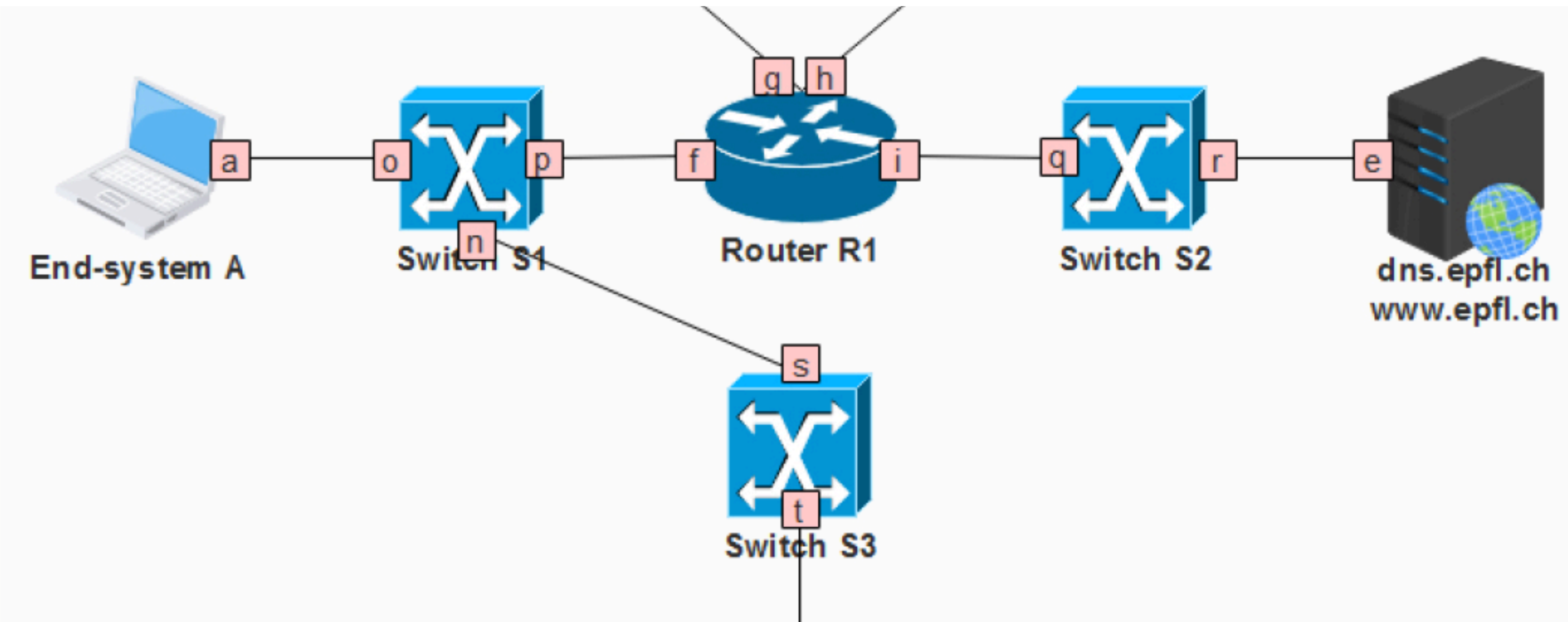
DNS response from server to A

HTTP GET request for base file from A to server

HTTP GET response from server to A

HTTP GET request for image file from A to server

HTTP GET response from server to A



DNS request from A to server

ARP request, MAC: A—broadcast

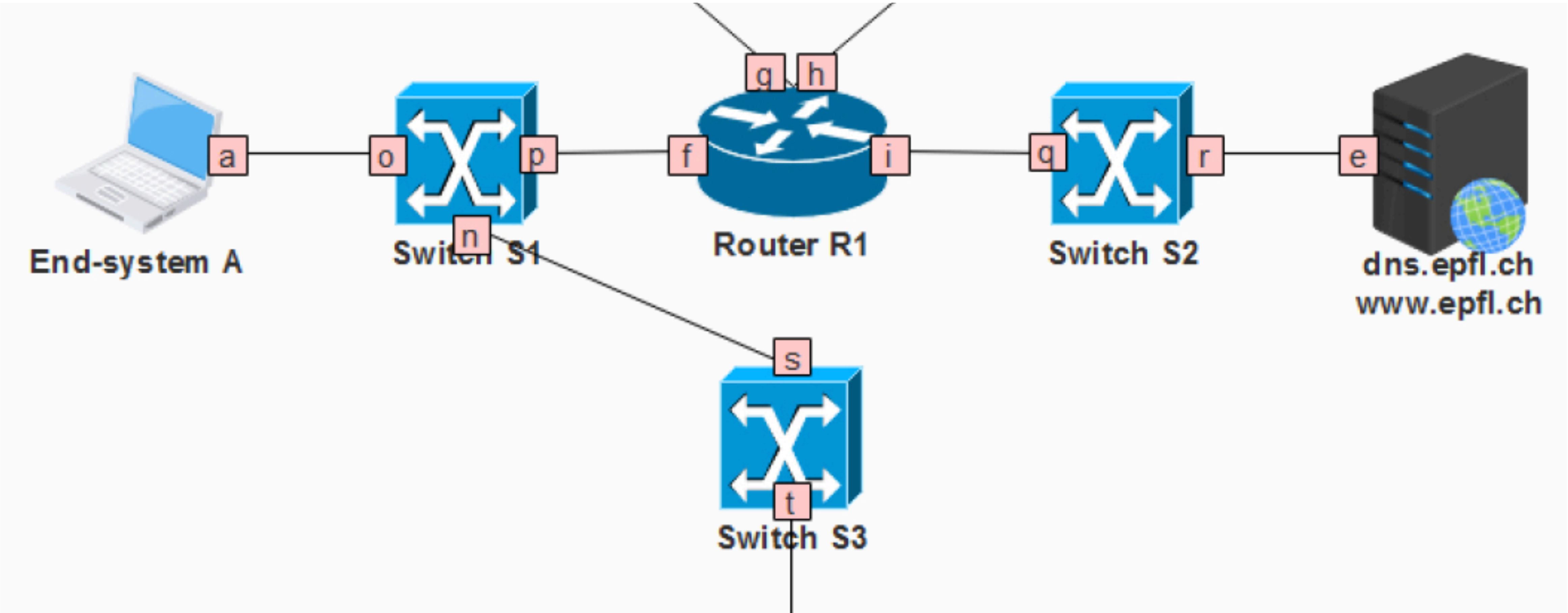
ARP response, MAC: R1—A

DNS request, MAC: A—R1, IP: A—DNS

ARP request, MAC: R1—broadcast

ARP response, MAC: DNS—R1

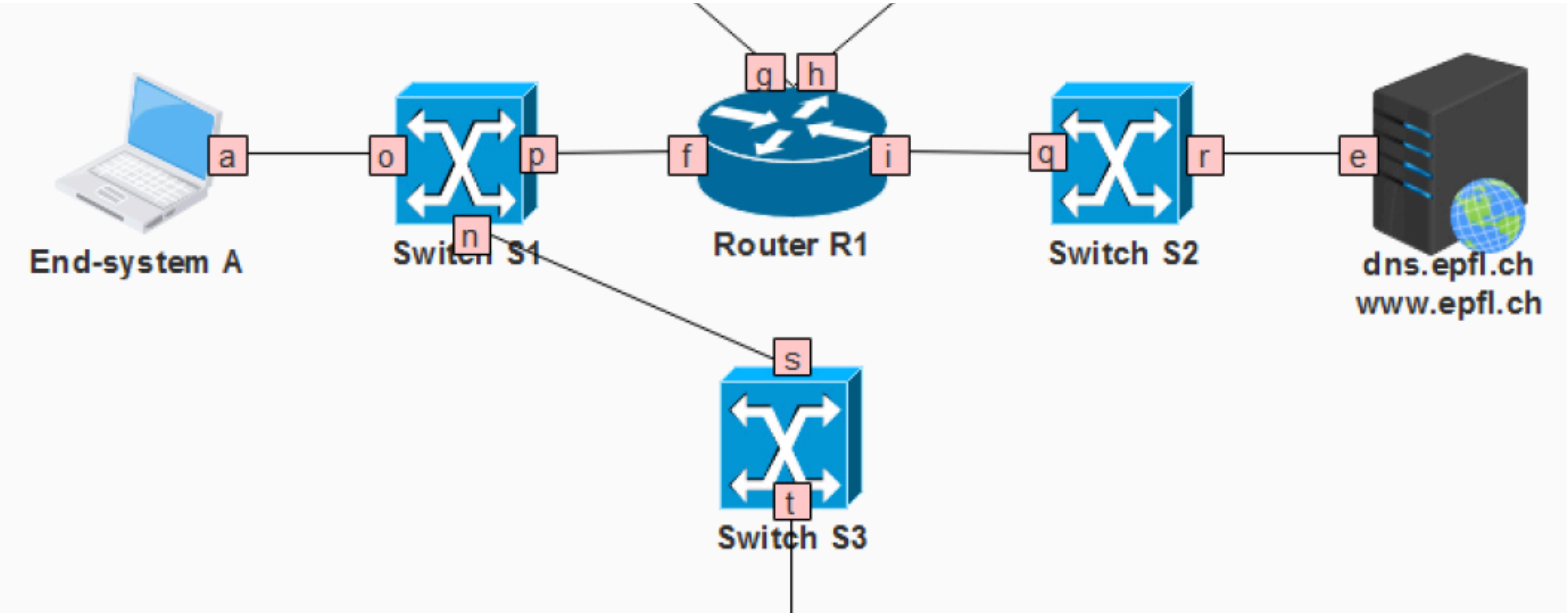
DNS request, MAC: R1—DNS, IP: A—DNS



DNS response from server to A

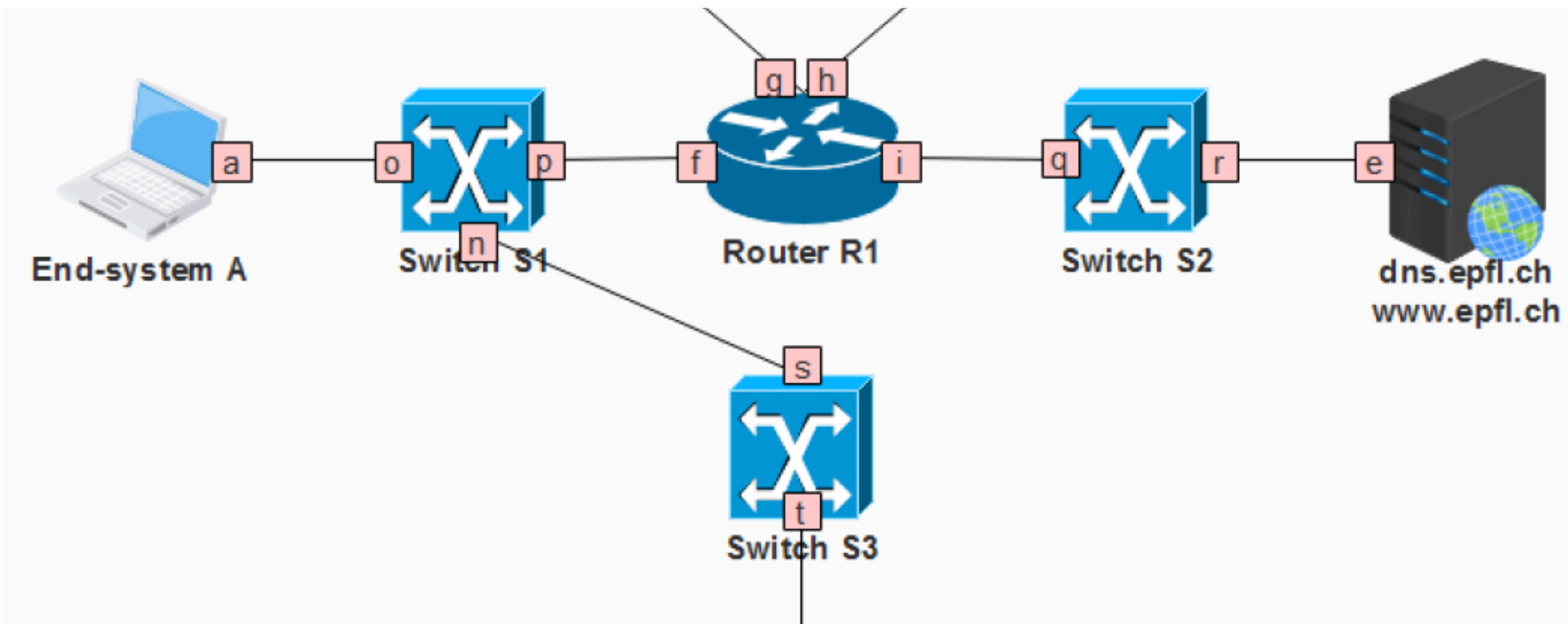
DNS response, MAC: DNS—R1, IP: DNS—A

DNS response, MAC: R1—A, IP: DNS—A



HTTP GET request from A to server

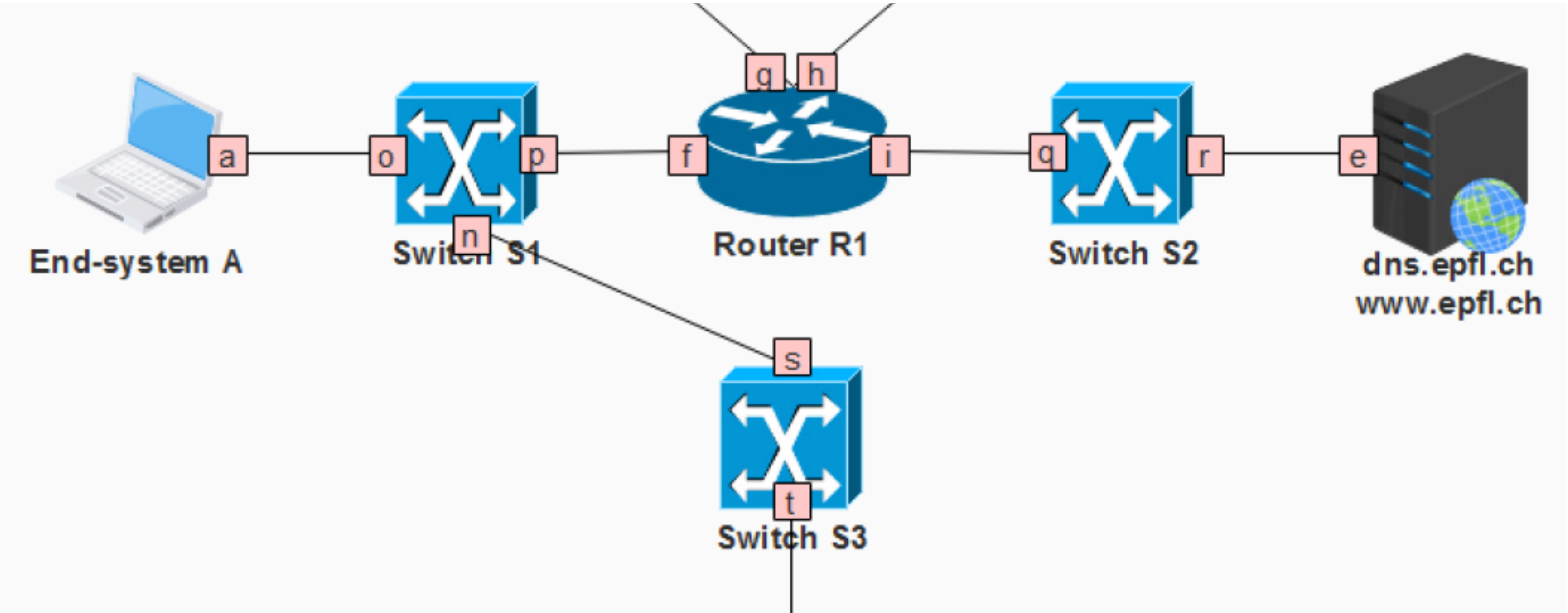
- TCP SYN, MAC: A—R1, IP: A—DNS
- TCP SYN, MAC: R1—DNS, IP: A—DNS
- TCP SYN ACK, MAC: DNS—R1, IP: DNS—A
- TCP SYN ACK, MAC: R1—A, IP: DNS—A
- HTTP GET request, MAC: A—R1, IP: A—DNS
- HTTP GET request, MAC: R1—DNS, IP: A—DNS



HTTP GET response from server to A

HTTP GET response, MAC: DNS—R1, IP: DNS—A

HTTP GET response, MAC: R1—A, IP: DNS—A

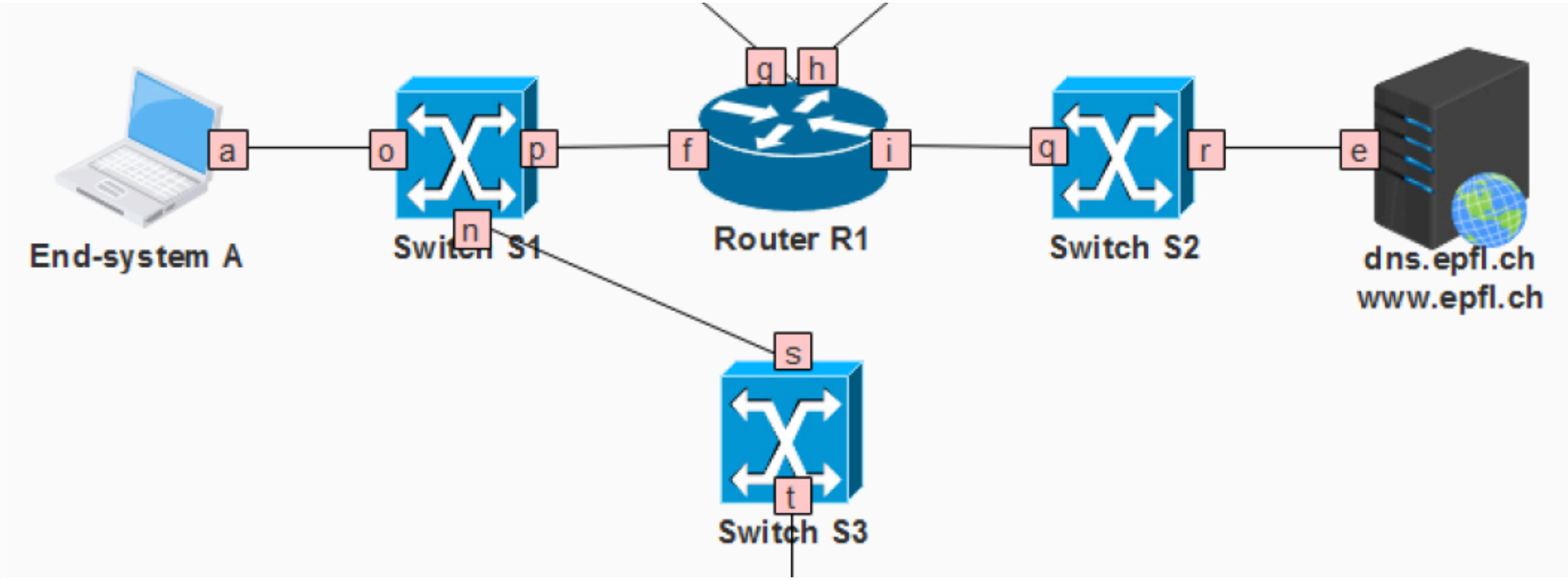


Question: Show switch tables

- Given a communication scenario, show switch forwarding tables
- Final 2018, Problem 2, Question 4

A's MAC o
R1's MAC p

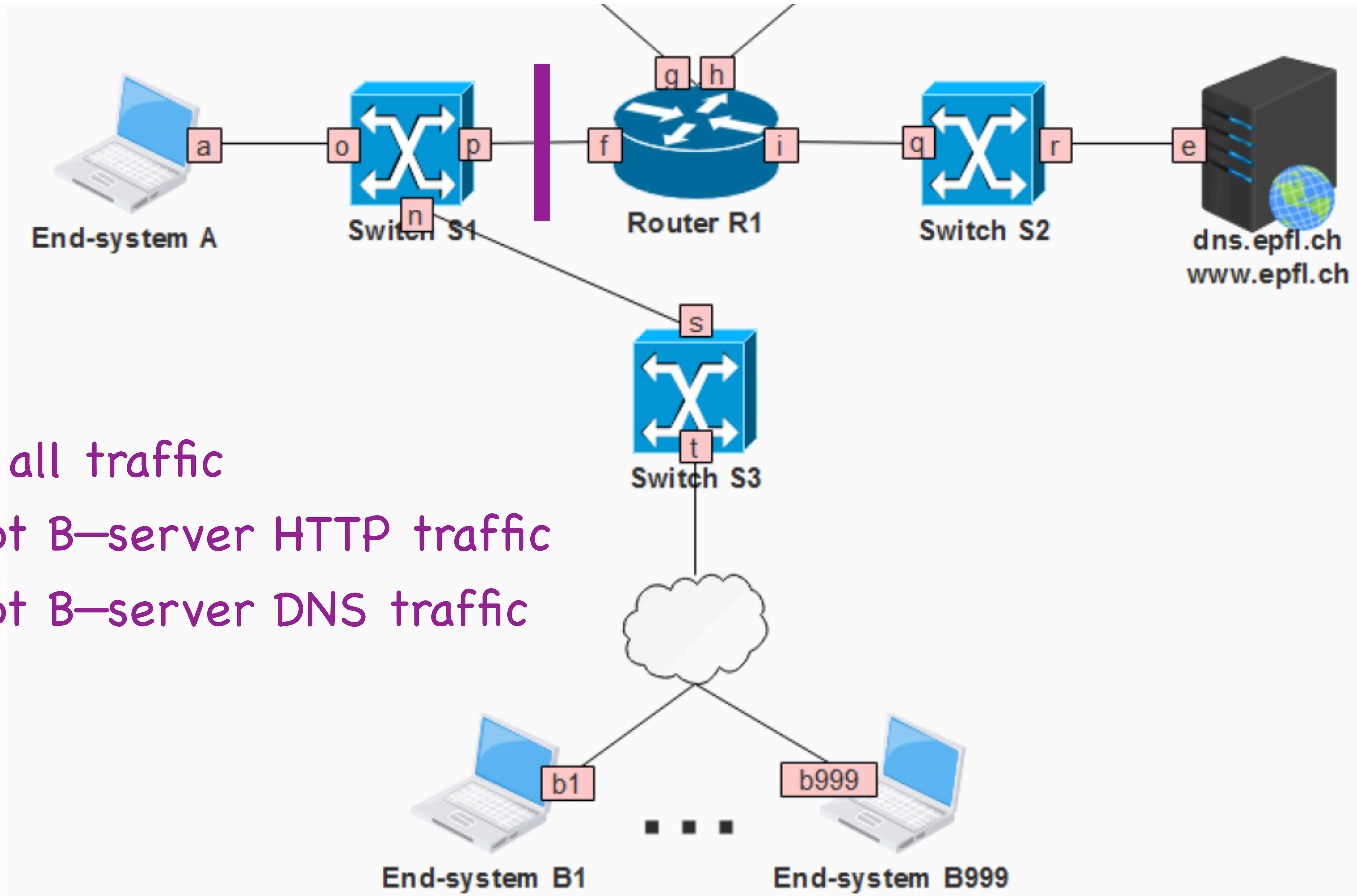
R1's MAC q
DNS's MAC r



A's MAC s

Question: Show filtering table

- Show filtering table that allows a given communication pattern
- Final 2018, Problem 2, Question 5



Deny all traffic

Except B–server HTTP traffic

Except B–server DNS traffic

Question: Show filtering table

- List filtering table fields
  - action, TCP/UDP, src IP, dst IP, src port, dst port
- List entries that achieve given pattern
  - allow TCP B-prefix server-IP any 80
  - allow TCP server-IP B-prefix 80 any
  - allow UDP B-prefix server-IP any 53
  - allow UDP server-IP B-prefix 53 any
  - deny any any any any any any

TCP elements

- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
- Flow control
- Congestion control

TCP elements

- Connection setup and teardown
- Connection hijacking
- Connection setup (SYN) flooding
- Flow control
- Congestion control

Flow control

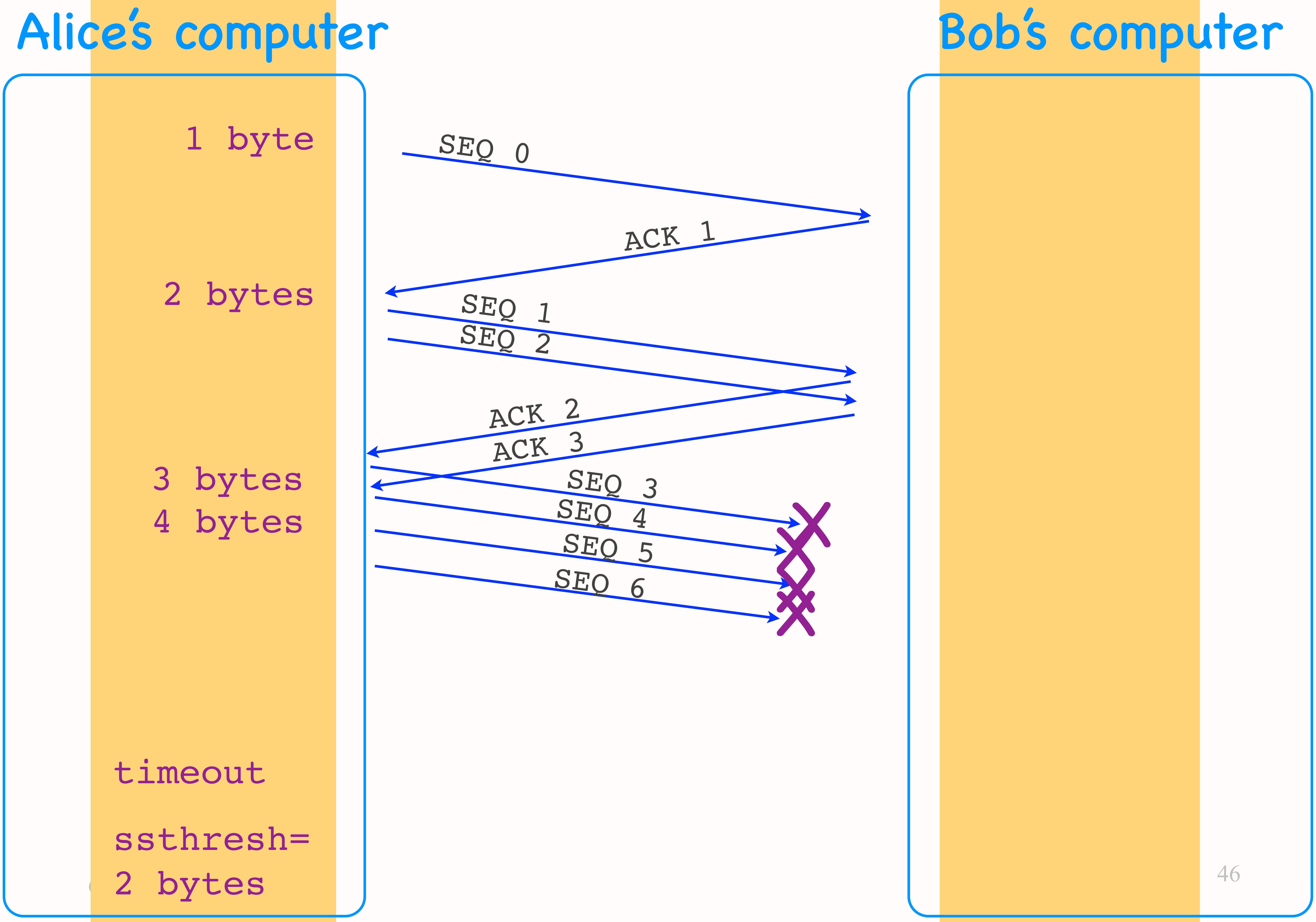
- Goal: not overwhelm the receiver
  - not send at a rate that the receiver cannot handle
- How: "receiver window"
  - spare room in receiver's rx buffer
  - receiver communicates it to sender as TCP header field

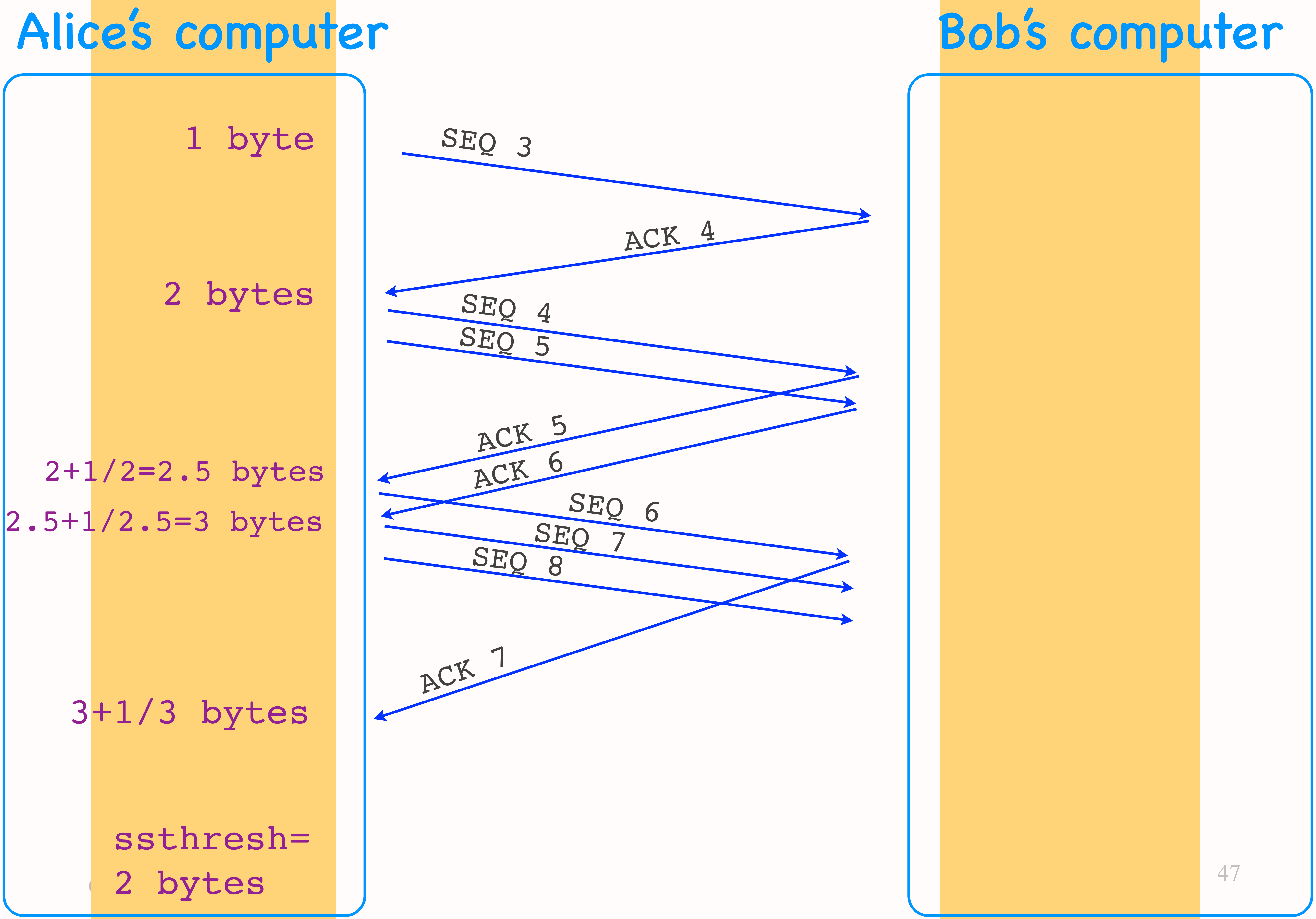
Congestion control

- Goal: not overwhelm the network
  - not send at a rate that the would create network congestion
- How: "congestion window"
  - number of unacknowledged bytes that the sender can transmit without creating congestion
  - sender estimates it on its own

Self-clocking

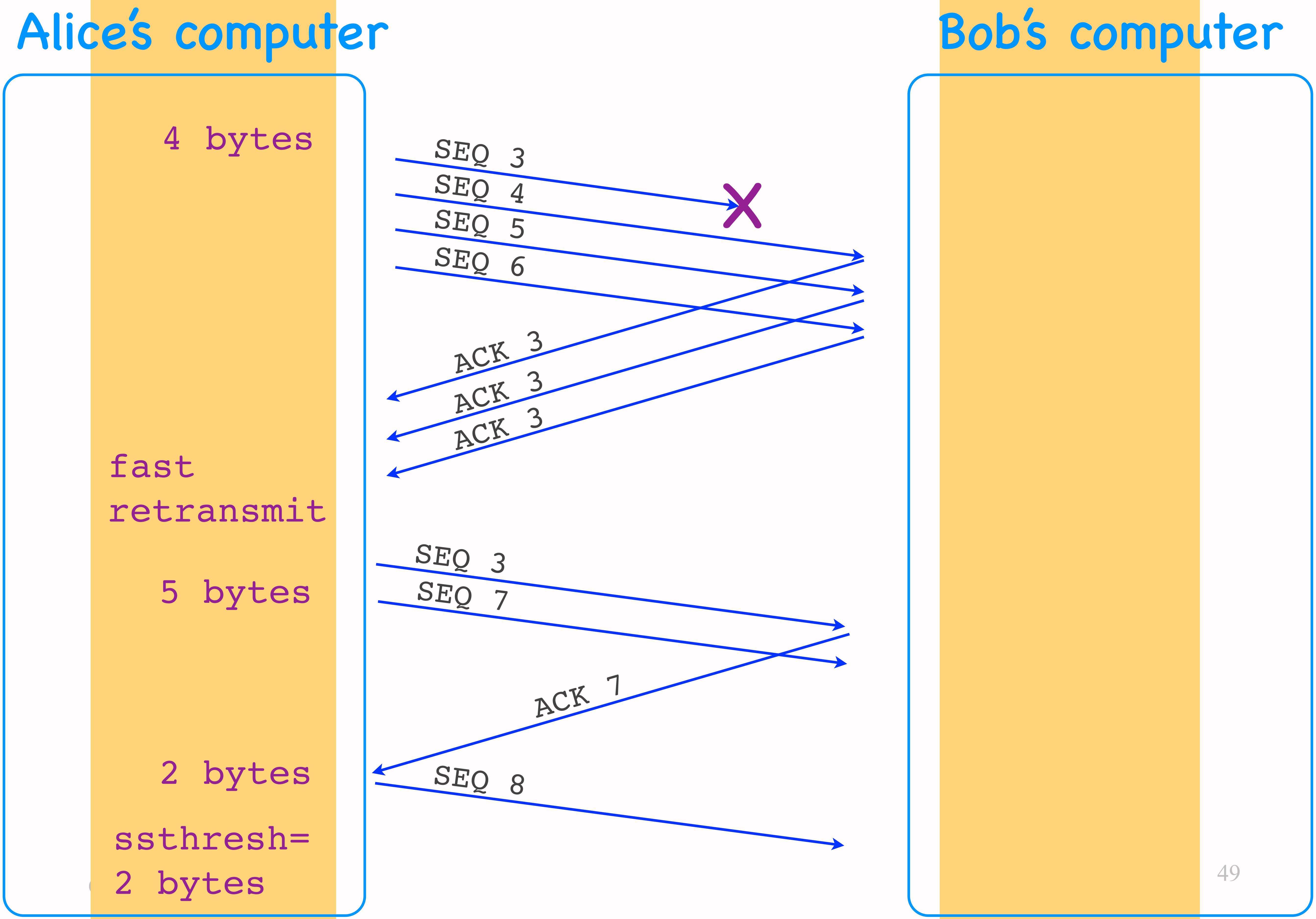
- Sender guesses the “right” congestion window based on the ACKs
- ACK = no congestion, increase window
- No ACK = congestion, decrease window


Alice's computer
Bob's computer
1 byte
SEQ 0
ACK 1
2 bytes
SEQ 1
SEQ 2
ACK 2
ACK 3
3 bytes
4 bytes
SEQ 3
SEQ 4
SEQ 5
SEQ 6
timeout
ssthresh=
2 bytes


Alice's computer
Bob's computer
1 byte
SEQ 3
ACK 4
2 bytes
SEQ 4
SEQ 5
ACK 5
ACK 6
2+1/2=2.5 bytes
2.5+1/2.5=3 bytes
SEQ 6
SEQ 7
SEQ 8
ACK 7
3+1/3 bytes
ssthresh=
2 bytes

Basic algorithm (Tahoe)

- Set window to 1 MSS,
  increase exponentially
- On timeout, reset window to 1 MSS,
  set ssthresh to last window/2
- On reaching ssthresh,
  transition to linear increase



Alice's computer
Bob's computer
4 bytes
SEQ 3
SEQ 4
SEQ 5
SEQ 6
ACK 3
ACK 3
ACK 3
fast retransmit
5 bytes
SEQ 3
SEQ 7
ACK 7
2 bytes
SEQ 8
ssthresh=
2 bytes

Basic algorithm (Reno)

- Set window to 1 MSS,
  increase exponentially

- On timeout, reset window to 1 MSS,
  set ssthresh to last window/2

- On reaching ssthresh or 3 duplicate ACKs,
  transition to linear increase

Two retransmission triggers

- Timeout => retransmission of oldest unacknowledged segment
- 3 duplicate ACKs => fast retransmit of oldest unacknowledged segment
  - avoid unnecessary wait for timeout
  - 1 duplicate ACK not enough <= network may have reordered a data segment or duplicated an ACK

TCP terminology

- Exponential increase = slow start
  - on timeout, reset window to 1 MSS
  - set ssthresh to last window/2
- Linear increase = congestion avoidance
  - on window reaching ssthresh
  - on receiving 3 duplicate ACKs

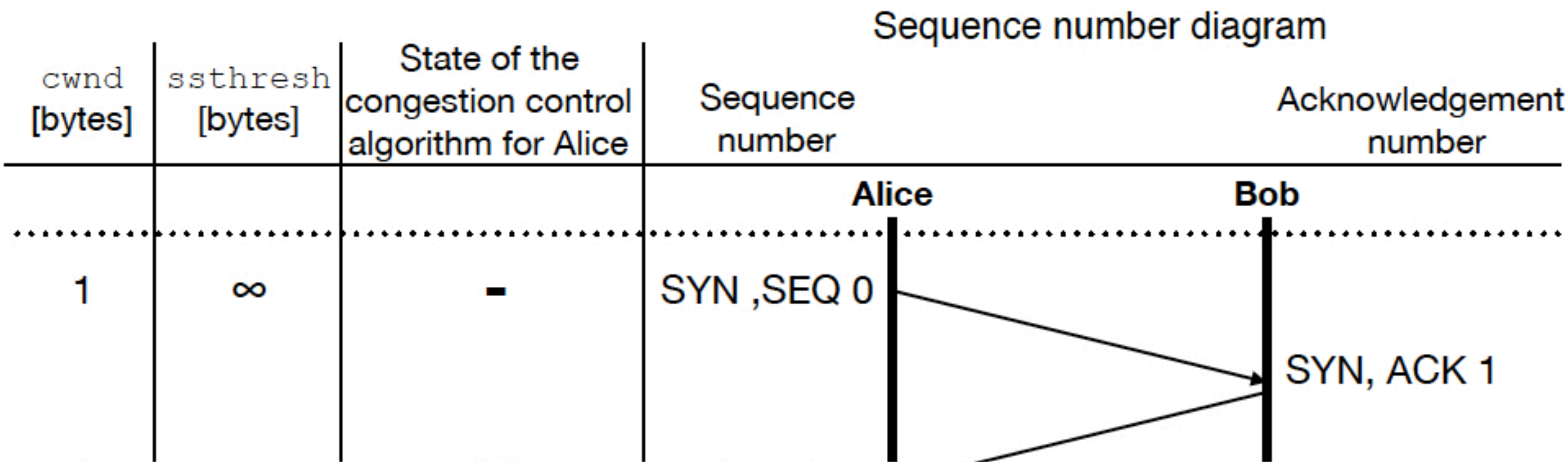
Question: Show TCP diagram

- Given Alice-Bob communication scenario, show all TCP events between them
- Final 2018, Problem 4, Question 1

cwnd [bytes]	ssthresh [bytes]	State of the congestion control algorithm for Alice	Sequence number diagram: Sequence number	Acknowledgement number
			Alice	Bob

Alice sends 12 bytes of data

Bob's 3,5,6,8,9,10th segment lost



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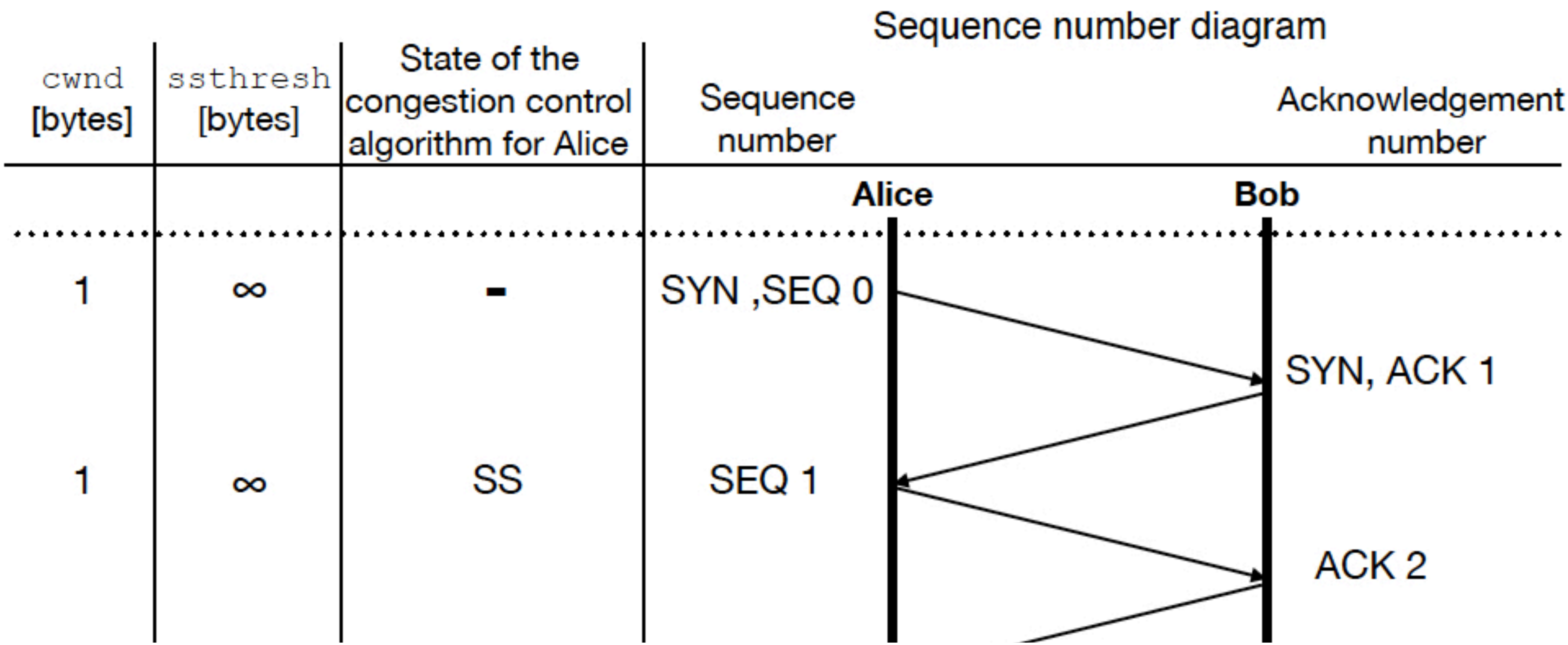
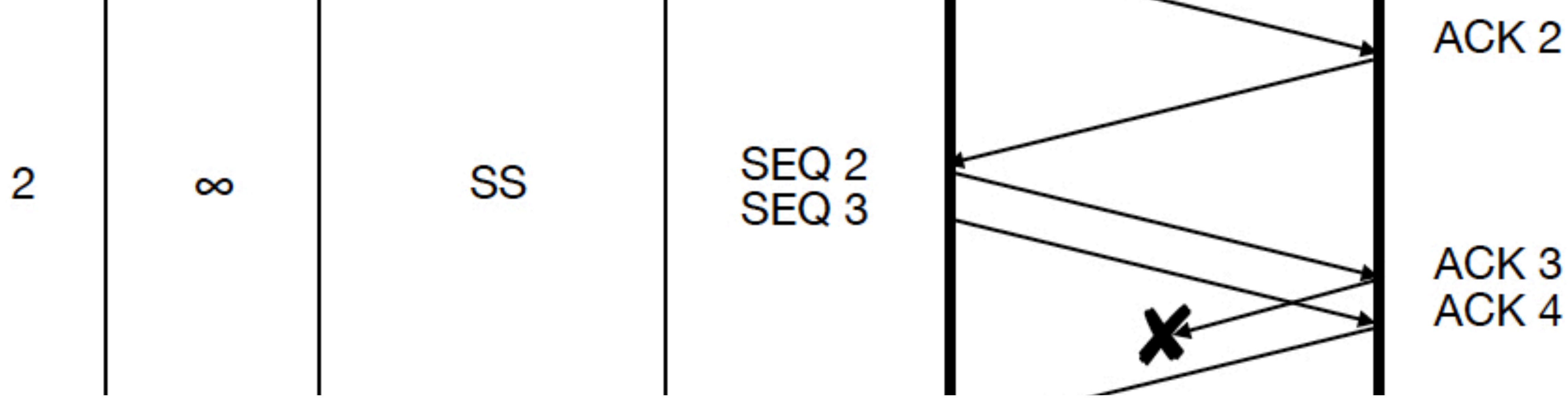


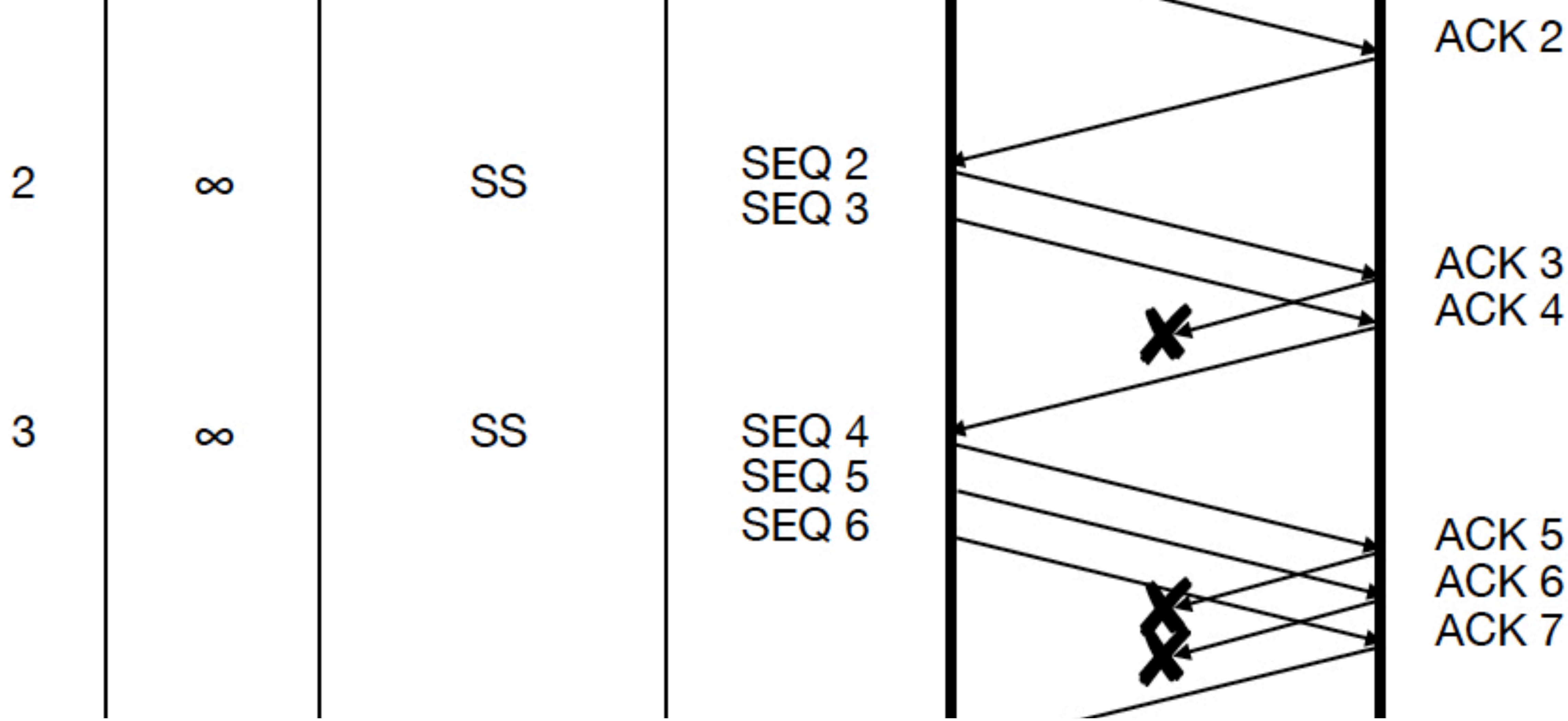
Alice sends 12 bytes of data

Bob's 3,5,6,8,9,10th segment lost



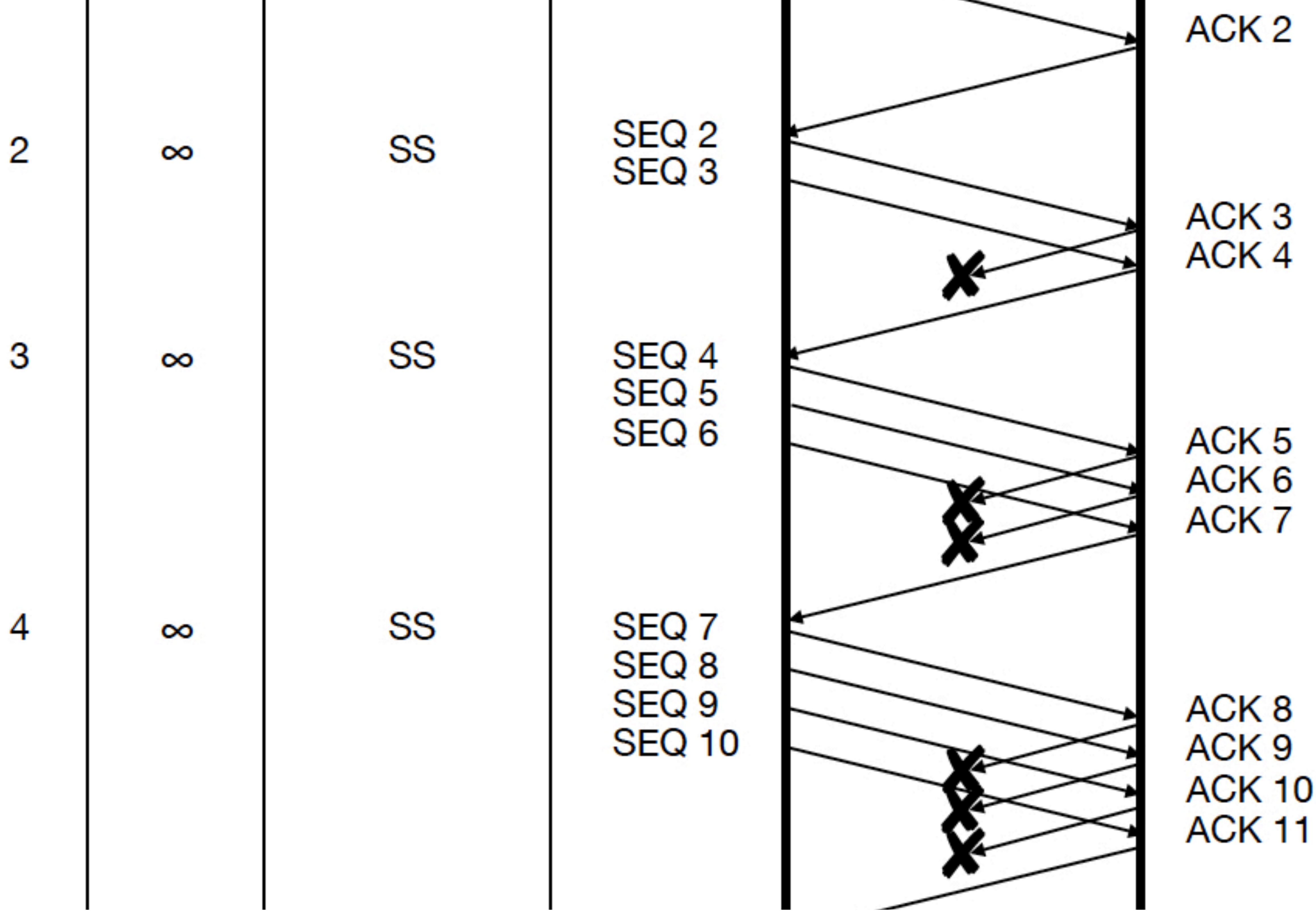
Alice sends 12 bytes of data

Bob's 3,5,6,8,9,10th segment lost



Alice sends 12 bytes of data

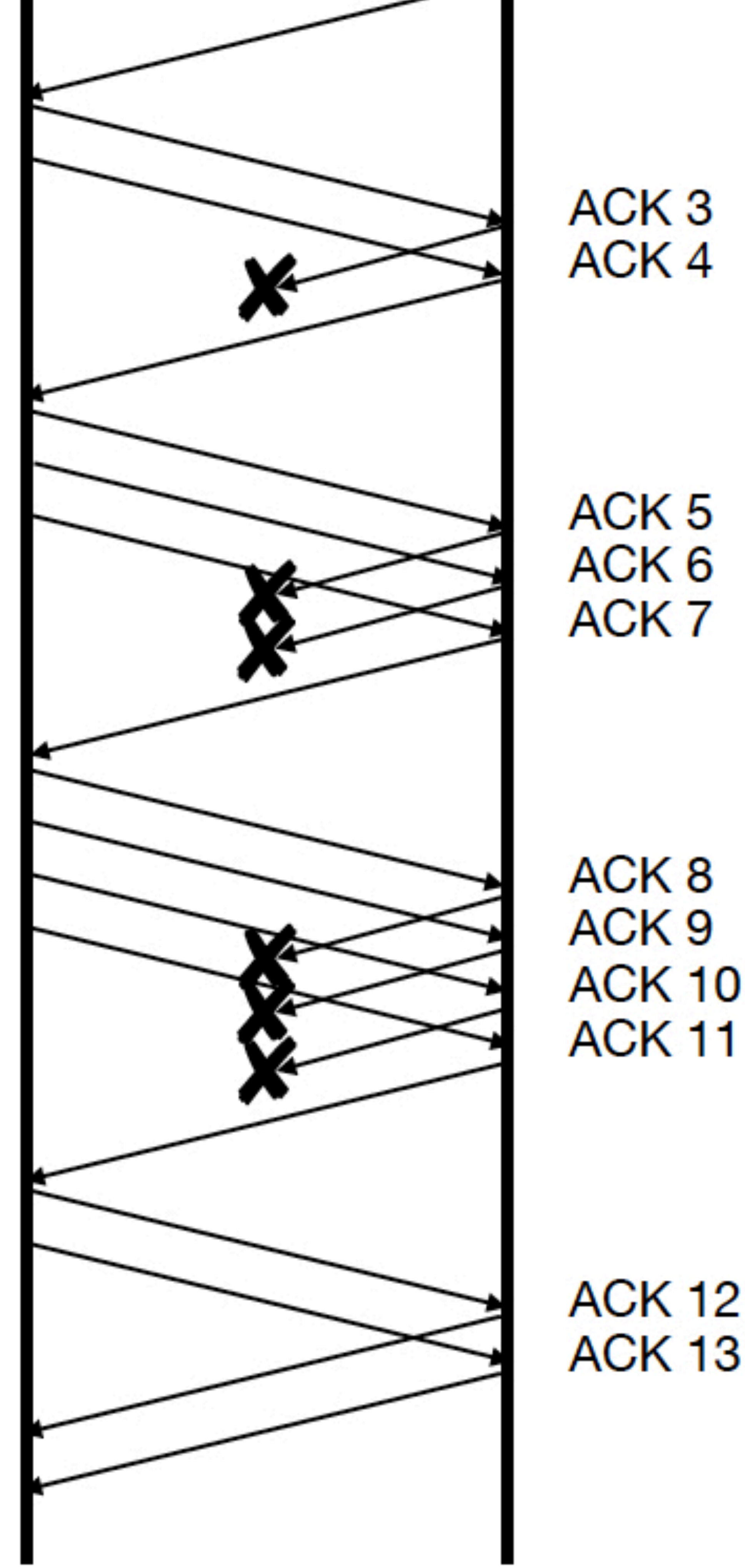
Bob's 3,5,6,8,9,10th segment lost



Alice sends 12 bytes of data

Bob's 3,5,6,8,9,10th segment lost

2	∞	SS	SEQ 2 SEQ 3
3	∞	SS	SEQ 4 SEQ 5 SEQ 6
4	∞	SS	SEQ 7 SEQ 8 SEQ 9 SEQ 10
5	∞	SS	SEQ 11 SEQ 12
6 7	∞	SS	



Exam material

- All lectures, homework, labs from semester start
- Emphasis on material after midterm
- Lab-related questions: <=20% of the points

Priorities

- Past final exams
  - solve them from start to end without looking at the solutions
- Lecture slides + homework
- Labs